

**LAND-USE CHANGE AND CARBON SINKS:  
ECONOMETRIC ESTIMATION OF THE  
CARBON SEQUESTRATION SUPPLY FUNCTION**

**Ruben N. Lubowski**

*John F. Kennedy School of Government  
Harvard University*

**Andrew J. Plantinga**

*Department of Agricultural and Resource Economics  
Oregon State University*

**Robert N. Stavins**

*John F. Kennedy School of Government  
Harvard University*

*and*

*Resources for the Future*

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*MPDvorscak*

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**Mark P Dvorscak**

**Date**

(630) 252-2393

E-mail: mark.dvorscak@ch.doe.gov

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## ABSTRACT

Increased attention by policy makers to the threat of global climate change has brought with it considerable interest in the possibility of encouraging the expansion of forest area as a means of sequestering carbon dioxide. The marginal costs of carbon sequestration or, equivalently, the carbon sequestration supply function will determine the ultimate effects and desirability of policies aimed at enhancing carbon uptake. In particular, marginal sequestration costs are the critical statistic for identifying a cost-effective policy mix to mitigate net carbon dioxide emissions. In this paper, we develop a framework for conducting an econometric analysis of land use for the forty-eight contiguous United States and employing it to estimate the carbon sequestration supply function. By estimating the opportunity costs of land on the basis of econometric evidence of landowners' actual behavior, we aim to circumvent many of the shortcomings of previous sequestration cost assessments. By conducting the first nationwide econometric estimation of sequestration costs, endogenizing prices for land-based commodities, and estimating land-use transition probabilities in a framework that explicitly considers the range of land-use alternatives, we hope to provide better estimates eventually of the true costs of large-scale carbon sequestration efforts. In this way, we seek to add to understanding of the costs and potential of this strategy for addressing the threat of global climate change.

# LAND-USE CHANGE AND CARBON SINKS: ECONOMETRIC ESTIMATION OF THE CARBON SEQUESTRATION SUPPLY FUNCTION

Ruben Lubowski, Andrew J. Plantinga, and Robert N. Stavins\*

## 1. INTRODUCTION

The possibility of expanding forest area as a means of sequestering carbon dioxide has received considerable attention because of concerns about the threat of global climate change due to the greenhouse effect (National Academy of Sciences (NAS) 1992; Bruce, Lee, and Haites 1996, Watson *et al.* 2000).<sup>1</sup> In general, forested land stores more carbon than land in other uses, such as agriculture, and thus afforestation (the conversion of non-forest land to forest) provides a means of increasing terrestrial carbon storage. Encouraging forest expansion 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).

The Kyoto Protocol, completed in December 1997, at the Third Conference of the Parties of the Framework Convention on Climate Change, explicitly recognizes carbon sequestration through forest expansion as a potentially important means of mitigating carbon dioxide (CO<sub>2</sub>) emissions (United Nations Environment Program 1998). According to the Protocol, countries can count carbon dioxide sequestered as a result of "direct human-induced land-use change and forestry activities, limited to afforestation, reforestation, and deforestation

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\* Lubowski is a candidate for the Ph.D. degree in Political Economy and Government at Harvard University; Plantinga is an Assistant Professor in the Department of Agricultural and Resource Economics at Oregon State University; and Stavins is the Albert Pratt Professor of Business and Government at the John F. Kennedy School of Government, Harvard University, and a University Fellow of Resources for the Future. The authors acknowledge support from the U.S. Department of Energy under grant number DE-FG02-99ER62742. All errors are the authors' responsibility.

<sup>1</sup> After fossil-fuel combustion, deforestation is the second largest source of carbon dioxide emissions. Estimates of annual global emissions from deforestation over the past decade range from 0.8 to 2.4 billion tons, compared with 5.7 to 6.9 billion tons annually from fossil-fuel combustion, cement manufacturing, and natural gas flaring, combined (Houghton *et al.* 1999, 2000; Watson *et al.* 2000). There are three pathways along which carbon sequestration is of relevance for atmospheric concentrations of carbon dioxide: carbon storage in biological ecosystems; carbon storage in durable wood products; and substitution of biomass fuels for fossil fuels (Richards and Stokes 1995).

since 1990" as a credit towards meeting their targeted reductions in gross CO<sub>2</sub> emissions (Article 3, Paragraph 3). The text is sufficiently ambiguous, however, that multiple interpretations quickly emerged.<sup>2</sup> The potential use of sinks by the United States in meeting its emissions reductions targets under the Protocol became a critical (and ultimately fatal) issue at the Sixth Conference of the Parties (COP-6) in The Hague in November, 2000.

The high level of interest in carbon sequestration 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 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; NAS 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.

Our focus is on the marginal costs of sequestering carbon by means of afforestation and reducing deforestation.<sup>3</sup> The marginal cost curve is equivalent to the sequestration supply function, which indicates the total carbon sequestered for given incentives provided to landowners for afforesting their land. Reliable estimates of marginal sequestration costs are critical inputs for researchers developing Integrated Assessment Models (IAMs) of global climate change to simulate both status quo and policy scenarios (Plantinga and Mauldin 2000) and for efforts to model the impact of land-use changes on the global environment (Turner *et al.* 1995).

In addition, knowledge of the carbon sequestration supply function is necessary for assessing the cost-effectiveness of carbon sequestration policies relative to other strategies for abating greenhouse gas concentrations. Most alternative strategies that have been discussed, such as carbon taxes or tradable carbon rights, aim at reducing carbon dioxide emissions by encouraging fuel switching or enhanced energy efficiency. For any target level of atmospheric

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<sup>2</sup> Watson *et al.* (2000) review different scenarios for defining and implementing Article 3.3 and the various implications for how much area and which types of land would be included under its provisions.

<sup>3</sup> Related approaches include increasing tree growth on existing forest lands through enhanced silvicultural practices and increasing the longevity of solid wood products.

CO<sub>2</sub> concentrations or any target of net change in concentrations, knowledge of the marginal costs of alternative mitigation options, including carbon sequestration, will permit policymakers to identify the portfolio of policies that will achieve the objective at minimum cost.

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; Masera, Bellon, and Segura 1995). In a number of cases, it has been assumed, implicitly or explicitly, that land (opportunity) costs are zero (Dixon, *et al.* 1994; New York State Energy Office 1993; Winjum, 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). Simulation models include a model of the lost profits due to removing land from agricultural production (Parks and Hardie 1995), a mathematical programming model of U.S. agricultural commodity and timber markets used to estimate the net loss of consumer surplus from higher food prices and lower timber prices related to changes in agricultural and forest land area (Adams, *et al.* 1993; Alig, *et al.* 1997; Adams, *et al.* 1999), a related model incorporating the effects of agricultural price support programs (Callaway and McCarl 1996), and a dynamic simulation model of forestry (Swinehart 1996).<sup>4</sup>

Each of these previous analyses has its own comparative advantages, and a number of the studies have absolute advantages along particular dimensions. Most of the previous analyses are limited by their inability to reflect the actual preferences of landowners, as revealed -- for example -- by landowners' decisions regarding the disposition of their lands in the face of

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<sup>4</sup> 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 surveys of the literature, see: Richards and Stokes 1995; and Sedjo, Wisniewski, Sample, and Kinsman 1994. The studies by Adams, *et al.* (1993), Alig, *et al.* (1997), and Adams, *et al.* (1999) have the distinction of being the only analyses that have included endogenous prices for relevant products.

relevant economic signals. There are a number of reasons why landowners' actual behavior might not be well predicted by "engineering" or "least cost" analyses: (1) land-use changes can involve irreversible investments in the face of uncertainty (Parks 1995), and so option values may be important (Pindyck 1991); (2) there may be non-pecuniary returns to landowners from forest uses of land (Plantinga 1997), 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; (4) risk-aversion may lead landowners to choose land uses to create a diversified portfolio of investments (Parks 1995); and (5) there may be private, market benefits or costs of alternative land uses (or of changes from one use to another) of which an analyst is unaware.

This study seeks to address some of the shortcomings of earlier analyses by employing an econometric model to derive the costs of carbon sequestration. The major advantage of the econometric approach is that estimates of marginal costs build directly upon observations of how landowners have actually responded to the economic incentives they continually face regarding the alternative uses of their lands. As such, the estimates may capture the effects on land conversion decisions of the factors noted above. The methods employed in this study build upon earlier work by Plantinga (1997), Plantinga, *et al.* (1999), Stavins (1999), Newell and Stavins (2000), and Plantinga and Mauldin (2000). Cost estimates in these studies are based on econometric estimates of the relationship between shares of land allocated to forest and agriculture and land rents or proxies for land rents. The authors estimate the costs of afforestation programs and policies to retard deforestation by simulating the effects of relevant taxes and subsidies on land-use allocations.

The earlier econometric-based analyses focused on relatively small geographic areas (for example, single states). In this study, we estimate the marginal costs of carbon sequestration at the level of the forty-eight contiguous United States. Moving to the national level requires that the methodology used in earlier studies be extended in several ways. First, while earlier analyses modeled just two land uses (forestry and agriculture), our broader geographical scope requires consideration of a wider range of land-use alternatives. Hence, rather than modeling shifts in land use between forestry and agriculture, we estimate a complete



matrix of transition probabilities among a set of possible land uses. Second, given the focus on relatively small regions in previous work, it was possible to treat land rents as exogenous. While plausible at a state or regional level, price exogeneity cannot be justified at a national level, and in this study we develop a model of agricultural commodity and timber markets to endogenize prices in our simulations.<sup>5</sup> Finally, a national analysis requires the development of a carbon accounting model that reflects regional variation in tree species, climatic conditions, wood processing and landfilling technologies, and end uses of wood products.

The remainder of this paper consists of four sections. Section 2 describes the econometric modeling approach. We begin with a description of the dynamic optimization problem for an individual landowner faced with the choice of allocating land among a set of alternative uses. From the solution to the landowner's decision problem, we specify an econometric model representing land-use change as a first-order Markov process. Markov transition probabilities are specified as functions of land-use decision variables, as identified by the landowner's optimization problem, and parameters to be estimated. Section 3 discusses the data which we plan to use to estimate the econometric model. We review our data, but do not include our (preliminary) econometric results. Our principal data source is the National Resources Inventory (NRI), which provides plot-level observations of land use and physical land characteristics at different points in time. County-level observations of net returns to alternative uses are constructed with data from a variety of sources. Section 4 describes the method by which we intend to derive the carbon sequestration supply function by drawing upon the econometric parameter estimates, as well as much additional information. We discuss the procedure to be used to simulate taxes and subsidies related to carbon sequestration, the model of agricultural commodity and timber markets to be used to endogenize prices, and our national carbon accounting model. Section 5 summarizes where this project currently stands.

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<sup>5</sup> In a partial equilibrium context, a given conversion tax/afforestation subsidy decreases agricultural production, thereby increasing agricultural product prices and carbon sequestration costs (since the opportunity cost of the land is increased). Likewise, a conversion tax/afforestation subsidy increases forest production, thereby decreasing timber prices and increasing carbon sequestration costs (since the private benefits of forestry relative to agriculture decrease). Thus, taking account of the potential endogeneity of agricultural and forest product prices may lead to greater sequestration cost estimates.

## 2. ECONOMETRIC MODELING FRAMEWORK

We develop a framework for using observed data on land-use decisions to estimate the probabilities that a landowner allocates his land to various uses based on the anticipated economic returns from those land-use alternatives and observed characteristics of the land.

### 2.1 Dynamic Optimization Model of Landowner Decision Making

Previous theoretical treatments of land-use decision-making have generally focused on land conversion between two uses (Stavins and Jaffe 1990, Plantinga 1996, Parks 1995).<sup>6</sup> In this section, we develop a theoretical model of a landowner's decision to allocate a parcel of land among a variety of possible uses. We cast the landowner's decision-making problem in a general dynamic programming framework so as to identify the effects of a broad range of factors that may affect the timing of land-use changes. We subsequently impose more restrictive assumptions and discuss the implications.

We focus on the problem of a landowner choosing how to use a small plot of land of homogeneous quality, given multiple land-use options. We posit that the landowner chooses the use at each point in time in order to maximize the present discounted value of the stream of expected future net benefits. Assuming that land-use returns are linear in the quantity of land, the size of the plot will not affect the relative profitability of alternative land use options. Assuming no spatial externalities, the land-use decision does not depend on the choices made for other plots. Thus, the land-use decisions for a larger area of heterogeneous quality can be viewed as the sum of land-use decisions regarding constituent uniform-quality plots.

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<sup>6</sup> A notable exception is Claassen (1993) who presents a theoretical model of land use choice with three uses in a deterministic setting. He uses a static optimization framework and views land as an input into production functions corresponding to different land-use options. Although his qualitative results are similar, our model differs from Claassen's in that the parcel size is fixed and the optimization problem is set in a dynamic framework in our approach. Lichtenberg (1989) and Hardie and Parks (1997) model the decision of a landowner choosing how to divide a heterogeneous land base among multiple crops and multiple land uses respectively. They highlight the importance of land quality in determining the optimal use for a parcel but do not specify the landowner's condition for land conversion. Albers (1996) derives numerical solutions for a model with three land uses in a dynamic programming framework with uncertainty and spatial externalities.

Consider a profit-maximizing landowner with a parcel of land of size  $L$ , with multiple land use options  $j$  ( $j=1, \dots, J$ ). The stock of land on the parcel in use  $j$  at time  $t$  ( $t=0, \dots, \infty$ ) is  $S_{jt}$  and thus  $\sum_{j=1}^J S_{jt} = L$  at all points in time. At starting time  $t=0$ , the parcel contains an initial stock  $S_{jt_0}$  of land in use  $j$ . At each point in time  $t$ , the landowner's problem is to choose how much of his land in each use to allocate to every other use so as to maximize the present discounted value of the stream of expected net benefits net of conversion costs:

$$\max_{a_{jkt}} \int_{t=0}^{\infty} \left\{ \sum_{j=1}^J E_t [R_{jt}] S_{jt} e^{-rt} - \sum_{j=1}^J \sum_{k=1}^K E_t [C_{jkt}(a_{jkt})] e^{-rt} + E_t [V_{t+1}] e^{-r(t+1)} \right\} dt \quad (1)$$

subject to:

$$\dot{S}_{jt} = \sum_{k=1}^K (a_{kjt} - a_{jkt}) \quad (2)$$

$$\sum_{k=1}^K a_{jkt} \leq S_{jt} \quad (3)$$

$$a_{jkt} \geq 0 \quad (4)$$

where:

$J = K =$  number of different land uses and ( $j=1, \dots, J$ ), ( $k=1, \dots, K$ );

$S_{jt}$  = stock of land on the parcel in use  $j$  at time  $t$  ( $t=0, \dots, \infty$ ), as noted above;

$a_{jkt}$  = number of acres converted from use  $j$  to  $k$  at time  $t$ ;

$R_{jt}$  = the instantaneous net benefits from an acre of land in use  $j$  at time  $t$ ;

$C_{jkt}(a)$  = total costs of converting  $a$  acres of land from use  $j$  to use  $k$  at time  $t$ ;

$r$  = discount rate ( $r > 0$ );

$V_{t+1}$  = the continuation value of the optimal program starting at time  $t+1$ .

The landowner's problem at time  $t$  is thus to choose  $JK$  control variables  $a_{jkt}$ , denoting the number of acres from each of the  $J$  stocks  $S_{jt}$  of land in use  $j$  to convert to possible use  $k$  at time  $t$ . By switching from use  $j$  to use  $k$  at time  $t$ , the landowner can earn returns  $R_k$  rather than  $R_j$  per acre but will incur a one-time conversion cost  $C_{jkt}(a)$  for  $a$  acres converted. Landowners

do not know variables  $R_{jt}$ ,  $C_{jkt}$ , and  $V_{t+1}$  with certainty. For simplicity, we assume that landowners are risk-neutral and thus base their decisions on expected values.<sup>7</sup>

As expressed by equation (2), there are  $j$  state variables,  $S_{jt}$ , which evolve according to the net effect of all conversions to use  $j$  from every other land use category minus all the conversion away from use  $j$  to every other category. Constraints (3) and (4) indicate that at most the entire stock of land in use  $j$  can be converted from  $j$  to any other use (or maintained in use  $j$ ) and that the amount of land converted must be non-negative.

Letting  $V_t(a_{jkt})$  equal the instantaneous payoff plus the continuation value given the choice of  $a_{jkt}$  at time  $t$ , the optimal solution is to choose  $a_{jkt}$  if  $V_t(a_{jkt}) \geq V_t(a_{jkt'})$  for all  $k \neq k'$ . Until now, we have imposed no restrictions on the continuation value  $V_{t+1}$ . How landowners view this value will be a critical determinant of their land-use choice. If land-use change is irreversible, then the expected continuation value which is obtained from converting to another use is the expected net present value of the stream of returns from staying in that use forever. The landowner's decision problem here is to choose a single optimal time of conversion  $T^*$  and a single optimal use to which to convert. If conversion is reversible, the problem becomes more complicated as  $V_{t+1}$  includes the maximum value of all future conversions which remain possible (including a return to the original use).

With multiple and reversible conversions, the dynamic programming problem requires identifying the sequence of conversions (a sequence of optimal conversion times and of uses to which to convert at each stage) which will maximize the current payoff plus the continuation value.<sup>8</sup> In addition to the possibility of future conversions, flexibility in terms of delaying land-use changes will alter the value of  $V_{t+1}$  in the case of uncertainty over the value of land-use choices. When land use conversion is irreversible (or at least there are costs of conversion), the

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<sup>7</sup> Parks (1995) discusses the case in which landowners are risk-averse and shows that a landowner will not convert all lands of a given quality to a single use as per condition (10) below. Instead, the landowner has an incentive to create a diversified portfolio of different land uses. Risk aversion introduces an additional term on the left hand side of equation (11), which captures the cost (benefit) from adding (reducing) risk by converting a marginal acre from use  $j$  to  $k$ . This term will be negative if moving lands from  $j$  to  $k$  increases the variance of returns to the land portfolio and positive if this decreases the variance.

<sup>8</sup> Amin and Capozza (1993) consider the problem of sequential conversions in terms of developing urban land and different levels of intensity. They find that allowing flexibility in terms of multiple allowable conversions increases land values and leads to earlier development at lower intensities than in the single conversion case.

presence of uncertainty generates an option value, which is part of the continuation value  $V_{t+1}$  from remaining in a particular use. As Titman (1985) first noted in the context of vacant land for urban development, the possibility of converting land to another use can be thought of as a call option, that is an option to purchase an asset with a different return for a given price (the conversion cost).<sup>9</sup>

In order to highlight other aspects of the land-use conversion problem in this paper, we do not incorporate option values. We model landowners' land-use choices as if they ignore the value of information to be gained by delaying irreversible decisions. More generally, we assume that landowners do not account for future conversion possibilities when evaluating alternative land-use options, including remaining in a given use. In other words, they only plan ahead one conversion at a time, acting as if all land-use choices are irreversible. This is not to say that land remains in a given use forever, but that landowners do not take into account future conversion possibilities when choosing a particular land use at a given time.<sup>10</sup>

Given these assumptions, the maximization problem in equation (1) becomes:

$$\max_{\{a_{jt}\}} \int_{t=0}^{\infty} \left\{ \sum_{j=1}^J E_t [R_{jt}] S_{jt} - \sum_{j=1}^J \sum_{k=1}^K E_t [C_{jkt}(a_{jkt})] \right\} e^{-rt} dt \quad (5)$$

subject to constraints (2), (3), (4).

Dropping the expectations operators for notational simplicity, the current value Hamiltonian with shadow prices  $\mu_j(t)$  ( $j=1, \dots, J$ ) is:

<sup>9</sup> More specifically, this option is an American option because generally there is no set date by which the land must be converted. Authors examining urban development have considered the case of conversion from an initial use with certain returns to a developed use with stochastic returns (Clarke and Reed 1988; Capozza and Helsley 1990; Williams 1991; Capozza and Li 1994; Capozza and Sick 1994). Schatzki (1998) considers the case of conversion between two land uses (forestry and agriculture) when returns to both uses are stochastic. Geltner, Riddiough, and Stovanovic (1996) examine the option to convert a parcel of land to the best of two developed uses with stochastic returns. Theoretically, the value of the option on one or more risky assets (land-use alternatives) will increase with the number of assets, the price of the assets, the interest rate, and the time to maturity and will decrease with the strike price (the conversion cost). Moreover, higher volatility and lower correlation among asset prices increases option value (Stultz 1982; Geltner *et al.* 1996).

<sup>10</sup> This assumption will be more problematic, the greater the differences in the continuation values of different land uses as determined by the differences in conversion costs. For example, if forestry is irreversible but cropping is not, then failing to consider this will lead the solution of the model to diverge from the true dynamic programming solution more than in the case where both uses are equally reversible.

$$\tilde{H} = \sum_{j=1}^J R_{jt} S_{jt} - \sum_{j=1}^J \sum_{k=1}^K a_{jk}(t) C_{jk}(t) + \sum_{j=1}^J \mu_j(t) \left\{ \sum_{k=1}^K [a_{kj}(t) - a_{jk}(t)] \right\} \quad (6)$$

The necessary and sufficient conditions for an optimum are:

$$-\frac{\partial \tilde{H}}{\partial S_{jt}} = \dot{\mu}_{jt} - r\mu_{jt} = -R_{jt} \quad (7)$$

$$\frac{\partial \tilde{H}}{\partial a_{jkt}} = -C'_{jkt}(a_{jkt}) + \mu_{kt} - \mu_{jt} \leq 0 \quad (8)$$

$$a_{jkt} \frac{\partial \tilde{H}}{\partial a_{jkt}} = a_{jkt} [C'_{jkt}(a_{jkt}) + \mu_{kt} - \mu_{jt}] = 0 \quad (9)$$

for all  $j$  and  $k$  along with constraints (2), (3), (4).

These conditions imply that if marginal conversion costs are constant ( $C'(a_{jkt})=0$ ) or decreasing ( $C'(a_{jkt})<0$ ), the following "bang-bang" solution will be optimal:<sup>11</sup>

$$a_{jkt} = \begin{cases} 0 \\ a_{jkt}^* \\ a_{jkt}^{\max} \end{cases} \left\{ \text{whenever } \frac{\partial \tilde{H}}{\partial a_{jkt}} = -C'_{jkt}(a_{jkt}) + \mu_{kt} - \mu_{jt} \begin{cases} < \\ = \\ > \end{cases} 0 \right. \quad (10)$$

Thus, when conversion from use  $j$  to  $k$  is desirable, the landowner should convert  $a_{jkt}^{\max}$ , the maximum amount of land in use  $j$  available for conversion. In the model presented here,  $a_{jkt}^{\max}$  simply equals  $S_{jt}$ , the total stock of land in use  $j$  at time  $t$ . However, as per Stavins and Jaffe (1990) and Parks (1995), some technical or resource constraint on conversion could be imposed so that  $a_{jkt}^{\max} \leq S_{jt}$ . Note that if the landowner has no land currently in use  $j$ , then  $a_{jkt}^{\max} = 0$ , so no land will be converted from  $j$  to  $k$  at time  $t$ .

Rearranging, the condition for conversion from use  $j$  to  $k$  becomes:

$$\mu_{kt} - C'_{jkt}(a_{jkt}) > \mu_{jt} \quad (11)$$

<sup>11</sup> If conversion costs are increasing in acreage so  $C'(a_{jkt})>0$ , there is a threshold level of  $a_{jkt}$  beyond which conversion costs rise high enough so that the inequality in equation (10) will no longer hold. If this threshold level is below  $a_{jkt}^{\max}$ , then lands will only be converted up to this threshold and the bang-bang solution will no longer be optimal.

Thus, the optimal policy calls for the landowner to convert all land in use  $j$  to  $k$ , when the shadow value of the land in use  $k$  (after deducting the costs of conversion) exceeds the shadow value of the land in use  $j$ . If the shadow value of the land in use  $k$  net of conversion costs is less than the shadow value in use  $j$ , then no land will be converted. If  $\mu_{kt} - C'_{jkt}(a_{jkt}) = \mu_{jt}$ , then the landowner is indifferent between the two land uses and the optimal conversion amount from use  $j$  to  $k$  is the singular solution  $a_{jkt}^*$ .

The difference between the multiple-use and the two-use models is that equation (11) is a necessary but not a sufficient condition for conversion to a particular use  $k$  when there are multiple uses. To see this, note that with multiple uses, equation (11) might hold for more than one use  $k$ . For example, the shadow value of land in forests minus the costs of conversion as well as the shadow value of land in urban use minus conversion costs might both exceed the shadow value of land in crops. The additional condition for conversion from use  $j$  to  $k$  is:

$$\mu_{kt} - C'_{jkt}(a_{jkt}) = \max\{\mu_{1t} - C'_{j1t}(a_{j1t}), \mu_{2t} - C'_{j2t}(a_{j2t}), \dots, \mu_{jt} - C'_{jjt}(a_{jjt})\} \quad (12)$$

All the land in use  $j$ ,  $a_{jkt}^{\max}$ , will be converted to the use  $k$  that has the highest shadow value net of conversion costs. Once all land is converted to the use with the highest value net of conversion costs, then no other use will dominate, so condition (8) will hold for all uses  $j$ . Thus, while forestry and urban uses might both be better options than maintaining a parcel in crops, the parcel will be converted to the option that is best.<sup>12</sup>

If we restrict our attention to the steady state,  $\dot{\mu}_{jt} = 0$ , then equation (7) becomes  $\mu_{jt} = \frac{R_{jt}}{r}$ , the present discounted value of an infinite stream of (expected) net returns  $R_{jt}$  from use  $j$ . Assuming the steady state values can be interpreted as assuming that landowners have static expectations. Substituting this value in equation (11) and rearranging terms yields the following condition for conversion from use  $j$  to  $k$ :

$$\frac{R_{kt}}{r} - C'_{jkt}(a_{jkt}) > \frac{R_{jt}}{r} \quad (13)$$

<sup>12</sup> Note that the first order conditions imply that  $a_{jkt}$  can only be positive for only one use  $k$  at time  $t$  (unless the shadow values of the two uses minus the conversion costs are identical).

Conversion from use  $j$  to  $k$  is optimal only if the (expected) present discounted value of an infinite stream of returns to use  $k$  minus conversion costs exceeds the (expected) present discounted value of an infinite stream of returns to use  $j$ .

We can also arrive at this condition by explicitly solving for the optimal time of conversion with two land uses. Under the assumption that landowners only think ahead one conversion at a time, the optimal time for converting land area  $S_j$  from use  $j$  to  $k$  is given by  $T_{jk}^*$  which solves:

$$\max_{T_{jk}} V_j = \left\{ \int_{t=0}^{T_{jk}^*} R_{jt} S_{jt} e^{-rt} dt + \int_{t=T_{jk}^*}^{\infty} [R_{kt} S_{kt} e^{-rt} dt] - C_{jkT_{jk}^*} (a_{jkT_{jk}^*}) e^{-rT_{jk}^*} \right\} \quad (14)$$

subject to  $T_{jk}^* \geq 0$ . The first order conditions are:

$$\frac{\partial V_j}{\partial T_{jk}^*} \leq 0 \text{ and } T_{jk}^* \frac{\partial V_j}{\partial T_{jk}^*} = 0.$$

Dropping the subscript on the  $T$ 's and letting  $C'$  denote the partial derivative of  $C$  with respect to, this implies that:

$$\frac{\partial V_j}{\partial T^*} = R_{jT^*} S_{jT^*} e^{-rT^*} - R_{kT^*} S_{jT^*} e^{-rT^*} + rC'_{jkT^*} (a_{jkT^*}) S_{jT^*} e^{-rT^*} - \frac{\partial C_{jkT^*}}{\partial T^*} S_{jT^*} e^{-rT^*} \leq 0 \quad (15)$$

Dividing by  $S_{jT^*} e^{-rT^*}$  and rearranging, the first order condition for the optimal conversion time becomes:

$$R_{kT^*} - rC'_{jkT^*} (a_{jkT^*}) + \frac{\partial C_{jkT^*}}{\partial T^*} \geq R_{jT^*} \quad (16)$$

The second order condition for an optimum conversion time is:

$$\frac{\partial R_{kT^*}}{\partial T^*} - r \frac{\partial C_{jkT^*}}{\partial T^*} + \frac{\partial^2 C_{jkT^*}}{\partial T^{*2}} \geq \frac{\partial R_{jT^*}}{\partial T^*} \quad (17)$$

As equation (16) indicates, the landowner will wait until time  $T^*$  such that the instantaneous return to use  $k$  minus the opportunity cost of delaying conversion costs plus  $\frac{\partial C_{jkT^*}}{\partial T^*}$  exceeds the instantaneous return to use  $j$ .  $\frac{\partial C_{jkT^*}}{\partial T^*}$  is the amount by which conversion costs will change over the instant  $T^*$  and can be viewed as a capital gain or loss to the current



land use caused by the change in conversion costs.<sup>13</sup> If conversion costs are expected to decrease, this term will be negative and conversion will be delayed. On the other hand, if conversion costs are expected to increase, this term will be positive and conversion will be accelerated.

Only current returns enter into equation (16) without any measure of future returns. However, converting according to this condition will only produce an optimum if the second order condition (17) also holds. This condition states that conversion from  $j$  to  $k$  will only be optimal when the net benefits from use  $k$  are rising faster than the net benefits from use  $j$  (minus the change in the opportunity cost of delaying conversion costs and the change in the capital gain from delaying conversion costs).<sup>14</sup>

Again, assuming static expectations, all derivatives with respect to time will be zero, and equations (16) and (17) collapse to  $R_{kT} - rC'_{jKT} \cdot (a_{jKT}) \geq R_{jT}$ . This is equivalent to condition (13), implying that optimal conversion from use  $j$  to  $k$  will occur when the expected net present value of returns to one acre of land in use  $k$  (equal to the discounted value of an infinite stream of the current return to use  $k$ ) net of conversion costs exceeds the expected net present value of returns to one acre of land in use  $j$  (equal to the discounted value of an infinite stream of the current return to use  $j$ ).

## 2.2 Econometric Specification for Estimating Probabilities of Land-Use Changes

In moving to the econometric model, we consider the case of the landowner's decision rule summarized in (13). According to this rule, the landowner will choose the use yielding the highest present discounted stream of returns net of conversion costs. Accordingly, for a

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<sup>13</sup> The conversion cost term may include both one-time windfalls as well as one-time costs of conversion. In Stavins and Jaffe (1990), for example, conversion of forest to crops entails a conversion cost  $C$  but also provides a one-time windfall of forestry revenue. An expected increase (decrease) in this windfall will delay (accelerate) conversion by raising (lowering) the opportunity costs of early conversion.

<sup>14</sup> Similar conditions have been derived for the optimal conversion times between agriculture and urban development (Plantinga and Miller 200, Capozza and Helsley 1990), for the irreversible development of vacant land (Arnott and Lewis 1979), for the conversion of land between crops and forestry (Stavins 1990), and for the optimal time to retrofit a house with energy-saving technology (Stavins and Jaffe 1994).

landowner with a parcel of land  $i$  ( $i=1, \dots, J$ ) in use  $j$  at the start of time  $t$ , the profit function may be written:

$$\pi_{ijt} = \max(NPV_{i1t} - C_{ij1t}, NPV_{i2t} - C_{ij2t}, \dots, NPV_{iJt} - C_{ijJt}) \quad (18)$$

where  $NPV_{ikt}$  is the net present value of returns from allocating parcel  $i$  to use  $k$  in time  $t$  and  $C_{ijkt}$  is the cost of converting parcel  $i$  from use  $j$  to use  $k$  in time  $t$  ( $C_{ijjt} = 0$ ). While we might assume the landowner knows the profit function with certainty, it is unlikely that we perfectly observe the landowner's decision variables. Thus, the landowner's profit function is assumed to contain observed and unobserved components, as follows:

$$\pi_{ijt} = \max(NPV_{i1t}^o - C_{ij1t}^o + \varepsilon_{i1t}, NPV_{i2t}^o - C_{ij2t}^o + \varepsilon_{i2t}, \dots, NPV_{iJt}^o - C_{ijJt}^o + \varepsilon_{iJt}) \quad (19)$$

where  $NPV_{ikt}^o$  and  $C_{ijkt}^o$  are observed net returns and conversion costs and  $\varepsilon_{ikt}$  is an unobserved error term ( $i=1, \dots, J$ ).

The probability that the owner of parcel  $i$  will convert the land from use  $j$  to  $k$  during time  $t$  is then:

$$pr(NPV_{ikt}^o - C_{ijkt}^o + \varepsilon_{ikt} \geq NPV_{iJt}^o - C_{ijJt}^o + \varepsilon_{iJt}) \quad (20)$$

for  $i=1, \dots, J$ . We assume the error terms have Generalized Extreme Value distribution, which gives us a nested logit model for estimation (McFadden, 1974). The non-nested specification of the probability that parcel  $i$  changes from use  $j$  to use  $k$  between  $t$  and  $t+1$  can be written:

$$P_{ijk} = \frac{\exp(\alpha_{jk} + \beta_{jk} NPV_{ikt}^o + \gamma_{jk} C_{ijkt}^o)}{\sum_{l=1}^J \exp(\alpha_{jl} + \beta_{jl} NPV_{iJt}^o + \gamma_{jl} C_{ijJt}^o)} \quad (21)$$

where the  $\alpha$ ,  $\beta$ , and  $\gamma$  are parameters assumed to vary by land-use transition, but not over time.  $P_{ijk}$  embodies the first-order Markov property since the probability of the parcel changing use depends only on decision variables in time  $t$ . With observations of  $I \times (T-1)$  land-use transitions, we can form the likelihood function:

$$\Psi = \prod_{i=1}^I \prod_{j=1}^J \prod_{k=1}^J \prod_{t=2}^T [P_{ijk}]^{y_{ijk}} = \prod_{i=1}^I \prod_{t=2}^T \prod_{k=1}^J P_{ijk} \quad (22)$$

where  $y_{ijk}$  equals 1 if parcel  $i$  changes from use  $j$  to  $k$  during period  $t$  and is 0 otherwise. Maximum likelihood procedures are used to derive parameter estimates, and the estimated

parameters can be used to form estimates of  $J \times J$  sets of non-stationary Markov transition probabilities,  $\{\hat{P}_{ijkt}\}$ .

### 3. DATA

This section describes the data used to estimate the econometric land-use model. We present summary statistics for a selection of plot-level variables and for all county-level variables in Tables (1.1) and (1.2) respectively.

#### 3.1 Land Use and Land Characteristics

We use plot-level data on land-use decisions and land characteristics from the Natural Resources Inventory (NRI) conducted by the USDA Natural Resources Conservation Service in cooperation with the Iowa State University Statistical Laboratory. The NRI is a panel survey of land use, land cover, soil characteristics, erosion, and conservation practices conducted at five year intervals on a sample of non-federal lands across the United States.<sup>15</sup> Data is currently available for 1982, 1987, and 1992, with the final data for 1997 forthcoming. We currently thus have observations on two land-use transitions for each plot and will add a third transition with the release of the 1997 data.

The NRI survey covers the entire United States except for Alaska and Washington, DC. We consider only the forty-eight contiguous states, dropping Hawaii and the Caribbean. We focus on plots which are privately-owned in all time periods, excluding federal, state, county, municipal and Indian and individual trust lands, because profit-maximization is unlikely to be a reasonable approximation of the decision-making criteria for these ownership groups.<sup>16</sup> We limit our analysis to private lands so as to focus on the types of lands which are likely to respond to economic incentives for carbon sequestration.

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<sup>15</sup> The NRI uses a random, stratified two-stage sampling scheme, and each NRI "plot" is a point observation which is assigned a particular acreage weight depending on the sampling features of that area. Each NRI plot can be identified to the level of the county (as well as to constituent hydrological units) (Nusser and Goebel 1997; Fuller 1999).

<sup>16</sup> Private lands cover approximately 1.3 billion acres between 1982 and 1997, representing about 70% of the total land area of the contiguous forty-eight states.

We further limit our focus to lands that can be classified in all time periods as either crops, pasture/range, forests, or urban/built-up.<sup>17</sup> We exclude lands under rural roads and transportation as these land uses are likely to change through a different decision-making process than profit maximization by private landowners. We also exclude streams and water bodies, marshlands, and "barren lands" such as sand dunes, permanent snow fields, and bare rock. Finally, we exclude about 8.12 million acres of additional private lands which the NRI classifies under "miscellaneous/minor" uses and which cannot be assigned to any of our four land-use categories.<sup>18</sup> With these adjustments, the land-base for our analysis comprises approximately 1.23 billion acres, representing about 66% of the total land area and about 94% of the privately-owned land area in the lower forty-eight states.

Summarizing this data for these forty-eight states, Tables (2.1) and (2.2) show the changes in the areas under the four major land uses during the periods 1982 to 1987 and 1987 to 1992 respectively. The diagonal elements of these tables show that land areas tend largely to remain in their previous use, with 98% to 99% of forest areas remaining in forests between 1982-1987 and 1987-1992. The tables also show that lands in pasture/range were the major source of new lands coming into forestry during the two transition periods. Urban uses were the major destination of lands leaving forests during these times.

In addition to data on land use, the NRI provides an extensive set of variables on land characteristics. These include soil quality descriptors that are composites of other factors: land capability class (LCC), hydric and highly erodible soil classification, and erodibility indexes for wind and water. The NRI also provides less aggregate variables including soil surface texture, irrigation type, flood proneness, wetland status, t-factor (soil loss tolerance), r-factor (rainfall factor), k-factor (inherent soil erodibility factor), i-factor (wind erodibility factor), slope class, slope length, and conservation practices established.

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<sup>17</sup> We group lands listed under the Conservation Reserve Program (CRP) as forests and pasture/range if the NRI reports their CRP contracted cover practice as either trees or grasses and legumes respectively.

<sup>18</sup> These lands include "other rural lands," Conservation Reserve Program lands under wildlife cover practice, and lands in agricultural uses unidentifiable as either crops or pasture/range ("farmsteads and ranch headquarters" and "other lands in farms").

### 3.2 Land-Use Returns and Conversion Costs

We calculate annual county-level per acre net returns for each year from 1978 to 1997 for four different land uses (crops, pasture/range, forestry and urban use). Returns for crops and pasture are naturally computed in annual terms. We derive annualized returns for forestry and urban use by multiplying net present value measures of returns from each use by an assumed interest rate. Below, we further describe our methods and data for measuring each of these sets of returns.

#### 3.2.1 Crops

To measure the returns from land in crops, we compute an annual county-level weighted average of the net returns per acre from different varieties of crops from 1978 to 1997. The weights are the proportion that the planted acreage of a particular crop represented of the total county's crop acreage in a given year, using acreage information from the National Agricultural Statistics Service (NASS) of the USDA. We consider the following major crop types tracked by NASS: wheat (winter wheat, durum wheat, and other spring wheat are treated separately), rye, rice, corn, oats, barley, sorghum, cotton, sugarcane, sugar beets, tobacco, flaxseed, peanuts, soybeans, sunflowers, all dry edible beans, hay (alfalfa hay and all other hay are treated separately), and potatoes.

To calculate gross per acre returns for each crop in each year, we multiply state-level market-year-average (MYA) prices from the USDA's Economic Research Service (ERS) by the average county-level yields.<sup>19</sup> These yields are derived by dividing the annual production of that crop by the planted acreage for each county obtained from NASS. In computing net returns, we use ERS data on total crop costs and returns at the level of multi-state crop production regions for twelve major crops (barley, corn, cotton, oats, peanuts, rice, sorghum, soybeans, sugar beets, sugarcane, tobacco, and wheat). We calculate the percentage that

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<sup>19</sup> Market-year-average prices are computed by weighing monthly prices by the amount of the crop marketed that month. Missing years in the state price series were imputed by extrapolation using the average trend of either a more inclusive commodity group for that state (such as "all wheat" instead of "winter wheat") or else the average of the trends for a particular crop from all bordering states. When possible, trends were computed and applied using a five-year average price as the baseline. Extrapolation procedures were similar for the forest and pasture prices below.

production costs represent of the total returns from a particular crop at the regional level.<sup>20</sup> Multiplying the county-level returns for that crop by one minus this percentage then yields the net returns from that crop.<sup>21</sup>

### 3.2.2 Pasture/Range

We base our measure of annual net returns to land under pasture/range on state-level per acre cash rental rates for pasture reported annually by the ERS (Jones 1997). We scale these state-level rents to the county-level using the ratio of the county-level yield for hay (all varieties) to the state-level average hay yield so as to account for differences in the productivity of growing forage at the county level.

### 3.2.3 Forestry

We compute annualized forestry returns using a weighted county-level measure of the net present value of sawtimber revenues from different forest types. We employ state-level stumpage prices for different timber species gathered from a variety of state and federal agencies and private data reporting services.<sup>22</sup> Whenever possible, we use state-level stumpage prices reported for private landowners obtained from state agencies or private data sources.<sup>23</sup>

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<sup>20</sup> We use the measures of cash (as opposed to economic) costs and returns, including direct government payments when those are reported. The cash costs include expenditures on seed; fertilizer, lime and gypsum; chemicals; custom operations; fuel, lube and electricity; repairs; hired labor; other variable cash expenses; general farm overhead; taxes and insurance; and interest. For crop varieties for which production cost data is not available, we use the state-level weighted average production cost percentage for all crops.

<sup>21</sup> NASS does not provide county acreage and production data for six states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont). For these states, we use an alternative method for calculating crop returns using data from the Census of Agriculture conducted in 1982, 1987, 1992, and 1997. We use total county-level cash returns from agricultural sales (minus sales of livestock and poultry) divided by the total acreage in crops in the county. We compute net returns using the Census data on the share that production costs represent of all agricultural sales in the county, including livestock and poultry, as crop costs are not separately reported.

<sup>22</sup> When sources report prices only at a sub-state level, we compute a weighted state-level price for each timber type using acreages of the relevant forest types in the price reporting regions.

<sup>23</sup> Stumpage prices are the prices for the timber in a standing tree and in theory will differ from delivered log prices (at the mill) by the amount of logging and transport costs. In the case of Indiana, as stumpage prices were unavailable, we compute "pseudo" stumpage prices, using delivered log prices, weighted by the average quality mix, and subtracting estimates of logging and hauling costs provided by Bill Hoover at Purdue University. For California and Eastern Washington, we use the stumpage price values reported by the state tax authorities for assessing timber tax rates.

When prices from private sales are not available, we employ stumpage prices from "cut and sold reports" for state forest timber sales or, otherwise, US Forest Service timber sales.<sup>24</sup>

We match our forest prices with regional merchantable timber yield estimates for different forest types developed by Richard Birdsey of the USDA Forest Service.<sup>25</sup> In order to match individual species prices (such as hard maple, soft maple, beech, yellow birch) with more aggregate forest types (such as maple-beech-birch), we weigh prices using state-level sawtimber production volumes from the Forest Inventory Analysis (FIA) Timber Product Output database for 1996. Using the Birdsey yields and these annual weighted prices, we then calculated the net present value of an infinite stream of forestry revenues for each forest type based on an optimal rotation age determined with the standard Faustmann formula. We assume a discount rate of 5% for the values reported in Table (1.2).

In computing the net present value measures, we assume that the forest starts at year zero in an already planted state; initial planting costs vary depending on the previous use and are dealt with separately as conversion costs. However, we include an estimate of replanting costs at the end of the first rotation in the calculation of the net present value and the optimal rotation length. We use regional estimates of planting costs plus annual management costs from Moulton and Richards (1990). Management costs are assumed to keep up with inflation while planting costs vary over time according to a cost index developed from data for the South from Dubois, McNabb and Straka (1999).<sup>26</sup> Finally, to construct county-level returns, we weigh the

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<sup>24</sup> We employ "cut" prices which are the prices actually paid when stands are harvested rather than the "sold" prices paid for timber to be harvested in the future. Cut prices have the disadvantage of being volume weighted composites rather than species-specific but provide a more precise measure of the stumpage value for a variety of reasons (Haynes 1998). We use stumpage prices from state forest sales for Idaho, Montana, and Oregon and data from US Forest Service sales in Colorado, Wyoming, Nevada, Utah, Arizona, New Mexico, and South Dakota. There remain seven states for which no stumpage price data is available: Delaware, Iowa, Kansas, Maryland, Nebraska, New Jersey, and North Dakota. We assign stumpage prices to these areas using prices for relevant timber species from neighboring states.

<sup>25</sup> We use yields for medium quality sites (site index 60 through 78). We convert volumes from cubic feet to board feet using regional conversion factors, differentiated by hardwoods and softwoods, from Haynes (1990). To make prices comparable across the nation, we convert prices to the international 1/4 inch log rule (a system for estimating the number of board feet in a log). If a particular data source reports a log rule conversion factor, we use that factor for the reported prices. Otherwise, we use the log rule conversions for Pennsylvania from Finley and Rickenbach (1996) as these are the most consistent with other sources.

<sup>26</sup> Our planting cost index is based on average seedling densities and on a weighted average of tree planting (hand and machine) and site preparation costs (mechanical and chemical) for an acre in the South.

state-level net present value measures for each forest group using county acreages from the FIA.<sup>27</sup>

### 3.2.4 Urban Use

We proxy the returns from developing a parcel of land in a county with the price of an acre of land used to build a single-family home. No county-level data exists on lot prices for developed land (the value of the land without a house). However, we construct a county-level annual measure of developed lot prices by taking county-level data on single-family home prices, which include both the value of the house and of the land, and backing out the price of the underlying land.

We obtain median county-level prices for single family homes for 1980 and 1990 from the decennial Census of Population and Housing Public Use Microdata Samples (PUMS 5% sample), which provide owner estimates of the price of single family-homes at the level of county groups and subgroups. We consider only the value of single-family houses built within the five years preceding each census to ensure that the prices reflect the characteristics of the houses being built in 1980 and 1990. Using 1980 and 1990 as base years, we can extrapolate yearly data for each year between 1980 and 1999 using the Office of Federal Housing Enterprise Oversight (OFHEO) House Price Index. Based upon repeat home sales data, this index tracks quarterly changes in the price of a single-family home for each U.S. state. While this data only provides the state average home price trend, we capture some of the county-level differences in annual home price changes by scaling the state trend up or down for each county to fit the change in home prices between 1980 and 1990 from the census.

To back out the underlying land price, we multiply our annual estimate of the median single-family home price in each county by an estimate of the median share that the value of the lot represents in the total price of a single-family home. We compute this "lot share" from data in the annual Characteristics of New Housing Reports (C-25 series) from Census Bureau and

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<sup>27</sup> Forest type compositions are likely to be highly correlated over time and we use weights based on a single FIA survey. When possible, we use the latest survey conducted prior to 1982, the date of the first NRI observation. For counties for which the FIA reports no data or zero forest areas, we assume the mean state-level forestry return for that year.



the U.S. Department of Housing and Urban Development. Based upon surveys of developers, these reports provide estimates of the price per square foot of single family homes sold (the price of the house plus the land) as well as an estimate of the price per square foot of the house excluding the value of the lot. This data thus permits the calculation of the lot share for single-family homes sold each year. The data from the C-25 reports from 1978-1995 is only at the level of the four main census regions. However, we scale these regional estimates to the level of metro and non-metro areas within each of the nine census divisions using the Survey of Construction (SOC) micro-data, available from 1995-1999.

Combining the home price and lot share data thus yields a measure of median lot prices for single-family homes in each county for each year from 1980 to 1999 (estimates going back to 1978 are obtained using the regional home price data from the Census of Construction reports). To obtain a per acre measure of developed lot values, we divide the estimated median lot prices in each county by an estimate of lot sizes derived from the C-25 reports (making the assumption of constant returns to scale in land). The C-25 reports from 1978-1995 only provide data on lot sizes at the national level but these are scaled to the level of metro and non-metro areas within each of the nine census divisions using the SOC micro-data.

### **3.2.5 Conversion Costs**

Tree planting cost estimates from Moulton and Richards (1990) provide estimates of conversion costs from crops to forests and pasture to forests for different regions of the country. As with the costs of reforesting stands after harvest, these costs are adjusted over time based on the cost indexes for the South constructed from Dubois, McNabb and Straka (1999).

## **4. THE CARBON SEQUESTRATION SUPPLY FUNCTION**

The econometric land-use model will be used to simulate policies for afforestation and derive the supply function for carbon sequestration. The first step is to establish a baseline land use scenario against which we can measure changes in land use induced by afforestation policies. The next step is to identify the form of the afforestation incentives and then integrate them into our econometric model to simulate land use under alternative levels of the incentives.

Conversion of agricultural land to forest decreases the supply of agricultural commodities and increases the future supply of timber, both of which affect the net returns to agriculture and forestry. We model endogenous price effects with a partial equilibrium model of agricultural commodity and timber markets. The final step is to measure the policy-induced changes in land use relative to the baseline and translate land-use changes into changes in terrestrial carbon storage. The carbon sequestration supply function is then derived by arraying per unit afforestation incentives against total carbon sequestration.

#### 4.1 Baseline Land Use

The baseline scenario describes how land use changes in the absence of any policies for afforestation. The baseline can be constructed in any number of ways, depending on what one wants to assume about future values of net returns and other variables in the model. For simplicity, we will focus here on a baseline in which all variables remain constant at their value in the initial year of the simulation (denoted year 0). In this case, the set of Markov transition probabilities and corresponding rates of land-use change remain constant throughout the baseline simulation.

The simulation begins with the total area of land in each use in the initial year 0, denoted by the vector  $\mathbf{A}_{m0} = (A_{1m0}, A_{2m0}, \dots, A_{Jm0})$  where  $A_{jmt}$  is the total area of land in use  $j$ , region  $m$ , and time  $t$ . For instance, we might start with the area of land in each use at the county- or state-level. For each county or state, we estimate the full set of Markov transition probabilities using the corresponding set of landowner decision variables (for example, county- or state-level average net returns) in year 0. This yields a  $J \times J$  transition probability matrix for each region,  $\Pi_m$ , where the elements of the matrix are the estimated probabilities,  $\hat{P}_{jkm}$ , defined as the probability that land in use  $j$  changes to use  $k$  in region  $m$ .<sup>28</sup> Baseline land use is determined by iteratively multiplying the transition probability matrix by the land-use vectors. In year  $t$  of the simulation, baseline land use is given by:

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<sup>28</sup> The transition probability matrix and the transition probabilities would be further indexed by time were we to allow for changes in the model variables (for example, net returns) during the simulation period.

$$\mathbf{A}_{m,t}^b = \mathbf{A}_{m,t-1}^b \mathbf{\Pi}_m^b = \mathbf{A}_{m,t-2}^b (\mathbf{\Pi}_m^b)^2 = \dots = \mathbf{A}_{m,0} (\mathbf{\Pi}_m^b)^t \quad (23)$$

The matrix of land-use changes between  $t-1$  and  $t$ , denoted  $\mathbf{\Omega}_{m,t}^b$ , is recovered by multiplying the probabilities in the  $j$ th row of  $\mathbf{\Pi}_m^b$  ( $\hat{P}_{j1m}, \hat{P}_{j2m}, \dots, \hat{P}_{jJm}$ ) by the total area of land in use  $j$  in period  $t-1$  ( $A_{j,t-1}^b$ ).

#### 4.2 Policy Simulations

The next step involves identification of policies to encourage afforestation. We follow Stavins (1999) and consider a two-part policy that combines a subsidy for afforested land with a tax on forest land conversion. In the context of the landowner model presented above, the necessary condition for conversion (of a one-acre parcel of land in use  $j$ ) to forestry (use  $k$ ) is:

$$NPV_{ikt} - C_{ijk} + Z_t \geq NPV_{ilt} - C_{ijl} \quad (24)$$

for all uses  $l \neq k$ , where  $Z_t$  is the per-acre subsidy in time  $t$ . Alternatively, the condition for preventing conversion of land in forestry (use  $k$ ) to use  $l$  is:

$$NPV_{ilt} - C_{ilt} - Z_t \geq NPV_{ikt} \quad (25)$$

where  $Z_t$  is the per-acre conversion tax in time  $t$ . For a variety of reasons, a symmetric tax/subsidy with identical values for the two instruments is not necessarily efficient, but it is a reasonable first approximation for our purposes (Stavins 1999).

The effects of the combined conversion subsidy and tax are simulated by modifying in similar fashion the  $NPV$  expressions embedded in the transition probabilities. The conversion subsidy increases the probability that land in use  $j$  is converted to forestry (use  $k$ ). That is, provided the subsidy applies to all land,  $\hat{P}_{jkm}$  increases for all values of  $j=1, \dots, J$ . The conversion tax decreases the probability that land in forestry (use  $k$ ) shifts into other uses, or  $\hat{P}_{kjm}$  decreases for all values of  $j=1, \dots, J$ . For each level of the subsidy and tax, changes in the transition probabilities define the new transition probability matrix  $\mathbf{\Pi}_m(Z)$ . Land use in the simulation period is computed as above. In year  $t$  of the simulation, the land-use vector is given by:

$$\mathbf{A}_{m,t}(Z) = \mathbf{A}_{m,t-1}(Z) \mathbf{\Pi}_m(Z) = \mathbf{A}_{m,t-2}(Z) [\mathbf{\Pi}_m(Z)]^2 = \dots = \mathbf{A}_{m,0} [\mathbf{\Pi}_m(Z)]^t \quad (26)$$

The corresponding matrix of land-use changes between  $t-1$  and  $t$  is given by  $\Omega_{mt}(Z)$  and computed as above.

### 4.3 Endogenous Price Effects

We have assumed that agricultural commodity and timber prices remain constant in the baseline, but we need to consider how prices are affected by land-use changes resulting from the afforestation policy. Specifically, in period  $t$ , the policy-induced net change in land use relative to the baseline is given by  $\Delta A_{mt}(Z) = A_{mt}(Z) - A_{mt}^b$ . We are developing a partial equilibrium model of agricultural commodity and timber markets that will allow us to estimate price effects for separate regions, agricultural commodities, and timber species. We focus on output prices (for example, for timber and crops) and assume input prices are exogenous.

To illustrate the basic approach, we consider the change in the area of a single land use, cropland (use  $j$ ), given by  $\Delta A_{jt}(Z)$ . Further, for ease of exposition, assume there is only one crop produced, with output price  $P_{jt}$ , yield  $Y_{jt}$ , and exogenous production costs  $C_{jt}$ . Assuming the crop is inelastically supplied, the change in the total output of the crop resulting from the change in land use is  $\Delta Q_{jt}(Z) = Y_{jt} \times \Delta A_{jt}(Z)$ . Suppose there is a constant price elasticity of demand for the crop given by  $\epsilon_j$ .<sup>29</sup> Then, the estimated percentage change in price is  $\% \Delta P_{jt}(Z) = \% \Delta Q_{jt}(Z) / \epsilon_j$ , where  $\% \Delta Q_{jt}(Z)$  is the change in output in percentage terms, and the new crop price is  $\tilde{P}_{jt}$ . Given our assumption of static price expectations, the net present value of crop returns becomes  $(\tilde{P}_{jt} Y_{jt} - C_{jt}) / r$ .

This expression is incorporated into the transition probabilities, resulting in the new matrix  $\tilde{\Pi}(Z)$  and a new value of crop area changes  $\tilde{\Delta A}_{jt}(Z)$ . This procedure is repeated until the changes in crop area converge to an equilibrium, denoted  $\Delta A_{jt}^*(Z)$ .

In practice, estimation of endogenous price effects is more complicated. First, we need to account for different varieties of crops. As noted above, the net present value expressions

<sup>29</sup> Elasticity estimates are being collected through an extensive review of demand studies in the agricultural and forest economics literature.

are formed by computing a weighted average of the discounted net revenue streams for different crops, where the weights are county crop shares. If we assume the weights are fixed,<sup>30</sup> we can apportion the total change in cropland area to the individual crops and proceed as above, utilizing crop-specific demand elasticities. Changes in the net returns to forestry present more of a challenge because, in addition to modeling multiple tree species, we must account for the delay between the conversion of land to forest and the increase in timber output. This delay occurs because it takes a period of years for the forest to become established and then for trees to grow to merchantable size. The simplest approach is to assume that the length of the growth period is fixed and that price changes occur at the end of the period. Alternatively, we might recognize that the length of the growth period depends on prices and is thus itself endogenous.

#### **4.4 Translating Land-Use Changes into Carbon Sequestration**

Carbon is stored in biomass, soils, and other components of agricultural and forest lands. On cropland and pasture, most of the carbon is found in soils. On forest lands, a large amount of the carbon is also found in above-ground biomass (for example, tree stems) and below-ground biomass (for example, root systems). Over time, carbon in agricultural soils tends to build up until it reaches a steady-state level. Steady-state carbon is influenced by management practices, particularly the use of conventional or conservation tillage on cropland and the intensity of grazing on pasturelands. In an undisturbed forest, the total amount of carbon will also tend toward a steady-state. The level of steady-state carbon varies with species, site productivity, previous land uses, and management intensity.

Periodic harvesting of trees from the forest converts a substantial portion of the carbon in the forest back to CO<sub>2</sub>, including most of the carbon in the litter and understory vegetation and some of the carbon in trees (for example, nonmerchantable parts of trees such as branches). Current evidence suggests that typical timber harvesting operations do not greatly affect the carbon in forest soils. The merchantable portion of trees is processed into primary wood products such as lumber and paper, which typically release additional CO<sub>2</sub> (for example,

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<sup>30</sup> In general, the crop shares would depend on output prices and, thus, would also be endogenous.

wood waste is burned for energy production). Additional carbon is converted to CO<sub>2</sub> when primary products are processed into end-use products and end-use products are disposed. However, carbon may remain fixed in end-use products (for example, lumber used in home construction) and landfills for decades and even centuries following a harvest.

In order to estimate carbon sequestration resulting from the afforestation policies, we need to translate the matrices of equilibrium land-use changes ( $\Omega_{mt}^b$  and  $\Omega_{mt}^*(Z)$  for each time  $t$  during the simulation period and level of  $Z$ ) into changes in carbon storage. To accomplish this task, we have developed a carbon budget for the U.S. that accounts for carbon in three uses (forest, cropland, and pasture) over time. The model parameters reflect regional differences in tree species, cropping patterns, climatic conditions, and other factors affecting carbon sequestration. The model also tracks the carbon in timber harvested from forests as it moves through processing, use, and disposal stages. For each possible land-use transition, we describe below the basic structure of the carbon budget model.

#### 4.4.1 Changes from Cropland and Pasture to Forest

Consider land in cropland or pasture (use  $j$ ) in region  $m$  that is converted to forest (use  $k$ ) in time 0. If this change occurs in the baseline, an estimate of the acres of afforested land is given, from above, by  $\hat{P}_{jkm} A_{jm0}$ . The following equation gives the carbon stored in the forest at time  $t$ :

$$FC_{jm}(0, t) = \hat{P}_{jkm} A_{jm0} \sum_l SP_{lm0} \times (TR_{lmt} + US_{lmt} + FL_{lmt} + SO_{jlm}) \quad (27)$$

where  $SP_{lm0}$  is the percentage of forests in the region composed of species  $l$  in time 0, and  $TR_{lmt}$ ,  $US_{lmt}$ ,  $FL_{lmt}$ , and  $SO_{jlm}$  are tons of carbon in the tree, understory vegetation, floor litter, and soil components, respectively, of the forest in time  $t$  (species  $l$ , region  $m$ ). Soil carbon is indexed by  $j$  since the previous land use determines the initial level of carbon in the soils. The data on carbon in forests comes from recently updated versions of the carbon yield tables originally presented in Birdsey (1992). Data on tree species composition is from forest inventories conducted periodically by the U.S. Department of Agriculture, Forest Service.

#### 4.4.2 Changes from Forest to Cropland and Pasture

From above,  $\hat{P}_{kjm} A_{km0}$  gives the baseline acres of forest (use  $k$ ) converted into cropland or pasture (use  $j$ ) in region  $m$  and time 0. Suppose the average age of trees in the forest is  $a$  at the time of conversion and the trees are processed into wood products, then the following equation gives the release of  $\text{CO}_2$  at the time of harvest:

$$HC_m(a,0) = \hat{P}_{kjm} A_{km0} \sum_l SP_{lm0} \times [NTR_{lmu} + US_{lmu} + FL_{lmu} + MTR_{lmu} \times (1 - WP_{lm0})] \quad (28)$$

where  $NTR_{lmu}$  and  $MTR_{lmu}$  are the carbon in the non-merchantable and merchantable portions, respectively, of  $a$  year-old trees and  $WP_{lm0}$  is the portion of carbon in merchantable trees sequestered in wood products, landfills, etc., immediately (0 years) after harvest. The carbon sequestered in wood products declines over time as these products are processed and disposed. The amount of carbon remaining  $t$  years after harvest is given by:

$$HC_m(a,t) = \hat{P}_{kjm} A_{km0} \sum_l SP_{lm0} \times MTR_{lmu} \times WP_{lmt} \quad (29)$$

A similar procedure is used to account for carbon removed from forests through periodic timber harvests.

Following the timber harvest, the carbon in the soils adjusts from the amount at harvest ( $\sum_l SP_{lm0} \times SO_{lmu}$ ) to the steady-value value corresponding to agricultural use  $j$  ( $AC_{jmo}$ ). The amount of carbon in the soils  $t$  years after conversion is:

$$AC_{jm}(0,t) = \hat{P}_{kjm} A_{km0} \left\{ AC_{jmo} + \left[ \sum_l (SP_{lm0} \times SO_{lmu}) - AC_{jmo} \right] e^{-\lambda_m t} \right\} \quad (30)$$

where  $\lambda_m$  is the rate at which soil carbon adjusts to the steady-state value. The adjustment rate depends on climatic conditions in region  $m$ .

#### 4.4.3 Changes from Cropland to Pasture and from Pasture to Cropland

To model shifts between cropland and pasture, we need to account only for carbon in soils. As above, it is assumed that soil carbon adjusts from its level at the time of conversion to the steady-state level corresponding to the new land use. For land converted from agricultural use  $j$  to use  $k$  in time 0, the carbon in soils after  $t$  years is:

$$AC_{km}(0, t) = \hat{P}_{jkm} A_{jm0} [AC_{km\infty} + (AC_{jm0} - AC_{km\infty}) e^{-\lambda_m t}] \quad (31)$$

where  $AC_{jm0}$  is the soil carbon associated with use  $j$  at the time of conversion.

#### 4.5 Derivation of the Carbon Sequestration Supply Function

Using the carbon budget model described above, changes in carbon storage associated with baseline land-use changes are computed from each year during the simulation period. A similar calculation is made for equilibrium land-use changes associated with each level of the subsidy/tax. The difference between the two is the net carbon sequestration resulting from the afforestation policy, which we denote  $CS_{mt}(Z)$ . In general,  $CS_{mt}(Z)$  will vary over the course of the simulation and may take negative values.

The intertemporal nature of net carbon sequestration raises a question: how can we associate a number – the marginal cost of carbon sequestration – with units of carbon that are sequestered in different years? This is important if we wish to compare the costs of carbon sequestration with the costs of conventional carbon abatement measures, such as fuel switching and energy-efficiency enhancements. Previous sequestration studies have used a variety of methods to calculate costs in terms of dollars per ton, the desired units for a cost-effectiveness comparison (Richards and Carrie Stokes 1995). We follow Stavins (1999) and consider the ratio of the discounted present value of costs to the discounted present value of tons sequestered. This may be thought of as assuming that the marginal damages associated with additional units of atmospheric carbon are constant and that benefits (avoided damages) and costs are to be discounted at the same rate. Such an assumption of constant marginal benefits is approximately correct if marginal damages are essentially proportional to the rate of climate change, which many studies have suggested.

To derive total costs for a given level of the subsidy/tax, we must compute the product of  $Z$  and the difference between the acres afforested and deforested in the simulation and the baseline. Specifically, the present value of total costs in region  $m$  equals:

$$PTC_m(Z) = \sum_t \frac{Z \times [\sum_j A_{jmt}^* P_{jkm}^* - A_{jmt}^b \hat{P}_{jkm}^b]}{(1+r)^t} \quad (32)$$



and the present value of carbon sequestered is  $PCS_m(Z) = \sum_t CS_{m,t}(Z) / (1+r)^t$ , where  $r$  is the discount rate. Having computed  $PTC_m(Z)$  and  $PCS_m(Z)$  for a range of values of  $Z$ , the carbon sequestration supply function is constructed by arraying changes in  $PCS_m(Z)$  per unit of carbon against total carbon sequestered.<sup>31</sup>

## 5. CONCLUDING COMMENTS

In a preliminary paper such as this, which consists of no more than theoretical modeling plus a description of our data, it is not possible to offer substantive conclusions. Instead, we use this final part of the paper to summarize the highlights of our work thus far, and to speculate on the challenges that lie ahead.

We have developed a theoretical and empirical framework for estimating a marginal cost function for carbon sequestration from afforestation and reduced deforestation in the contiguous forty-eight U.S. states. This framework is grounded in a procedure for the econometric estimation of the parameters of a matrix of Markov transition probabilities among a set of multiple land use alternatives. We have constructed a database of county-level economic returns for the four major land uses so as to estimate these parameters using plot-level data on land use changes from the National Resources Inventory. In addition, we have developed a procedure and gathered the necessary biophysical information to construct a carbon sequestration supply function based on the estimated econometric parameters.

Our study expands on previous work in its national scope, which requires the consideration of an array of land-use categories in the theoretical and empirical models as well as a method for endogenizing land use returns in the simulation phase. In addition, by estimating a Markov matrix of land use transition probabilities among a variety of land uses, we enable examination of the carbon sequestration consequences of gross rather than net land use changes. We incorporate information on the carbon sequestration changes resulting from

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<sup>31</sup> As currently written, we are considering the opportunity cost of land that moves into forest use (or is prevented from leaving forest use). Since it seems unlikely that the subsidy/tax policy which we model would have the effect of inducing land-use changes among the other use categories (that is, between cropland, pasture, and developed use), the results ought not to be sensitive to this construction of the problem.

transitions between forests and all the other major land use categories; we also include the effects of regional variation in various biological and economic factors that affect carbon sequestration levels.

Conducting the econometric estimation and the policy simulation in practice will entail various challenges related to the large scale of our modeling effort. In addition to the computing challenges of working with a large data set, we face the challenge of ensuring that we have included all the appropriate variables to account for the cross-sectional and longitudinal variation. We will test empirically whether coefficients are constant across the whole nation and across time periods or whether it is more appropriate to estimate the model separately for different regions and time periods. A related challenge in the estimation will be accurately specifying the impacts of the numerous land quality variables on land use returns as well as the role of current and historical prices in landowner expectations.

An important feature of the work in constructing the marginal cost curve for carbon sequestration will be studying the sensitivity of the results to different economic assumptions and scenarios as well as to different carbon accounting assumptions. Finally, future extensions of this work could incorporate additional complexities at all of the stages of the analysis. In particular, we will explore means to incorporate the effects of uncertainty and spatial autocorrelation into the empirical estimation of the land use transition probabilities. We also aim to incorporate additional factors during the simulation phase, including accounting for endogenous changes in the average quality of lands allocated to different uses. In this way, we seek to develop a nation-wide econometric model of land-use changes and use it to provide better estimates of the costs of large-scale carbon sequestration efforts.

**Table 1.1**  
**Summary of Select Plot-Level Variables<sup>32</sup>**

<b>Variable</b>	<b>Number of Observations</b>	<b>Mean</b>	<b>Standard Deviation</b>	<b>Minimum</b>	<b>Maximum</b>
Plot in crops in 1982	716,972	0.354	0.478	0	1
Plot in crops in 1987	716,972	0.339	0.473	0	1
Plot in crops in 1992	716,972	0.317	0.465	0	1
Plot in pasture/range in 1982	716,972	0.266	0.442	0	1
Plot in pasture/range in 1987	716,972	0.264	0.441	0	1
Plot in pasture/range in 1992	716,972	0.271	0.445	0	1
Plot in forests in 1982	716,972	0.290	0.453	0	1
Plot in forests in 1987	716,972	0.285	0.451	0	1
Plot in forests in 1992	716,972	0.279	0.448	0	1
Plot in urban use in 1982	716,972	0.090	0.286	0	1
Plot in urban use in 1987	716,972	0.112	0.315	0	1
Plot in urban use in 1992	716,972	0.133	0.339	0	1
Plot irrigated <sup>2</sup>	716,972	0.018	0.135	0	1
NRI acre weight (acres/plot)	716,972	1719.711	1983.658	100	181,100
Plot in wetland	716,972	0.049	0.216	0	1
Land Capability Class <sup>33</sup>	716,972	3.666	2.297	1	8
Slope percentage <sup>2</sup>	716,972	3.003	6.094	0	90
t-factor (soil tolerance)	716,972	3.433	1.876	0	5

<sup>32</sup> Plots included in this table cover lands which remained privately owned and in the four major uses between 1982 and 1992, as discussed in more detail in section 3.1

<sup>33</sup> Average of values reported in 1982, 1987 and 1992.

<b>k factor (erodibility factor)</b>	<b>716,972</b>	<b>0.237</b>	<b>0.141</b>	<b>0</b>	<b>0.64</b>
<b>flood proneness</b>	<b>716,972</b>	<b>0.217</b>	<b>0.675</b>	<b>0</b>	<b>3</b>
<b>Plot in Conservation Reserve Program</b>	<b>716,972</b>	<b>0.023</b>	<b>0.151</b>	<b>0</b>	<b>1</b>

Table 1.2

Summary of County-Level Variables (Years 1978-1997)  
(monetary values in 1990 dollars<sup>1</sup>)

Variable	Number of Observations	Mean	Standard Deviation	Minimum	Maximum
Annualized urban profit/acre <sup>2</sup>	62,220	1,862.96	2437.31	149.67	47,936.13
Annualized crop profit/acre	62,220	59.68	77.89	-241.95	6,575.47
Annual pasture profit/acre	62,220	18.28	8.19	0.51	90.46
Annual forest profit/acre <sup>3</sup>	62,220	4.52	9.75	-4.17	192.33
Annualized conversion cost (crop to forest) <sup>2</sup>	62,220	4.92	2.01	2.69	12.06
Annualized conversion cost (pasture to forest) <sup>2</sup>	62,220	6.16	2.70	2.97	14.40

<sup>1</sup> Monetary values are deflated using the producer price index for all commodities from the Bureau of Labor Statistics.

<sup>2</sup> Values are annualized by multiplying a net present value measure times a 5% interest rate.

<sup>3</sup> Forest returns are calculated by estimating a net present value using a 5% discount rate and then multiplying this by a 5% interest rate. Costs for intensive management practices are used in this estimate.

**Table 2.1**

**Changes in Major Private Land Uses between 1982 and 1987  
in the Lower Forty-Eight States\*  
From National Resources Inventory (NRI)  
(in thousands of acres)**

Land Use In 1982	Land Use In 1987				
	Cropland	Pastureland/ Rangeland	Forest Land	Urban Land	1982 Total
<b>Cropland</b>	379,671 93.61%	21,706 5.35%	2,626 0.65%	1,571 0.39%	405,574 100%
<b>Pastureland/ Rangeland</b>	12,046 2.72%	423,769 95.65%	5,639 1.27%	1,594 0.36%	443,047 100%
<b>Forest Land</b>	1,015 0.30%	1,904 0.56%	334,878 98.52%	2,111 0.62%	339,907 100%
<b>Urban Land</b>	1 0%	0 0%	2 0%	44,454 100%	44,456 100%
<b>1987 Total</b>	392,732 31.85%	447,379 36.28%	343,144 27.83%	49,730 4.03%	1,232,985 100%

\*Percentages are of 1982 totals (far right column). Totals include only lands which remained privately owned and in the four major uses between 1982 and 1992, as discussed in more detail in section 3.1. Read the table horizontally to see how land that was under a particular land use in 1982 (row heading) was subsequently divided in terms of land use in 1987 (column heading). Read the table vertically to see where land that was in a particular land use in 1987 (column heading) was previously divided in terms of land use in 1982 (row heading).

**Table 2.2**

**Changes in Major Private Land Uses between 1982 and 1987  
in the Lower Forty-Eight States\*  
From National Resources Inventory (NRI)  
(in thousands of acres)**

Land Use In 1987	Land Use In 1992				
	Cropland	Pastureland/ Rangeland	Forest Land	Urban Land	1982 Total
<b>Cropland</b>	362,454 92.29%	25,930 6.60%	2,675 0.68%	1,674 0.43%	392,732 100%
<b>Pastureland/ Rangeland</b>	8,211 1.84%	433,573 96.91%	3,723 0.83%	1,872 0.42%	447,379 100%
<b>Forest Land</b>	503 0.15%	1,671 0.49%	338,488 98.64%	2,482 0.72%	343,144 100%
<b>Urban Land</b>	1 0%	1 0%	1 0%	49,728 99.99%	49,730 100%
<b>1992 Total</b>	371,168 30.10%	461,174 37.40%	344,888 27.97%	55,755 4.52%	1,232,985 100%

\*Percentages are of 1987 totals (far right column). Totals include only lands which remained privately owned and in the four major uses between 1982 and 1992, as discussed in more detail in section 3.1. Read the table horizontally to see how land that was under a particular land use in 1987 (row heading) was subsequently divided in terms of land use in 1992 (column heading). Read the table vertically to see where land that was in a particular land use in 1992 (column heading) was previously divided in terms of land use in 1987 (row heading).

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