AN ABSTRACT OF THE DISSERTATION OF

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Title: Three Essays on the Economics of Climate Change, Land Use and Carbon Sequestration

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Andrew J. Plantinga

This dissertation's three essays explore the effects of climate change on land use changes in the U.S., how future land areas in all major land uses change by projecting land use at the regional scale under two IPCC climate change scenarios. Investigate how and what role should carbon sequestration plays as a mitigation strategy given uncertainty of climate impacts and, estimate how responsive the demand for and the supply of urban land is to changes in its price and how different climatic variables effect both the supply and the demand for urban land.

The first essay uses an econometric model to project regional and national land-use changes in the U.S. under two IPCC climate change scenarios. The key driver of land-use change in the model is county-level measures of net returns to five major land uses. The net returns are modified for the IPCC scenarios according to assumed trends in

population and income and projections from integrated assessment models of agricultural prices and agricultural and forestry yields. For both scenarios, we project large increases in urban land by the middle of the century, while the largest declines are in cropland area. Significant differences among regions in the projected patterns of land-use change are evident, including an expansion of forests in the Mountain and Plains regions with declines elsewhere. Comparisons to projections with no climate change effects on prices and yields reveal relatively small differences. Thus, our findings suggest that future land-use patterns in the U.S. will be shaped largely by urbanization, with climate change having a relatively small influence.

The second essay explores the optimal time path of carbon sequestration and carbon abatement in stabilizing CO_2 levels under uncertainty of climate impacts. We question the conventional wisdom that carbon sequestration should be used as a near-term strategy by recognizing the fact that sequestration, unlike abatement, can actually remove CO_2 from the atmosphere. Two related models are examined: a deterministic fixed end point and finite time horizon model and a two-period sequential decision making model. In the latter, uncertainty regard the stabilization level of the atmospheric stock is resolved prior to the decision on how much to control the stock in the second period. Present value costs of abatement and sequestration are minimized subject to two state variables; the level of CO_2 stock in the atmosphere and the stock of suitable land that can be converted to forestland. Both models show that carbon sequestration may play an important role in climate change mitigation under certain conditions. In addition, the stochastic model finds that an increase in the variability of climate impacts results in higher rates of abatement today while leaving some sequestration capacity as a safety value for the future.

In the third essay, a structural model of the demand for and the supply of urban land is estimated using panel data on 3032 counties in the contiguous U.S for the four time periods 1982, 1987, 1992 and, 1997. A two-step estimation procedure is applied. In the first step, fixed effects and time-varying variables are used to estimate the structural system of demand and supply equations via Two-Stage Least Squares (2SLS) procedure. This yields consistent estimates of the structural equations' parameters. The model is then extended to a hierarchical linear model. The contribution of observed time-invariant variables in explaining counties fixed effects is investigated. Among these variables are climatic and geographical variables that are assumed to affect both the supply and the demand for urban land, though in potentially different ways. Results suggest inelastic supply and demand at the national and regional levels with the exception of an elastic demand in the West region. Examined climatic and geographical variables are found to have significant effects on both the supply of and the demand for urban land.

Three Essays on the Economics of Climate Change, Land Use and Carbon Sequestration

by

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APPROVED:

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I understand that my dissertation will become part of the permanent collection of Oregon State University Libraries. My signature below authorizes release of my dissertation to any reader upon request.

David Haim, Author

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Three Essays on the Economics of Climate Change, Land Use and Carbon Sequestration

CHAPTER ONE

INTRODUCTION AND OVERVIEW

The relationship between climate change and land use is complex. Climate change can directly affect commodity yields by changing temperature and precipitation patterns, the distributions of pests and disease, and the frequency and severity of forest fires. Climate change can also result in the loss of land area due to sea level rise in coastal areas. Climate change also can have indirect effects through markets. Changes in the prices for agricultural and forestry commodities or the availability of water for irrigation create incentives for landowners to reallocate their land to more profitable uses. As well, climate change may induce human migration (e.g., people may leave hotter and drier areas), affecting the demand for urban land.

Land is also an important component of the climate system. Land-use change, particularly deforestation in tropical areas, is a key factor in the increase of greenhouse gas concentrations in the atmosphere, along with fossil fuel use (WG I, IPCC, 2007). Land-use change can also play a role in mitigating the effects of greenhouse gas emissions. Afforestation and reforestation of land can reduce atmospheric CO_2 concentrations and many studies suggest that the costs of forest carbon sequestration are low compared to energy-based approaches (e.g., Stavins and Richards 2005). Forest and urban lands also have direct effects on temperature and precipitation patterns.

This dissertation's three essays explore the effects of climate change on land-use changes in the United States, how future land areas in all major land uses change by projecting land use at the regional scale under two IPCC climate change scenarios. Investigate how and what role should carbon sequestration play as a mitigation strategy while taking into account the fact that sequestration, unlike abatement, can actually remove CO_2 from the atmosphere and, understand how uncertainty regard future climate impacts influences near term versus long term deployment of sequestration. Estimate how responsive the demand for and the supply of urban land is to changes in its price and how different climatic variables effect the supply and the demand for urban land. .

Specifically, the first essay (Chapter 2), *Climate Change and Future Land Use in the United States: An Economic Approach,* uses an econometric model to project regional and national land-use changes in the United States under two IPCC climate change scenarios. This study contributes to the literature in several ways. First, we include all major land uses (crop, pasture, forest, urban, and range) and allow for movement of land among all categories. Second, in addition to timber yields, we consider effects of climate change on agricultural yields and prices and urbanization. Third, we present results for 6 regions covering the contiguous U.S. Finally, the econometric land-use model used in our study was estimated with historical data on the decisions made by private landowners in response to the incentives they faced. Our model can, thus, capture a number of factors that affect land-use decisions in practice (e.g., irreversibilities giving rise to option value, private non-market benefits from the land) but that are difficult to represent in sectoral optimization models. Key finding suggests that future land-use patterns in the U.S. will be shaped largely by urbanization, with climate change having a relatively small influence.

The second essay (Chapter 3), *The Optimal Time Path for Carbon Abatement and Carbon Sequestration under Uncertainty: The Case of Stochastic Targeted Stock*, explores the optimal time path of carbon sequestration and carbon abatement in stabilizing CO_2 levels under uncertainty of climate impacts. We question the conventional wisdom that carbon sequestration should be used as a near-term strategy by recognizing the fact that sequestration, unlike abatement, can actually remove CO_2 from the atmosphere. The contribution of this study to the literature is twofold. First, to our knowledge, this is the first deterministic optimal control study of abatement and sequestration reductions strategies to look at the problem of controlling CO_2 emissions for a fixed end point and finite time horizon. That is, the question that we ask is: what is the optimal way to use carbon sequestration and carbon abatement given that we would like to reach a predetermined target (a specific stabilization level of the atmospheric stock) at a given time? Second, by developing a two period sequential decision making model, we show analytically that as uncertainty about the variability of climate impacts increases, more sequestration capacity should be saved for the future as a safety valve. At the present time, we are unaware of an analytical study that carries out such an analysis.

In the third essay (Chapter 4), *Climate Change and Future Urban Development: An econometric Analysis of the Demand and Supply of Urban Land*, a structural model of the demand for and the supply of urban land is estimated using panel data on 3032 counties in the contiguous U.S. for four time periods 1982, 1987, 1992 and, 1997. To our knowledge, the proposed study is the first one to estimate the price elasticity of demand for and the price elasticity of supply of urban land at the county-level in the United States. All previous work has focused on either specific locations (e.g., cities in a specific state) or metropolitan areas in the U.S. Price elasticity estimations at the county-level are an important extension in the context of climate change research. A key finding in the first essay of this dissertation is that future land-use patterns in the U.S. will be shaped largely by urbanization. This result, however, assumes a perfectly elastic demand for urban land across the nation. This, in turn, may lead us to over predict urban land expansion. Incorporating price elasticity estimates of the demand for urban land as well as the supply of urban land in such projections will result in a better understanding of future land use in the United States. Furthermore, we sort out the effects of climate variables on demand for and supply of urban land separately. At the present time we are unaware of a study that quantifies such effects on the demand for and the supply of urban land. Results suggest inelastic supply and demand at the national and regional levels with the exception of an elastic demand in the West region. Examined climatic and geographical variables are found to have significant effects on both the supply of and the demand for urban land.

The three essays together improve the understanding of climate change impacts on major land uses in the United States and on short term and long term deployment of terrestrial carbon sequestration in climate change mitigation. Results have important implications on future land-use policies, especially with regards to urbanization processes drive by demographic changes and climate change polices in coping with uncertain future impacts of climate change.

CHAPTER TWO

CLIMATE CHANGE AND FUTURE LAND USE IN THE UNITED STATES: AN ECONOMIC APPROACH

2.1. Introduction

The relationship between climate change and land use is complex. Climate change can directly affect commodity yields by changing temperature and precipitation patterns, the distributions of pests and disease, and the frequency and severity of forest fires. Climate change can also result in the loss of land area due to sea level rise in coastal areas. Climate change also can have indirect effects through markets. Changes in the prices for agricultural and forestry commodities or the availability of water for irrigation create incentives for landowners to reallocate their land to more profitable uses. As well, climate change may induce human migration (e.g., people may leave hotter and drier areas), affecting the demand for urban land.

Land is also an important component of the climate system. Land-use change, particularly deforestation in tropical areas, is a key factor in the increase of greenhouse gas concentrations in the atmosphere, along with fossil fuel use (WG I, IPCC, 2007). Land-use change can also play a role in mitigating the effects of greenhouse gas emissions. Afforestation and reforestation of land can reduce atmospheric CO_2 concentrations and many studies suggest that the costs of forest carbon sequestration are low compared to energy-based approaches (e.g., Stavins and Richards 2005). Forest and urban lands also have direct effects on temperature and precipitation patterns.

Integrated Assessment Models (IAMs) are commonly used for assessing policy options for climate change mitigation. These comprehensive, global models combine key elements of natural and economic systems into a framework that allows for scenario analysis, such as those conducted by the Intergovernmental Panel on Climate Change (IPCC). Although IAMs are getting better at projecting climate change at fine spatial scales, they are still limited in this regard (WG III, IPCC 2007). Land-use decisions, in particular, are made at small scales and depend on site-specific conditions. Fine-scale differences in land quality, crop types, forest species, and other factors affecting land use are difficult to represent in a global model, but such information is critical to understanding the implications of climate change on a regional level. Effective strategies to mitigate and adapt to climate change are likely to include local, regional, and national responses. Downscaling the predictions from IAMs is, thus, needed to facilitate the design of effective and efficient policies to cope with climate change.

This paper estimates land-use changes in the United States for different IPCC scenarios. A land-use projection model is developed from an econometric model of land use originally used in a national (U.S.) analysis of the cost of sequestering carbon in forests (Lubowski 2002; Lubowski, Plantinga, and Stavins 2006). The econometric model was modified to enable regional land-use projections that are a central part of the 2010 Resources Planning Act assessment conducted by the U.S. Forest Service (Plantinga et al. 2007; Alig et al. 2010). The key driver of land-use change within the model is county-level measures of net returns to five major land uses (crop, pasture, forest, range, and urban). The net returns provide the critical link between private land-use decisions and the IPCC emissions scenarios. As such, we are able to project land-use change at regional scales within a framework that accounts for a high degree of heterogeneity among the determinants of land use.

We evaluate agricultural price projections under the A1 and A2 IPCC emissions scenarios, as well as agricultural and forestry yield changes under two closely-related scenarios, A1b and A2b. In each case, we adopt the population and income assumptions from the IPCC's Special Report on Emissions Scenarios (SRES) that underlie, respectively, the A1 and A2 emissions scenarios. The first step is to establish the link between these factors and the county-level net returns variables in our model. This is straightforward in the case of agricultural prices because county returns are a function of prices for globally-traded agricultural commodities. For the population, income, and yield projections, additional analysis was needed. For example, we developed a secondary model that relates net returns to urban land to changes in county-level demographic variables. In the second step, we develop projections of net returns consistent with the SRES scenarios. Then, finally, the land-use model is used to make projections to the middle part of this century of land use by category (crop, pasture, forest, range, and urban) and for six U.S. regions (west, mountain, plains, midwest, northeast, and south).

Our projection under climate change incorporates all climate-induced effects on net returns discussed above. On a national scale, we project large increases in urban land under the A1 and A2 emissions scenarios, while the largest declines are in cropland area. Significant differences exist among regions in the projected patterns of land-use change.

To gain insights into the importance of climate change for future land use, we develop a baseline projection without climate change. Recent historical changes in agricultural prices and agricultural and forestry yields are examined and used to develop baseline values. We find little difference between the projections of land use under the climate change scenarios and our baseline scenarios with no climate change. This suggests that urbanization is likely to be the main driver of future land-use changes in the U.S.

Important caveats to this research are noteworthy. First, we are unable to account for all of the potential impacts of climate change on land use (e.g., effects transmitted through global timber markets). Second, we do not model feedbacks into the global models. IAMs represent a closed economic and climate system and, within these models, feedbacks exist between changes at smaller scales to processes operating at higher scales. For example, regional changes in cropland area affect the global quantity of agricultural commodities produced and, thus, the prices at which these commodities trade in global markets.[1] Our land-use model is not integrated with the IAMs used to produce the IPCC scenarios and, thus, we cannot account for such feedbacks. The full coupling of global IAMs with regional-scale models is the desired long-term goal. The downscaling of climate change effects that we achieve in the research reported here is an important and necessary step in the overall process.

[1] How important these feedback effects are depends on how large regional land use changes are relative to the rest of the world. In the case of agricultural markets, the U.S. accounts for about 40% of the world's corn production but only 12% and 2%, respectively, of world wheat and rice production.

The paper is organized as follows. In the next section we review prior economic studies on the effects of climate change on U.S. agriculture and forestry, and indicate our contribution to this literature. Section 3 introduces the IPCC and baseline projections for the key variables in the study. In section 4 we describe the land-use projection model and the methods used to link IPCC projections to the county net returns. Regional projection results for the A1, A2, and baseline scenarios are presented in section 5, and section 6 concludes.

2.2 Literature Review

In recent years, an active economics literature has examined effects of climate change on U.S. agriculture (Mendelsohn et al. 1994; Schlenker et al. 2005, 2006; Deschenes and Greenstone 2007). In these studies, hedonic price models are estimated that relate county-level farmland values to climate variables such as temperature and precipitation. These models are then used to simulate the effects of climate change on the value of U.S. agricultural production. The advantage of the hedonic approach, relative to earlier studies based on crop production functions, is that it can better account for adaptation to climate change such as crop switching and shifts of land in or out of agriculture. Mendelsohn et al. (1994) find smaller impacts on U.S. agriculture compared to earlier studies, and in some cases their results indicate a positive overall effect. In a later study, Mendelsohn et al. (1999) found important effects of inter-annual and diurnal climate variation on farmland values. Increases in inter-annual climate variation were predicted to be harmful for U.S. agriculture whereas decreases in diurnal variation were found to be beneficial. Studies of agricultural sectors in other countries have yielded similar results (Kurukulasuriya and Ajwad 2007, Kurukulasuriya and Mendelsohn 2007).

Schlenker et al. (2005) argue that economic effects of climate change should be assessed differently for regions where agriculture is primarily dependent on irrigation as compared to rain-fed regions. Focusing on just the rain-fed areas in the U.S., the authors find larger effects than in Mendelsohn et al. (1994): declines from 10% to 25% in farm values (-$3.1 to -$7.2 billion annually) under four IPCC scenarios. Large regional differences were evident, with northern counties experiencing as much as a 34% increase in farm values from climate change and southern counties facing a decline as high as 69%. Schlenker and Roberts (2009) caution against the use of mean temperature in the analysis of climate change impacts on agriculture. They find that yields for major crops increase with temperature but then fall quickly at temperatures above a certain threshold.

A number of analyses have also examined impacts of climate change on the U.S. forestry sector. Sohngen and Mendelsohn (1998) estimate effects on U.S. timber markets by integrating an optimal control model with climate change scenarios and ecosystem model predictions. This framework allows for optimal dynamic responses to climate change, such as changes in forest management and selection of different tree species. The results show a net economic benefit to the U.S. timber sector ranging from 1 to 33 billion dollars annually. Other studies support these findings for U.S. timber productivity (Joyce et al. 2000, Alig et al. 2002, Sohngen and Sedjo 2005) as well as for global timber productivity (Perez-Garcia et al. 2002, Sohngen et al. 2001). At the regional level, productivity is more likely to rise in the Northern United States and to decline in the

Southern United States in response to low to moderate warming (Shugart et al. 2003, Sohngen and Sedjo 2005). In addition, the net gains in welfare tend to favor consumers over producers (Alig et al. 2002, Sohngen and Sedjo 2005).

Only a few studies have explored the combined effects of climate change on the agricultural and forestry sectors. Joyce et al. (2000), as a part of the national assessment of climate change, stated that land would likely shift between forest and agricultural uses as these two sectors adjust to climate change. In a related study, Alig et al. (2002) used a dynamic, nonlinear programming model of the U.S. agriculture and forestry sectors to evaluate four climate change scenarios from the national assessment. Their model, FASOM, solves for competitive market equilibrium by maximizing net surplus in agricultural and forestry markets, while allowing for land to move between agricultural and forest uses. In the climate change analysis, the authors modify timber yields under four alternative climate scenarios. They project a lower forest area in all scenarios relative to the base case with no climate change. Furthermore, climate change results in less cropland, but more pasture, being converted to forest under all scenarios.

Most of the studies discussed above focus on either the agriculture or forestry sector and do not explicitly account for exchanges of land between the sectors (Alig et al. 2002 is an exception). We extend their analysis in a number of respects. First, we model all major land uses (crop, pasture, forest, urban, and range) and allow for movement of land among all categories. Second, in addition to timber yields, we consider effects of climate change on agricultural yields and prices and urbanization. Third, we present results for 6 regions covering the contiguous U.S. Finally, the econometric land-use model used in our study was estimated with historical data on the decisions made by private landowners in response to the incentives they faced. Our model can, thus, capture a number of factors that affect land-use decisions in practice (e.g., irreversibilities giving rise to option value, private non-market benefits from the land) but that are difficult to represent in sectoral optimization models.

2.3. IPCC and Baseline Scenarios

Two scenarios (out of four alternative scenario families) from the IPCC 4th assessment, namely A1 AIM and A2 ASF, are applied in this study. These scenarios are storylines that represent different future developments regarding population growth, economic growth, energy use, and technological driving forces of greenhouse gas (GHG) and aerosol precursor emissions. We adopt the population and income assumptions for these two scenarios to develop associated projections of urban returns. We modify agricultural returns with projections of agricultural prices produced for each of these scenarios from an IAM. Finally, we incorporate agricultural and forest yield changes under two closely-related IPCC scenarios, A1b and A2b. Henceforth, we refer to the A1 AIM and A1b scenarios as A1 and A2 ASF and A2b as A2.

The national summary of population and income assumptions for the A1 and A2 scenarios are shown in Table 2-1 (Langner 2010). Population and personal income increase gradually to 2060. The population growth rate in the A2 scenario is the highest, producing a 13 percent larger population by 2060 relative to the A1 scenarios. The A1 scenario has higher personal income, which by 2060 is 44 percent larger than for the A2 scenario.

Most agricultural commodities are traded internationally and, therefore, it makes sense to focus on how climate change will affect global agricultural prices. Fischer et al. (2002) conducted an integrated global ecological-economic assessment of the effects of climate change on food and agricultural systems. The authors employed IIASA's Basic Linked System (BLS), a computable general equilibrium model that represents all of the major economic sectors, including agriculture, together with the FAO/IIASA Agro-ecological Zones (AEZ) model, which can assess the effects of climate change on agricultural systems. Using these models, Fischer et al. (2002) developed global agricultural price indices for the two IPCC scenarios discussed above (Table 2-2). The general pattern of price changes is similar under the two scenarios, with prices dropping by 2010 and rising until 2080. However, the levels differ by scenario, with A2 showing higher prices by 2080 than A1.

In Table 2-3, we summarize land productivity measures for the A1 and A2 scenarios produced with an ecological model (MAPSS) and three climate models (CSIRO, MIROC, Hadley). Overall, these models predict rising productivity in forest ecosystems, as measured by aboveground carbon in forests. With the MIROC climate model under the A2 scenario, however, there is a reduction over time in forest carbon, and with the HADLEY climate model under the A1 scenario during 2020-2040. Rising forest carbon translates into increased net growth in forested ecosystems and greater forest biomass in forest stands.

When examining agricultural productivity, net primary productivity (NPP) is a measure of potential growth in ecosystems, and thus provides an indication of potential changes in growth of agricultural crops. NPP rises in several scenarios and declines in others. For instance, NPP rises under each of the CSIRO climate model scenarios (A1 and A2), as well as the HADLEY scenarios, while it falls in the MIROC A1 and A2 scenarios.

In later sections, we develop a projection with no climate change in order to identify the importance of climate change for future land use. This requires that we specify baseline values for agricultural prices and agricultural and forest yields.[2] The challenge is to develop baseline values that are not influenced by expectations of climate change. We do this by examining recent historical changes in these variables and extrapolating these changes to the future. There were fluctuations in real prices for major agricultural commodities (corn, soybeans, and wheat) in the U.S. between 1976 and 2007, but the mean price was stationary.[3] Therefore, we adopt a no-change baseline for real agricultural commodity prices. Tweeten and Thompson (2008) report that between 1960 and 2010, the average 5-year percentage changes in U.S. corn, soybean, and wheat yields per acre were 9.04%, 5.57%, and 5.18%, respectively. For our baseline, we assume that agricultural yields will increase by 6% per acre every 5 years. Because most

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[2] As noted above, we adopt the assumed trends in population and income that underlie the A1 and A2 scenarios.
[3] See the agricultural price series provided by the U.S. Department of Agriculture, National Agricultural Statistics Service (www.nass.usda.gov)

U.S. forests are not intensively managed for yield gains, we adopt a no-change baseline for forest yields.

2.4. Methods

We describe here the methods used to project land use under the A1 and A2 IPCC scenarios. In the first subsection, we discuss the land-use projection model. The key driver of land-use change in the projection model is county-level measures of net returns to cropland, pasture, forest, urban, and rangeland. These variables are modified under the IPCC scenarios according to assumed changes in population and income and predicted changes in global agricultural prices, NPP, and forest carbon. Climate-induced changes in relative net returns affect the optimal allocation of land among uses (see Segerson et al. 2006 for a standard theoretical treatment). Subsequent subsections discuss how these projections are scaled down to the county level and linked to the net returns measures. A final subsection describes the scenarios we analyze.

<u>2.4.1 Land-use projection model</u>

Land-use projections are done with a model developed for the Resources Planning Act (RPA) assessment, a periodic evaluation of the nation's natural resources conducted by the U.S. Department of Agriculture, Forest Service. The projection model was built from a national econometric model of land use originally developed for a national-scale analysis of the cost of sequestering carbon in forests (Lubowski 2002; Lubowski, Plantinga, and Stavins 2006). The original econometric model was modified for use in the RPA assessment, as described in Plantinga et al. (2007) and Alig et al. (2010).

Below, we describe the essential features of the projection model and refer interested readers to the publications cited here for more details.

The National Resources Inventory (NRI) is the primary data set used by Lubowski (2002) to estimate a national econometric land-use model. The NRI is a panel survey of land use/cover and land characteristics on non-Federal lands conducted at five-year intervals from 1982 to 1997 for the entire United States, excluding Alaska. Data include approximately 844,000 plot-level observations, each representing a land area given by a sampling weight. For the model used here, NRI data for the 1992-1997 land-use transition were used. The econometric analysis focuses on the 48 contiguous states and six major land uses: crops, pasture, forest, urban, range, and cropland enrolled in the Conservation Reserve Program (CRP).[4] The land base in the study comprises 1.4 billion acres, representing about 74% of the total land area and about 91% of non-Federal land in the contiguous United States (wetlands and other miscellaneous uses are excluded).

The dependent variable in the econometric model is the choice of land use in 1997 at each NRI plot and the independent variables are the land use in 1992, the land quality rating of the plot, and measures of the lagged (1992) net returns from each land-use alternative. The land quality measure is based on the Land Capability Class (LCC) rating of the NRI plot, as described by the U.S. Department of Agriculture (1973). By assembling data from a variety of private and public sources, Lubowski (2002) constructed county-level estimates of annual net returns per acre for crops, pasture,

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[4] For reporting our results, we will include land in the CRP in the cropland category. We treat it as a separate category here to be consistent with the categories in the econometric model.

forest, range, and urban uses for 3,014 counties in the 48 contiguous states.[5] Because the net returns variables provide the link between land use and the climate scenarios, we describe them in detail.

For agricultural and forest uses, the general expression for the net return in county *c* is:

$$NR_c = \sum_n s_{nc}(p_{nc}q_{nc} - c_{nc}) \qquad (1)$$

where s_{nc} is the weight for commodity type *n* in county *c*, p_{nc} is the per-unit price for commodity type *n* in county *c*, q_{nc} is the per-acre average yield of commodity type *n* in county *c*, and c_{nc} is the per-acre cost of producing commodity type *n* in county *c*. For crop net returns, s_{nc} is the share of the total cropland area in county *c* devoted to crop *n*, and p_{nc}, q_{nc}, and c_{nc} are crop- and county-specific prices, yields, and costs. For forest net returns, $(p_{nc}q_{nc} - c_{nc})$ is the annualized net revenue from timber type *n* assuming the stand is grown on an economically optimal (Faustman) rotation and a 5% discount rate is used, and s_{nc} is the county share of total forest land area in timber type *n*. The net returns to pasture and range are defined for single commodities (pasturage and forage, respectively) using corresponding data on prices, yields, and costs.[6] Finally, urban net returns are estimated as the annualized median value of a recently-developed

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[5] Net returns estimates are, thus, constructed for all of the land-use categories, except for CRP which is modeled using a different procedure discussed in Lubowski (2002).

[6] Prices for pasturage and forage are difficult to measure directly. Lubowski (2002) used the price of hay to measure the price of pasturage and grazing rates to measure the price of forage.

one-acre parcel used for a single-family home, less the value of structures. Below, we describe how components of net returns such as prices and yields are modified according to the climate change scenarios.

Landowners are assumed to have static expectations of future net returns and to allocate their land to the use generating the highest return net of conversion costs.[7] Net returns are assumed to have deterministic and random components. The deterministic component includes the county net return, land quality dummy variables, and the interaction between the two variables. This specification allows for plot-level deviations from the average county return. Distributional assumptions (see Train 2003) are imposed on the random components of net returns to yield a nested logit model for estimation. Three nests include land uses with similar land quality requirements: crops, pasture, and CRP; forest and range; and urban. The econometric estimation yields probabilities for transitions between each of the six land uses. These probabilities are functions of independent variables and estimated parameters:

$$P_{ijkt} = P(\hat{\boldsymbol{\beta}}_{jk}, \mathbf{NR}_{it}, LQ_i) \qquad (2)$$

where P_{ijkt} denotes the probability that plot *i* changes from use *j* to *k* during the 5-year interval beginning in year *t*=1992, $\hat{\boldsymbol{\beta}}_{jk}$ is a vector of estimated parameters for the j to *k* transition, $\mathbf{NR}_{it}$ is a vector of net returns to the six uses in *t*=1992 and for the county

[7] One expects landowners to be response to the marginal return to a use, not the average return. Unfortunately, we cannot observe the actual returns obtained by landowners and must, therefore, rely on county average net returns.

where plot i is located, and $\mathbf{LQ}_i$ is a vector of land quality class dummy variables for plot i. Conversion costs are not measured explicitly, but rather are reflected in constant terms specific to each land-use transition.

The projection model operates at the NRI plot level and begins in the base year 2002. To simplify notation, we denote the years 2002, 2007, 2012, etc., as t = 0,1,2, etc. Based on the sampling design, each NRI plot is associated with a certain number of acres. We define A_{ijt} as the number of acres associated with plot i in use j in time t. In the initial period, each plot is in one of the six uses as indicated in the NRI data. Thus, A_{ij0} equals the acres represented by plot i if the plot is in use j in time 0, and equals 0 otherwise. Given a sequence of transition probabilities, as defined in (2), we can compute how this land will be distributed across the six use categories at each time in the future. We can then express the area of land represented by plot i in use j at time t+1 as,

$$A_{ijt+1} = \sum_k P_{ikjt} \cdot A_{ikt} \ . \qquad (3)$$

Changes in land use from period t to t+1 imply changes in the supply of land-based commodities and services and, hence, changes in related prices and the net returns from each use. In this study, prices for commodities from cropland and pasture and urban net returns are determined exogenously in accordance with IPCC scenarios. This leaves forest prices, for which we model endogenous price feedbacks using a procedure discussed in the papers cited above, and forage prices. No estimates were available on forage demand elasticities needed to compute price adjustments. Forage prices (and, thus, range returns) are held constant in the simulations.

Beginning with the initial acres in each use (A_{ij0}), we use (3) to project land-use areas associated with each plot *i* to 2052. The transition probabilities in (3), the P_{ijkt} , are functions of county-level net returns as defined in (2). If we know the time path of county-level net returns, then we can use (2) and (3) to develop projections of land use. We describe, next, how the time paths of net returns are determined for the A1, A2, and baseline scenarios.

2.4.2 Projections of urban net returns under the IPCC scenarios

According to standard urban rent theory, two central determinants of urban land value are the expectations of future population and income growth (e.g., Capozza and Helsley 1989). Two steps are required to link the population and income trends for each of the IPCC scenarios to our county-level measures of urban net returns. The first is to disaggregate national-level population and income to the county level and the second is to relate county population and income to urban net returns. The second step is accomplished with the use of a statistical model of the relationship between county-level urban net returns and county population and income.

The disaggregation of the national-level population and income trends assumed for the IPCC projections was done for the 2010 Resources Planning Act (RPA) Assessment as described by Langner (2010) and Zarnoch et al. (2010). These authors relied on county population projections to 2030 and county personal income statistics for 2006 from Woods and Poole Economics, Inc. (2006). The Woods Poole population projections were used to calculate county population shares in each period, which were then used to distribute the national population totals for the IPCC scenarios to the county level. County level projections following 2030 were prepared by using the previous period's absolute growth for each county and adjusting it so that the sum of projected population across all counties equaled the IPCC national total for that year. To allocate national per-capita personal income to counties, the projected county population from above was multiplied by the 2006 per-capita income for that county. This gave the total income in each county in each year. These figures were then adjusted to match the national totals for the IPCC projections.

On a regional level, the population and personal income trends assumed for the A1 and A2 scenarios reveal some differences with the national pattern reported in Table 2-1. The South region is the largest in terms of population, having 29 percent of the population in the contiguous United States. The Mountain and the Plains regions are the smallest, with a share of almost 10 percent each. Personal income changes in the North and Pacific Coast regions are assumed to be higher than the national average, while the South, Mountain, and Plains regions fall below the national average.

The statistical model of urban net returns was estimated with panel data on 3,063 counties and 16 years (1982-97). The dependent variable is the natural log of urban net returns from Lubowski (2002). The explanatory variables are lagged changes in population, calculated as average annual changes over the preceding 5-year period in population per acre (U.S. Census Bureau) and per-capita personal income (Regional Economic Information System, Bureau of Economic Analysis, U.S. Department of Commerce). From theory, both variables are expected to be positively related to urban land values. Higher per-capita personal income increases the demand for land for housing and higher expectations of population growth result in higher land prices at desirable locations. To estimate the model, all dollar figures are expressed in constant (1990) dollars and fixed effects are included for each county in order to capture time-invariant differences among counties. Alternative model specifications were examined, but the best fit was found when the dependent variable is specified in logs and the independent variables are entered in unlogged form.

Table 2-4 gives the estimation results for the urban net returns model. The adjusted R^2 for the model is 0.973 and the explanatory variables are significantly different from zero at the 5 percent level. The signs of the coefficients on population and income change reflect the expected positive effects of these variables on urban net returns. The results imply, for example, that a 1 dollar increase in per-capita personal income causes the annual urban net return to increase by 15 cents, all else equal. This marginal effect was evaluated at the average urban net return between 1982 and 1997.

County-level population and income was interpolated so that the years matched those in the land-use projection model. Then, the urban net return model was used to generate projections of urban net returns to 2052 for 3,063 counties in the contiguous U.S.[8] To gain perspective on the variation in the projected urban net returns, county-level results were averaged to produce regional and national means for the A1 and A2 (Table 2-5). At a national level, average urban net returns are considerably higher by 2052 under the A1 scenario compared to the A2 scenario. On a regional basis, under both

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[8] For 11 counties we assumed no change in urban net returns because population and income values associated with the IPCC scenarios were unavailable.

scenarios the largest percentage increases are projected for the Northeast, followed by the West. The West region shows the highest absolute gains in the average urban net return (about $55,000 per acre under A1 and $16,000 under A2). Percentage changes by 2052 in average urban returns are similar in the Mountain, Plains, Midwest, and South regions, with gains between 278 and 392 percent under A1 and between 74 and 108 percent under A2.

2.4.3 Projections of agricultural prices under the IPCC scenarios

Agricultural price projections for the A1 and A2 scenarios were produced with the price indices in Table 2-2. Interpolation was used to calculate 5-year percentage changes in agricultural prices corresponding to the years in the land-use projection model (2002-2007, 2007-2012, etc.). These national-scale percentages were used to change county-level crop and pasturage prices (p_{nc} in equation 1). Applying national price changes at the county level is justified given global markets for agricultural commodities. As noted above, we adopt a no-change baseline projection for agricultural prices.

2.4.4 Projections of forest and agricultural yields under the IPCC scenarios

Estimates of changes in forest and agricultural yields are developed from the MAPSS model (Bachelet et al., 2004). The MAPSS model uses inputs from climate models (GCMs, or General Circulation Models) and calculates outcomes for natural ecosystems. To date, ecosystem models have not been fully linked to economic or management models to assess the implications of climate change on managed ecosystems, so we must translate these effects for natural systems directly to the economic model. This likely misstates the implications of climate change in particular locations because these purely natural results do not account for human adaptation. Adaptation will tend to reinforce positive effects of climate change and mitigate against negative effects.

Although similar in some ways to earlier modeling efforts that linked ecosystem effects to timber models (e.g., Joyce et al., 1995), this study differs in particular by using results at a fairly disaggregated level, that is, for U.S. counties. This is possible in part because the ecological models project ecological changes at a similar level of disaggregation, e.g., in 0.5 degree grid cells. In order to calculate ecological changes for US counties, we utilize the result for the 0.5 degree grid cell that overlaps the centroid of each county.

This analysis requires estimates of changes in forest yields and changes in agricultural yields. To estimate the effect of climate change on forest yields, we use the change in aboveground carbon. This is consistent with earlier studies on the effects of climate change in forest yields (see Sohngen et al. 2001; Perez-Garcia et al. 2002). Aboveground carbon is a stock variable that represents the carbon in live components of trees at a given time period. If aboveground carbon is increasing, then gross growth exceeds mortality (there is no harvesting in ecosystem modeling), and if aboveground carbon is decreasing, then mortality is high and it exceeds gross growth. Within the MAPSS model, natural mortality is driven by forest fires.

To determine how crop yields are affected by climate change, we assume that changes in agricultural yields are proportional to changes in net primary productivity (NPP) projected by the MAPSS model. The link between our measure of NPP from the

MAPSS model and agricultural yield is of course complicated by other factors such as human management. NPP is gross productivity minus respiration needs for the natural ecosystem type on each site. The ecological model we use, MAPSS, models only natural ecosystems, not human adapted ones. Globally, humans have appropriated a large share of the available NPP (Imhoff et al., 2004; Haberl et al., 2007) by optimizing the selection of varieties and the management of crops over many millennia, but the direct link between the NPP of natural ecosystems and the NPP of agricultural ecosystems is affected by human management (Lobell et al., 2009). There is evidence that the harvested seed portion of plants correlates closely with agricultural NPP (Prince et al., 2001), and thus, if agricultural NPP rises, then crop yields should rise. Ciais et al. (2005) used similar process based ecological modeling as we use here, and find that changes in crop yields do correlate with changes in NPP for natural ecosystems.

The outputs from the ecological model were provided on an annual basis, but the results have been converted to 5-year average results for this analysis. Annual results from the MAPSS model contain substantial fluctuations in temperature and precipitation that have large influences on year-to-year variation in the ecological measures we use. Although this annual variation could have implications for land-use choices, we have chosen to ignore it for the long-term trend analysis we are conducting here. In the underlying econometric model, landowners are assumed to base decisions on mean net returns and, thus, do not explicitly consider the variance of returns. Future analysis could examine whether trends in the year-to-year yield variations alter land use outcomes.[9]

Using separately the results from the three climate models (CSIRO, MIROC, and Hadley), five-year percentage changes in aboveground carbon and NPP are computed for the periods (2002-2007, 2007-2012, etc.) in the land-use projection model. Percentage changes in carbon are then used to modify the forest yield variables, whereas percentage changes in NPP are applied to crop and pasture yields (q_{nc} in equation 1). Projections were done with the results from all three climate models, and it was found that the Hadley results produced the largest changes in land use. Only results for the Hadley model are presented below. These may represent an upper bound in terms of yield-related effects of climate on land use.

The county-level results for the Hadley model are averaged to produce the regional results shown in Figure 2.1-Figure 2.4. Under A1, all regions display the same general pattern in percentage changes in forest yields. Declines in yields during the 2020s are offset by gains during the 2040s. Regionally, the West shows the largest yield variation and the South shows the smallest. There are much larger regional differences in agricultural yields under A1, with large declines in the Midwest and Plains regions before 2020, followed by gains until 2050. The Mountain region shows positive yield gains throughout the entire period. Under the A2 scenario, forest yields are relatively constant, with the exception of the Plains region. Agricultural yields show initial gains everywhere

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[9] See Schatzki (2003) for an analysis of how uncertainty in the returns to agriculture and forestry affect afforestation decisions by agricultural landowners in Georgia.

under A2, followed by declines in the Midwest and Plains regions. The South and Northeast regions show gains in agricultural yields during the entire period. As discussed above, for the baseline scenario we assume a constant 5-year increase in agricultural yields of 6% and no change in forest yields.

2.4.5 Scenario analysis

We developed, above, county-level projections of net returns to crop, pasture, forest, and urban uses[10] corresponding to the IPCC A1 and A2 climate change scenarios. For our basic land-use projection, we incorporate all these changes in net returns simultaneously. That is, given the assumed changes in population and income and the projected changes in agricultural prices and agricultural and forest yields under the A1 (alternatively, the A2) scenario, we project land-use patterns by 2052 at regional and national scales. Our basic projections are then compared to no climate change projections under which agricultural prices and agricultural and forest yields are set to baseline values. We develop two such baseline projections. These differ according to whether we adopt the population and income trends assumed for the A1 or the A2 scenario.

2.5. Results

Table 2-6 and Table 2-7 present land-use projections to 2052 by region under the A1 and A2 scenarios. Under both scenarios, the area of urban land nationally is projected

[10] As noted above, range returns are held constant in the simulations.

to increase substantially, increasing from 85 million acres to 225 million acres under A1 and to 183 million acres under A2. The larger gains under A1 reflect the higher average urban net returns under that scenario, due to higher income growth (Table 2-5). The model predicts that per-capita consumption of land for urbanized uses rises from about 0.30 acres in 2002 to 0.52 acres in 2052 under A1 and 0.38 acres in 2052 under A2. Over the 20-year period from 1982 to 2002, per-capita consumption of urban land in the U.S. increased by about 0.06 acres (Alig et al. 2010). Thus, relative to recent changes, the rate of change in per-capita consumption of urban land increases under A1 and decreases under A2. This difference is driven by the per-capita personal income changes and population changes reported in Table 2-1. Under A1, per-capita personal income increases by 125% by 2052, whereas the gain is only 56% under A2. It is possible that the model over-predicts future changes in urban area because it lacks a mechanism for endogenous demand-side responses to greater urbanization. One expects that as urban area expands, downward pressure on urban net returns would limit further increases in urban area. In addition, one response to higher net returns is increases in housing densities, an effect not explicitly represented in the model.

The increase in urban area is mirrored by declines in the areas of land in crops, pasture, forest, and range. Despite increases in agricultural prices under both IPCC scenarios, the losses in crop and pasture area are significant (e.g., a 16% decline in crop area under A1). Because of the greater increase in urban area under A1 than A2, decreases in the areas of other uses are larger under A1. The change in urban area at the national scale is greater than the net change in any single non-urban category. To some degree, this reflects the fact that urban area only increases, whereas there are offsetting positive and negative changes in the other uses.

Under both the A1 and A2 scenarios, there are similarities between the regional changes in land use and the pattern at the national level. Crop area declines and urban area increases in all regions. However, pasture, forest, and rangeland area each increase in 2 regions, while declining in the others. The Plains region is the largest of the 6 regions and shows some of the largest absolute changes in land use. In particular, the largest changes in crop, forest, and rangeland area are projected in that region.[11] The largest increases in urban area are projected for the South, where the largest losses of pasture are also projected to occur. When the regional land use projections are expressed as a percentage of the initial land area in the corresponding use, much larger differences in regional patterns are evident. Cropland area declines by 62% under the A1 scenario in the West compared to only 4% in the South. Under both scenarios, forest area increases by over 200% in the Plains region (from a small base in 2002) and declines by about 7% in the South. As well, there is an approximate 15% decline in rangeland area in the Plains region under both scenarios, while it declines by only 1% in the Mountain region.

It is difficult to link the regional trends in net returns to the projected regional changes in land use. First, the regional averages in net returns and land uses (Table 2-5-Table 2-7) mask the variation in changes occurring at county scales within the model.

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[11] The large increase in forest area in the Plains region was unexpected, but not inconsistent with the forest yield increases predicted toward the end of the projection period. In a separate analysis that employs GIS data on Holdridge life zones and current land cover, we found significant potential for forest expansion in the Plains region under current climatic conditions.

Second, according to (2), the amount of land that transitions from a given use to another use depends on the levels of net returns to all uses. Thus, a large increase in the net return to a given use does not necessarily imply a large increase in the area of land in that use. To illustrate this point, consider that, under A1, the average urban net return in the Mountain region increases by about $26,000 per acre, which is a larger increase than in the Plains, Midwest, and South regions. However, as a percentage of the total land area, the Mountain region has the smallest increase in urban area among the 6 regions.

Projections for the baseline scenario with no climate change effects on agricultural prices and agricultural and forest yields are presented in Table 2-8 and Table 2-9. The first panel in each table gives the projected areas in 2052 under the A1 and A2 scenarios, respectively. The second panels give the 2052 areas for the corresponding baseline scenario and the third panel gives the percentage difference in areas between the scenarios with and without climate change. On a national scale, we find that the areas of cropland, pasture, and forest are lower under the A1 and A2 scenarios compared to the respective baseline. Increases in agricultural yields are typically higher under the baseline compared to the climate change scenarios, which may help explain the national pattern. Rangeland area is higher under climate change, which may reflect its expansion into areas that would otherwise be used for agriculture. Nevertheless, differences between the scenarios are small, suggesting minor effects of climate change on future land-use patterns. On a national scale, we find that climate change never affect the area of land in a given use by more than a few percent.

Some departures from the national pattern of climate change effects are evident in the regional results. We find that cropland area is lower under climate change in almost all regions, although it is slightly higher in the West under the A1 and A2 scenarios. Increases in rangeland area are found for most regions, with the exception of small declines in the Mountain region under the climate change scenarios. Pasture and forest area changes show more regional variation. Pasture is projected to be higher under climate change in the Mountain, Midwest, Northeast, and South region, but lower in the West and Plains regions. Forest area is lower under the A1 and A2 scenarios in the West, Plains, and South, but increases in some or all cases in the other regions. As with the national results, the regional differences between the scenarios are small in absolute and relative terms.

2.6. Discussion

We have projected land use at the regional scale under two IPCC climate change scenarios. Our methods involve linking projections from global IAMs of agricultural prices and agricultural and forest yields to county-level measures of net returns to alternative uses and then using an econometric model of land-use change to make associated projections of land use. We also adopt assumed trends in population and income and use these to project future net returns to urbanization. Projected land areas under the climate change scenarios are compared to those under baseline scenarios that assume historical trends in agricultural prices and agricultural and forest yields.

A key finding is that demographic changes resulting in urbanization have larger effects on future land use than climate-related changes within the agricultural and forest sectors. This is a notable result given that, on an area basis, urban land accounts for just 6% of the total nonfederal land base in our study in 2002. By 2052, urban land is projected to occupy 16% of the nonfederal land base under A1 and 13% under A2. Mirroring these increases, cropland area declines by the most of any categories, falling by 65 million acres under A1 and 43 million acres under A2. In contrast, climate change effects on prices and yields are found to have minor effects on future land use. On a national scale, projected land areas under the baseline scenarios with no climate effects differ by only a few percent from the projected area under the climate change scenarios. It may be surprising that an approximate doubling of real agricultural prices (relative to a baseline with constant prices) produces little difference in cropland and pasture areas. This can be explained, in part, by the fact that returns to urban uses are typically much higher than those from agricultural and other uses.

Although many earlier studies have been concerned with effects of climate change on agricultural yields, we find that climate-induced changes in agricultural and forest yields have relatively little aggregate effect on land use. Part of the explanation is that, within regions, negative and positive changes in yields tend to offset each other over the period of analysis (Figure 2.1-Figure 2.4). It is also possible that climate change has significant effects on net returns to agriculture, consistent with some of the hedonic studies of farmland values, but these changes are not sufficient to induce large shifts among the broad land-use categories used in this study. We plan to investigate this issue in future work. Finally, we have modeled the effects of changes in average yields at the county level. The recent work by Schlenker and Roberts (2009) indicates the importance of accounting for extreme temperature events that can result in severe crop damage. Investigation of this issue is left, as well, for future research.

On a regional level, urbanization is also found to be a key driver of land-use change. However, significant differences are projected among regions in the changes of the other land uses. For example, under the A1 scenario, pasture area gains by about 40% in the West and Plains regions, while it declines between 32% and 46% in the Midwest, Northeast, and South. The projected decline of 18% at the national level masks offsetting regional changes. Together, these results demonstrate the importance of downscaling projections of future land use. Although we find small effects of climate change on a regional level, some departures from the national pattern of changes were found. Of course, it is likely that our regional projections are obscuring changes at finer scales, such as counties. Refinement of the methods presented in this paper would allow for even more disaggregated results.

Among earlier studies, Alig et al. (2002) is the closest to ours. Across the 4 climate scenarios evaluated, they find timberland area changes between -0.5 and -5.9 million acres after 50 years as a result of climate change.[12] Relative to the total area of forest in the contiguous U.S. (approximately 400 million acres according to Table 2-6),

[12] These figures are based on the results in Table 2 in Alig et al. (2002). Changes in timberland area relative to the baseline are between -0.2 and -2.4 million hectares. We convert these changes to million acres.

these are very small changes. Although our results are not directly comparable,[13] we find climate change effects on forest area of a similar magnitude. Under the A1 and A2 scenarios, forest area is projected to be 5.3 and 5.8 million acres lower, respectively, compared to the baseline areas.[14] Although the evidence from these studies suggests relatively small effects on land use from climate change, Alig et al. (2002) find that small aggregate changes in land use translate into much larger distributional effects on the welfare of consumers and producers.

The long term objective of this research is to fully integrate regional models with global models of the climate and economy. Although we have achieved some of the steps in this process, much work remains to be done. As noted above, additional work is needed on the effects of yield variation on land-use decisions. Effects of climate change on timber prices also need attention. Finally, the largest task will be to model feedbacks from regional outcomes to IAMs. This will ensure consistency between predictions of climate change at global and regional scales.

2.7. References

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[13] We evaluate a different set of climate scenarios, include the Plains region and land-use change in the Pacific Northwest Westside, and also consider changes in agricultural yields.

[14] 5.3 million acres is the difference between 394.1 and 388.8 million acres (Table 8) and 5.8 million acres is the difference between 405.9 and 400.1 million acres (Table 9).

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2.8. Tables and Figures

Table 2-1: National trends in population and per-capita personal income assumed for the IPCC A1 and A2 scenarios.

	Year						
Scenario	2006	2010	2020	2030	2040	2050	2060
				(Thousand people)			
Population							
A1	286,850	294,818	320,800	347,639	375,099	402,199	428,922
A2	286,850	300,734	330,823	362,934	397,971	437,900	484,574
				(2006 dollars)			
Income							
A1	32,015	34,939	41,519	47,519	54,263	62,355	72,042
A2	32,015	31,796	35,972	38,973	42,006	45,681	50,203

Table 2-2: Global agricultural price indices for all crops by IPCC scenarios.

	Year				
Scenario	1990	2010	2020	2050	2080
A1	100	94	115	157	172
A2	100	97	106	152	209

Table 2-3: Percentage change in NPP and aboveground carbon relative to 2010 averaged for the entire US.

			Year				
			2020	2030	2040	2050	2060
CSIRO	A1b	NPP	4.2%	4.3%	4.6%	3.1%	4.9%
		Aboveground C	-0.8%	3.1%	8.1%	4.5%	8.8%
	A2	NPP	0.7%	5.2%	0.7%	5.4%	2.2%
		Aboveground C	1.3%	6.3%	0.0%	0.7%	3.6%
MIROC	A1b	NPP	0.5%	-2.5%	-1.1%	-4.3%	-3.9%
		Aboveground C	-1.4%	2.6%	1.6%	3.3%	14.2%
	A2	NPP	0.1%	2.2%	-3.0%	-2.0%	0.5%
		Aboveground C	-2.6%	1.0%	6.1%	-2.9%	-3.6%
Hadley	A1b	NPP	-1.1%	0.5%	2.7%	6.0%	-2.6%
		Aboveground C	1.7%	-1.0%	-1.9%	7.2%	0.3%
	A2b	NPP	0.3%	4.8%	4.4%	3.2%	2.4%
		Aboveground C	6.5%	2.8%	3.8%	10.1%	8.1%

Table 2-4: Estimated coefficient values for the urban rents econometric model.

Variable	**Estimate**	**Standard Error**
Intercept	6.590	0.042
Population change	0.204	0.065
Per-capita income	0.000074	0.000

Table 2-5: Projected average urban net returns per acre for the A1 and A2 scenarios, by region and 2002-2052, in 2006 dollars.

		Year					
Scenario	Region	2002	2012	2022	2032	2042	2052
A1	West	14,250	17,422	24,449	33,092	47,239	70,969
	Mountain	6,604	8,447	11,389	15,219	21,788	32,471
	Plains	2,690	3,289	4,322	5,585	7,639	11,284
	Midwest	2,826	3,184	4,242	5,543	7,660	11,350
	Northeast	4,909	5,800	8,377	11,917	18,498	30,996
	South	2,538	2,867	3,757	4,838	6,582	9,600
	National	3,741	4,444	6,016	7,999	11,333	17,140
A2	West	14,250	14,354	17,377	20,528	24,457	30,341
	Mountain	6,604	7,131	8,427	9,744	11,356	13,720
	Plains	2,690	2,809	3,283	3,753	4,312	5,103
	Midwest	2,826	2,696	3,178	3,658	4,232	5,048
	Northeast	4,909	4,705	5,784	6,921	8,354	10,527
	South	2,538	2,453	2,863	3,268	3,749	4,428
	National	3,741	3,737	4,435	5,143	6,004	7,260

Table 2-6: Projection of land use areas to 2052 under the IPCC A1 scenario, by region, in million acres.

		Area by land use in 2002				
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	21.6	4.0	39.2	7.9	33.2	105.9
Mountain	42.7	8.3	25.5	5.7	186.6	268.8
Plains	130.3	28.0	9.1	9.8	178.3	355.6
Midwest	133.9	29.4	77.3	17.7	0.1	258.3
Northeast	15.7	7.5	78.4	14.8	0.0	116.5
South	53.4	44.1	177.0	29.3	4.2	308.0
National	397.6	121.3	406.5	85.3	402.4	1413.1
		Area by land use in 2052				
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	8.2	5.5	32.7	37.7	21.9	105.9
Mountain	37.8	7.2	27.9	11.2	184.7	268.8
Plains	101.4	39.2	31.4	34.0	149.6	355.6
Midwest	120.0	19.1	65.2	53.2	0.7	258.3
Northeast	13.9	5.1	68.3	29.1	0.0	116.4
South	51.1	23.6	163.2	60.1	10.0	308.0
National	332.4	99.7	388.8	225.2	367.0	1413.1
		Change in area, 2002-2052				
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	-13.4	1.5	-6.5	29.8	-11.4	
Mountain	-4.9	-1.2	2.4	5.5	-1.8	
Plains	-28.9	11.2	22.3	24.1	-28.7	
Midwest	-13.9	-10.2	-12.0	35.5	0.6	
Northeast	-1.8	-2.4	-10.1	14.3	0.0	
South	-2.3	-20.5	-13.8	30.7	5.9	
National	-65.2	-21.6	-17.7	139.9	-35.4	

Table 2-7: Projection of land use areas to 2052 under the IPCC A2 scenario, by region, in million acres.

		Area by land use in 2002				
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	21.6	4.0	39.2	7.9	33.2	105.9
Mountain	42.7	8.3	25.5	5.7	186.6	268.8
Plains	130.3	28.0	9.1	9.8	178.3	355.6
Midwest	133.9	29.4	77.3	17.7	0.1	258.3
Northeast	15.7	7.5	78.4	14.8	0.0	116.5
South	53.4	44.1	177.0	29.3	4.2	308.0
National	397.6	121.3	406.5	85.3	402.4	1413.1
		Area by land use in 2052				
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	10.2	6.2	36.9	28.5	24.1	105.9
Mountain	42.1	7.3	27.9	6.8	184.7	268.8
Plains	102.9	38.6	32.1	29.2	152.8	355.6
Midwest	132.9	19.7	66.2	38.8	0.7	258.3
Northeast	14.5	5.6	71.5	24.8	0.0	116.4
South	52.5	24.7	165.5	54.8	10.5	308.0
National	355.1	102.1	400.1	183.0	372.8	1413.0
		Change in area, 2002-2052				
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	-11.4	2.2	-2.4	20.6	-9.1	
Mountain	-0.6	-1.0	2.4	1.1	-1.9	
Plains	-27.4	10.5	23.0	19.4	-25.5	
Midwest	-1.0	-9.7	-11.1	21.2	0.6	
Northeast	-1.2	-1.9	-6.9	10.0	0.0	
South	-0.9	-19.4	-11.5	25.5	6.4	
National	-42.6	-19.2	-6.4	97.7	-29.6	

Table 2-8: Projected areas of land uses in 2052 under the IPCC A1 climate change scenario and a no climate change scenario by region, in million acres.

			Climate Change (A1 scenario)			
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	8.2	5.5	32.7	37.7	21.9	105.9
Mountain	37.8	7.2	27.9	11.2	184.7	268.8
Plains	101.4	39.2	31.4	34.0	149.6	355.6
Midwest	120.0	19.1	65.2	53.2	0.7	258.3
Northeast	13.9	5.1	68.3	29.1	0.0	116.4
South	51.1	23.6	163.2	60.1	10.0	308.0
National	332.4	99.7	388.8	225.2	367.0	1413.1
			No Climate Change			
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	8.0	5.5	33.6	37.5	20.6	105.4
Mountain	38.0	6.7	27.9	11.2	184.9	268.8
Plains	101.3	42.5	35.0	34.6	142.2	355.6
Midwest	126.9	18.3	64.9	47.5	0.6	258.2
Northeast	14.1	5.0	68.4	28.9	0.0	116.4
South	51.4	23.1	164.2	59.8	9.5	308.0
National	339.7	101.2	394.1	219.5	357.8	1412.3
			Percentage difference			
Regions	Crop	Pasture	Forest	Urban	Range	
West	1.9	-1.2	-2.6	0.4	6.0	
Mountain	-0.4	6.8	0.0	-0.5	-0.1	
Plains	0.1	-7.8	-10.3	-1.8	5.2	
Midwest	-5.4	4.2	0.5	12.0	22.1	
Northeast	-1.6	1.4	-0.1	0.9	0.0	
South	-0.5	2.1	-0.6	0.5	5.3	
National	-2.1	-1.6	-1.3	2.6	2.6	

Notes: The no climate change scenario adopts the A1 population and income projections. Totals may differ due to rounding.

Table 2-9: Projected areas of land uses in 2052 under the IPCC A2 climate change scenario and a no climate change scenario by region, in million acres.

			Climate Change (A2 scenario)			
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	10.2	6.2	36.9	28.5	24.1	105.9
Mountain	42.1	7.3	27.9	6.8	184.7	268.8
Plains	102.9	38.6	32.1	29.2	152.8	355.6
Midwest	132.9	19.7	66.2	38.8	0.7	258.3
Northeast	14.5	5.6	71.5	24.8	0.0	116.4
South	52.5	24.7	165.5	54.8	10.5	308.0
National	355.1	102.1	400.1	183.0	372.8	1413.1
			No Climate Change			
Regions	Crop	Pasture	Forest	Urban	Range	Total
West	9.9	6.6	38.0	28.4	22.5	105.4
Mountain	42.4	6.7	27.9	6.8	184.9	268.8
Plains	103.0	43.8	36.0	29.7	143.1	355.6
Midwest	136.6	19.1	66.0	36.0	0.6	258.2
Northeast	15.3	5.5	70.8	24.8	0.0	116.4
South	52.6	24.2	167.2	54.4	9.7	308.1
National	359.8	105.9	405.9	180.1	360.8	1412.4
			Percentage difference			
Regions	Crop	Pasture	Forest	Urban	Range	
West	3.5	-6.4	-2.9	0.2	7.4	
Mountain	-0.7	9.5	-0.1	-0.3	-0.1	
Plains	-0.1	-11.9	-10.8	-1.6	6.8	
Midwest	-2.7	2.8	0.3	8.0	18.4	
Northeast	-5.4	1.4	1.1	0.0	0.0	
South	-0.2	2.1	-1.0	0.8	8.6	
National	-1.3	-3.7	-1.4	1.6	3.3	

Notes: The no climate change scenario adopts the A2 population and income projections. Totals may differ due to rounding.

Figure 2.1: Average percentage changes in forest yields, by region and time period, under the A1 scenario.

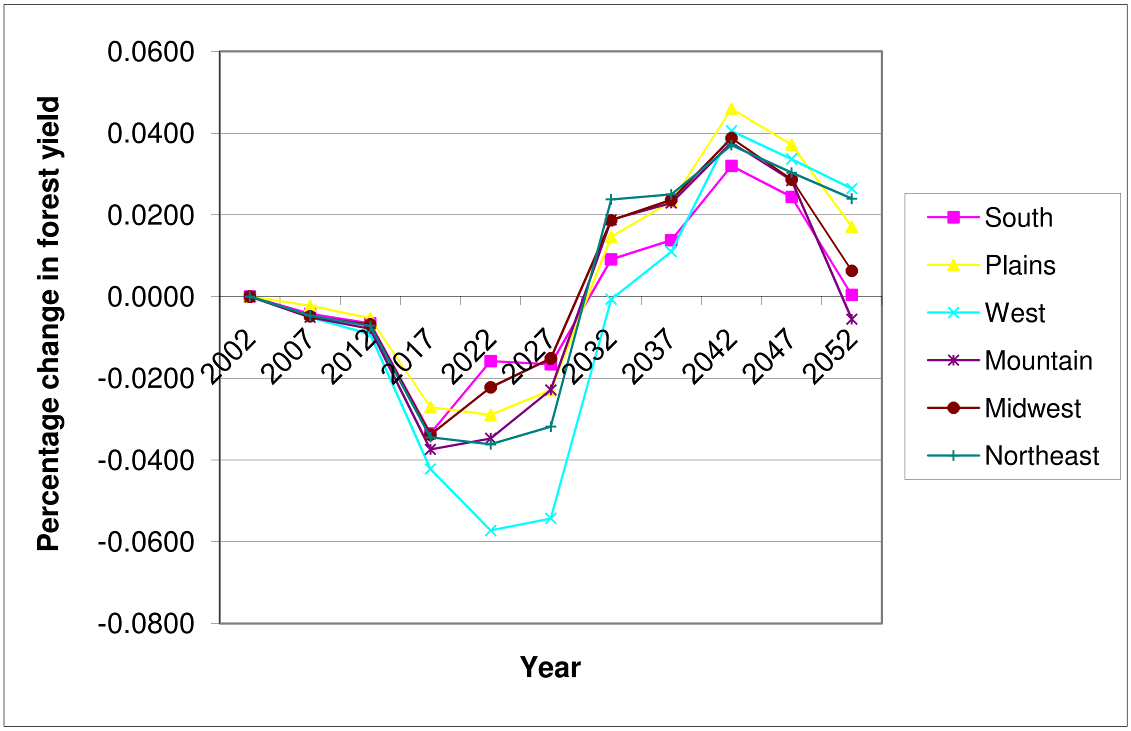


Figure 2.2: Average percentage changes in agricultural yields, by region and time period, under the A1 scenario.

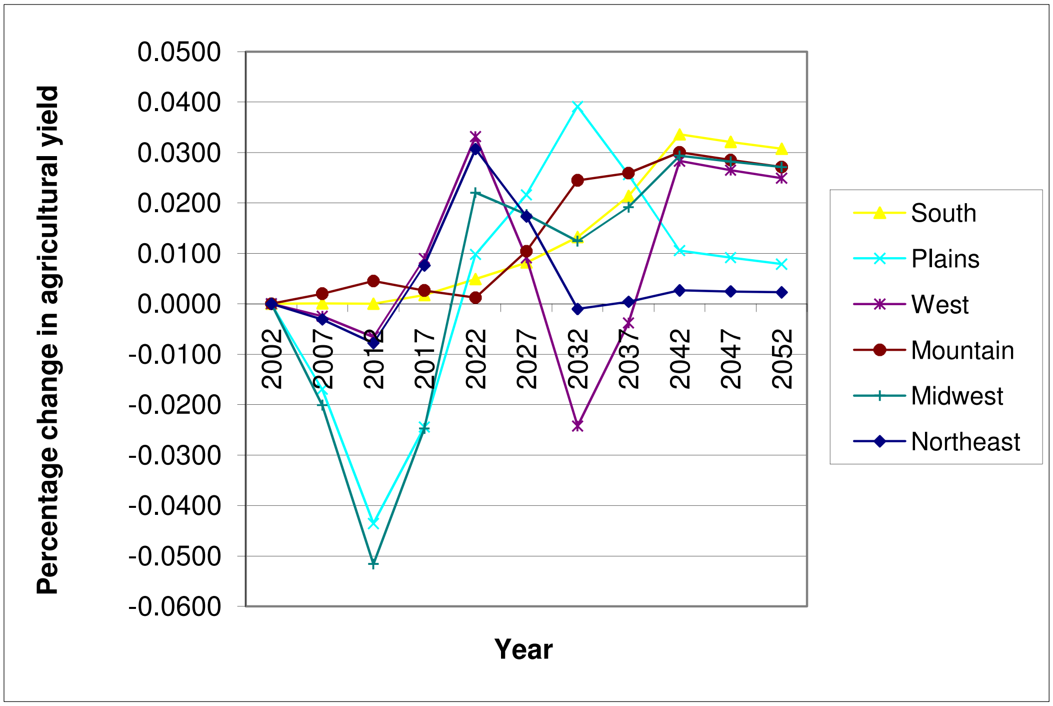


Figure 2.3: Average percentage changes in forest yields, by region and time period, under the A2 scenario.

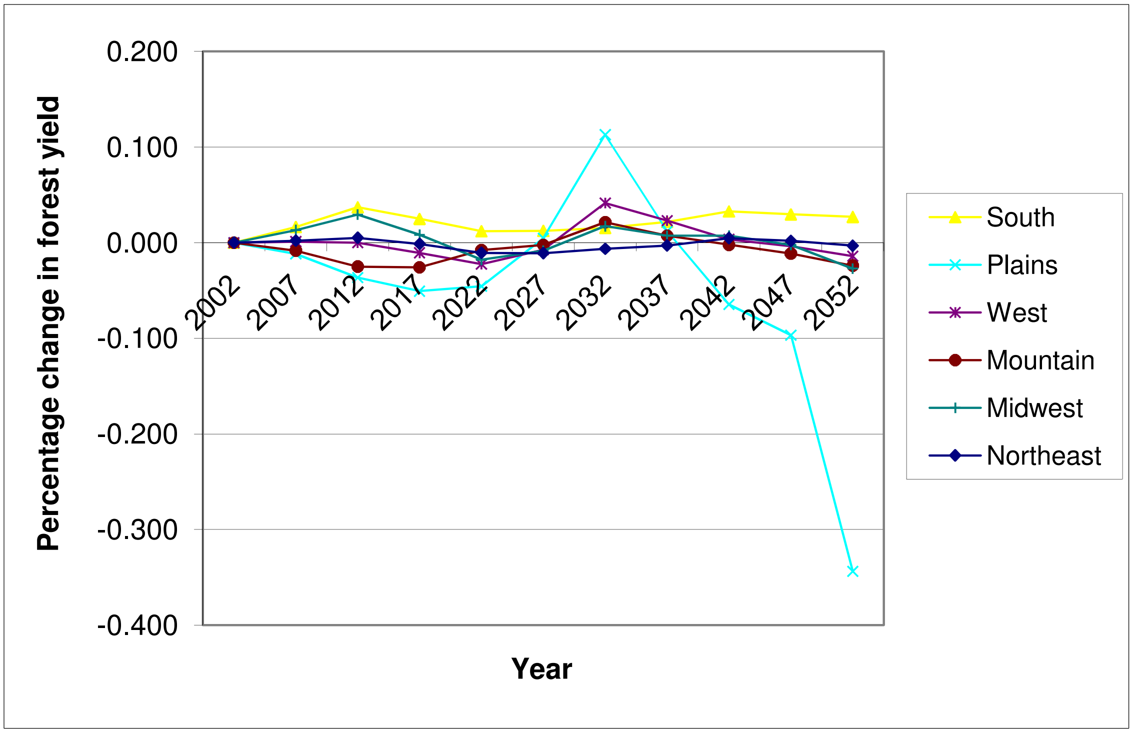
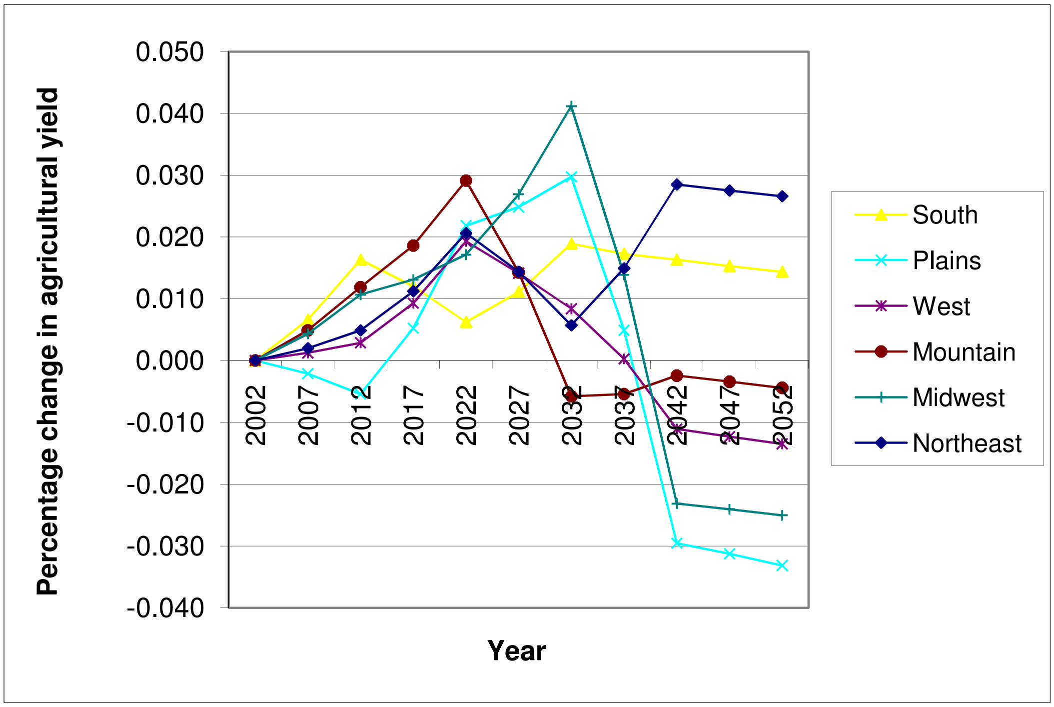


Figure 2.4: Average percentage changes in agricultural yields, by region and time period, under the A2 scenario.



CHAPTER THREE

THE OPTIMAL TIME PATH FOR CARBON ABATEMENT AND CARBON SEQUESTRATION UNDER UNCERTAINTY: THE CASE OF STOCHASTIC TARGETED STOCK

3.1. Introduction

The Kyoto protocol initiated a broad scientific discussion concerning the role of carbon sequestration as a strategy to limit greenhouse gases (GHG) emissions. Although there is a consensus in the scientific world that carbon sequestration should be included in a portfolio of GHG mitigation strategies (WG III, IPCC, 2007; Richards and Stokes, 2004) the optimal timing of its implementation is still debated. Some argue that carbon sequestration should be viewed as a short term reduction strategy either to buy time for other technologies to emerge (Metz et al, 2001; Feng et al, 2002) or because the attractiveness of carbon sequestration in term of its cost will decrease in the long run (Stavins, 1999). On the contrary, some argue that carbon sequestration should be delayed towards the end of the century given that carbon prices are increasing over time (Van't Veld and Plantinga, 2005; Sohngen and Mendelsohn, 2003). Other findings suggest that the rate of growth in carbon prices can influence the optimal timing of carbon sequestration (Sohngen and Sedjo, 2006).

An important feature that distinguishes sequestration from abatement technologies is the ability of carbon sequestration to actually reduce the level of the atmospheric CO_2 stock, while carbon abatement can only slow-down the accumulation of the stock in the atmosphere (the most, we abate all emissions at a given period of time). This asymmetry may play a crucial role in policy making. Consider the following example. Assume we would like to stabilize the atmospheric stock at B ppm at a given time in the future. But, currently, we are uncertain about the severity of impacts at that level of stabilization. For instance, choosing today a targeted level of B ppm could produce a likely global warming as low as 1.5°C, but warming could be as high as 4.5°C, increasing the severity of impacts. If sequestration is currently cheaper than abatement, should we use all sequestration capacity in the near future or should we save some as insurance in case the severity of impacts is large and we need to do more in terms of reducing the atmospheric stock.

According to the IPCC Fourth Assessment Report (WG III, IPCC, 2007), CO_2 emissions have grown between 1970 and 2004 by about 80 percent and represented 77 percent of total GHG emissions in 2004. Currently, CO_2 concentrations are about 390 parts per million (ppm). CO_2 emissions (from energy use) are projected to grow 40 to 110% over the next couple of decades (WG III, IPCC, 2007). A recent policy study that evaluates the Copenhagen Accord concludes that even if the high reduction scenario agreed upon in the United Nations Climate Conference (COP15) is fully implemented, a stabilization level of 450 ppm does not seem feasible (Den Elzen et al, 2010). A recent study by the Committee on Stabilization Targets for Atmospheric Greenhouse Gases Concentrations (National Research Council, 2010) suggests that to stabilize CO_2 levels for a century at a desired targeted level, a reduction larger than about 80 percent relative to whatever peak global emissions rate may be reached is needed.

This paper explores the optimal time path of carbon sequestration and carbon abatement in stabilizing the level of carbon dioxide in the atmosphere. Two related models are being examined. We start with a deterministic model that minimizes present value costs of abatement and sequestration over a finite time horizon subject to two state variables: the level of CO_2 stock in the atmosphere and the stock of suitable land which can be converted to forestland. We characterize all admissible outcomes of the system with respect to relative prices of abatement and sequestration and relative position of the initial and the targeted stock of CO_2.

Climate uncertainty is then introduced into the model by recognizing that today we cannot be sure of the amount of warming expected at different atmospheric CO_2 concentrations. However, as time progresses, society's understanding of the severity of climate impacts increases. Thus, it might be worthwhile saving some of the sequestration capacity as insurance in case the severity of impacts is large and we need greater reductions in the atmospheric stock to reach the desired stabilization level.

To this end, the deterministic model is modified. First, the model is simplified to a two period sequential decision-making problem,[15] where $t = 0,1$. Second, the decision on how much to control the stock with carbon abatement is restricted to the first period only. That is, the planner chooses the optimal rate of carbon abatement for both periods in the first period only. Thus, the decision on how much to abate in the first period can be viewed as an investment in abatement technology which yields benefits not only at the

[15] Such a model enables us to understand the general effect on the period 1 decision that would be obtained from a model with more decision periods.

current time but also in the future. The planner aims to minimize expected present discounted costs of sequestration and abatement while stabilizing the atmospheric stock at a given level at the end of the second period. Moreover, the planner is uncertain as to the desired level of stabilization when making reduction decisions in the first period but uncertainty is resolved prior to making reduction decisions in the second period.

We are abstracting from many real world issues to simplify our model. First, the movement of land from forestry uses to non forestry uses is not modeled. That is, we allow the movement from non-forest land to forestland but not the other way around. Second, forests play a twofold role in climate change. On one hand, carbon is stored in trees by the process of photosynthesis. On the other hand, CO_2 is emitted to the atmosphere when trees are burned, cut down or, decompose. We do not consider the permanence issue of carbon sequestration in our analysis. That is, we assume that sequestrated carbon is never released back to the atmosphere over the fixed finite time horizon of the model. Third, we do not include the rate of the natural decay of the atmospheric CO_2 stock in oceans in our model. Oceans play an important role in the carbon cycle. CO_2 dissolves into cold ocean water at high latitudes. In a process which takes a few hundred years, CO_2 is carried to the deep ocean and then slowly emerges back to the surface and is emitted by the ocean into the tropical atmosphere.

The chapter is organized as follows. In the next section we review prior studies which apply a dynamic approach to explore the optimal time path of carbon abatement and carbon sequestration in controlling GHG emissions. We also discuss an ongoing debate in the climate change economics literature over the sensitivity of model outcomes to the assumed functional form of the "damages function". Section 3 introduces the deterministic version of the optimal control model and the characterization of all admissible outcomes. Section 4 presents the stochastic version of the model and section 5 concludes.

3.2. Literature Review

There are a handful of studies in the economics literature on the optimal time path of carbon sequestration and/or carbon abatement in controlling GHG. The general approach is either to minimize the present value of costs of GHG (Falk and Mendelsohn 1993; Van Kooten et al, 1997; Webster 2002; Lecocq and Chomitz, 2001; Sohngen and Mendelsohn, 2003) or to maximize the social net benefits from emissions (Richards 1997; Nordhaus and Popp 1997; Feng et al, 2002; Gitz et al, 2006) subject to a transition equation describing the accumulation of the atmospheric CO_2 stock over time. Lecocq and Chomitz (2001) focus on differences between temporary and permanent sequestration. They suggest that when permanence can be guaranteed, sequestration and abatement are equivalent. If not, then temporary sequestration is cost effective only when current marginal damages of climate change are thought to be significant. Feng et al, (2002) find that carbon sequestration may play an important role as a reduction strategy during the transition path. However, according to their model, once reaching a steady state there is no role for additional sequestration of carbon.

Only four studies, to the best of our knowledge, divert from a deterministic model and incorporate uncertainty into the analysis. Webster (2002) shows, by using a two-period sequential decision-making model, that uncertainty in climate impacts which is resolved through time can lead to either more restrictive or less restrictive abatement reduction policies today. The author finds that decision making under uncertainty today will be affected by future learning (i.e., uncertainty is resolved before the decision making in the second period) only if the actions taken today change the marginal costs of abatement or marginal damage in the future. The author uses different specifications of cost functions (with and without cross period interactions) in demonstrating this result.

The other three studies explore uncertainty with respect to climate damages in a numerical analysis. Nordhaus and Popp (1997) analyze the value of improved information about climate change using the PRobabilistic Integrated model of Climate and the Economy (PRICE). The authors compare different times of information arrival regarding climate impacts in order to estimate the economic value of information about climate change. They estimate that the value of early information is between $1 and $2 Billion for each year that resolution of uncertainty is moved towards the present.

Sohngen and Mendelsohn (2003) build a general equilibrium model of sequestration by linking their optimal control model with other models of global timber prices and scarcity of land. Uncertainty is considered in the level of the damage function by examining two different scenarios in the Dynamic Integrated Climate Economy (DICE) model. Gitz et al (2006) consider uncertainty in the shape of the damage function.

They do so by applying a stochastic dynamic programming model[16] with three different levels of estimated climate damages, relative to a no climate change/no mitigation reference case. They assume that uncertainty regarding climate damages is resolved at a certain period of time, at which point a social planner has to choose carbon abatement and carbon sequestration using the distribution over climate damages.

Sohngen and Mendelsohn (2003) find that substantial amounts of carbon could be optimally sequestered in forests, especially towards the end of the century. Moreover, their model suggests that sequestration will play an important role in controlling GHG if the price of carbon is relatively high. (Gitz et al. 2006) find that it is most efficient to keep the major part of carbon sequestration potential as a safety measure for future use in case of catastrophic climate events. In addition, the researchers find that most of the afforested land is converted back to other uses by the end of the 21th century. Lastly, they conclude that sequestration can alleviate the rate of increase in the atmospheric CO_2 stock in early stages of the simulation but does not eliminate the need for carbon abatement during that time period. Comparing their results with Sohngen and Mendelsohn, (2003), Gitz et al (2006) conclude that the different results with respect to the importance of sequestration in optimal mitigation policies stem, most probably, from the different assumptions regarding the damage functions in the two studies.

[16] The stochastic programming model applied is DIAM: model of the Dynamics of Inertia and Adaptability for integrated assessment of climate change mitigation (DIAM). For more details on DIAM see the website http://hal.archives-ouvertes.fr/docs/00/05/28/01/PDF/iam.pdf

In fact, the influence of the so-called “damages function” on the outcomes of climate change economic assessments is getting a lot of attention recently by economists. Weitzman (2010) claims that climate economic assessments and especially those that include the impacts of catastrophic climate events are very sensitive to the specification of the damage function, among other things. He shows that a quadratic damage function and/or a thin-tailed temperature distribution cannot account for large damages from catastrophic climate events and thus will recommend relatively mild mitigation measures. Quiggin (2008) states that because the damage associated with climate change is potentially catastrophic, it is important to include the entire damage probability distribution rather than a limited number of parameters such as mean and variance. Sohngen and Mendelsohn (2003), in their empirical analysis, conclude that the assumed damage function for global warming consequently makes a large difference to the magnitude of the sequestration program. For such reasons, we do not include a damage function in our model. Instead, uncertain climate damages are reflected through the uncertainty as to the level where we would like to stabilize the atmospheric stock.

The contribution of this paper to the above literature is twofold. First, to our knowledge, this is the first deterministic optimal control study of abatement and sequestration reductions strategies to look at the problem of controlling CO_2 emissions for a fixed end point and finite time horizon. That is, the question that we ask is: what is the optimal way to use carbon sequestration and carbon abatement given that we would like to reach a predetermined target (a specific stabilization level of the atmospheric stock) at a given time? This formulation is in agreement with recent policy studies

(National Research Council, 2010; Den Elzen et al, 2010) as well as the United Nations Climate Conference (COP15) outcomes.

Second, developing a two period sequential decision making model, we show analytically that as uncertainty about the variability of climate impacts increases, more sequestration capacity should be saved for the future as a safety value. At the present time, we are unaware of an analytical study that carries out such an analysis. Only numerical estimations, mentioned in this literature review, have been conducted.

3.3. Deterministic Model

Carbon emissions are accumulated in the atmosphere resulting in higher CO_2 concentrations. Let X(t) be the level of CO_2 stock in the atmosphere at time t. Let E(t) be the rate of CO_2 emissions (CO_2 tons/unit of time) that is emitted to the atmosphere at time t. E(t) can be viewed as a base-line emissions path at time t and is exogenous to the model. Carbon stock at time t can be controlled by either carbon abatement A(t) and/or carbon sequestration S(t). The dynamics of the CO_2 stock is given by

$$\dot{X}(t) = E(t) - A(t) - S(t)$$

Note that the rate of abatement at a given time t cannot be greater than the rate of CO_2 emissions that are emitted to the atmosphere at the same period of time (i.e., $A(t) \leq E(t)$). The finite stock of suitable land which can be converted to forestland (and currently not in forest use) is denoted by $C(t)$. The dynamics of C is given by

$$\dot{C} = -S(t)$$

We assume that one unit of land is equal to the acreage that is needed to sequester one ton of carbon (so that sequestration can be measured in the same units of rate as abatement and carbon emissions). Furthermore, there is an upper limit $\bar{S}(t)$ on the quantity of land that can be converted to forestland at each period t due to conversion costs. Note that carbon sequestration at any given period is not bounded above by the omitted CO_2 emissions during the same period (E(t)). Put differently, the rate of carbon sequestration at any period t can be higher than the rate of CO_2 emissions in the same period and thus has the capability of actually reducing the level of the CO_2 atmospheric stock.

The objective of a central planner is to minimize the present discounted costs of abatement and sequestration while stabilizing the atmospheric stock at a level of B ppm over the fixed horizon [0,T]. We assume stabilization occurs at time $t = T_S < T$. We do so to account for costs of keeping the stock stabilized at a level of B ppm in a finite time interval $T_S < t < T$. That is, we assume the maintenance of stock level at B ppm is costly and thus should be considered in the model. Formally, we have

$$\underset{A(t),S(t)}{Min} \int_0^T [P_A A(t) + P_S(C(t)) \cdot S(t)] e^{-\delta t} \tag{1}$$

subject to:

$$\dot{X}(t) = E(t) - A(t) - S(t) \qquad X(T) = B, \text{ given} \qquad X(0) = X_0 \geq 0, \text{ given} \tag{2}$$

$$\dot{C}(t) = -S(t) \qquad C(0) = C_0 \geq 0, \text{ given} \tag{3}$$

$$0 \leq A(t) \leq E(t) \tag{4}$$

$$0 \leq S(t) \leq \bar{S} \tag{5}$$

where δ is the discount rate, P_A is the constant cost of abating one unit of CO_2 emissions and P_S is the cost of sequestrating one unit of carbon which is dependent on the stock of land available for sequestration at any given time t, (C(t)). Note that Ps'(C(t)) <0 because the marginal cost of sequestration is smaller when we have more land to convert to forestland.

3.3.1. Optimal Paths of Carbon Sequestration and Carbon Abatement

To derive the solution, form the current value Hamiltonian

$$\tilde{H} = P_A A + P_S(C)S + \mu_1(E - A - S) - \mu_2 S$$

Then the following conditions, along with (2) and (3) are necessary[17]:

$$A(t) = \begin{cases} 0, & P_A > \mu_1(t) \\ \in [0, E(t)], & P_A = \mu_1(t) \\ E(t), & P_A < \mu_1(t) \end{cases} \quad (6)$$

$$S(t) = \begin{cases} 0, & P_S(C(t)) > \mu_2(t) + \mu_1(t) \\ \in [0, \bar{S}], & P_S(C(t)) = \mu_2(t) + \mu_1(t) \\ \bar{S}, & P_S(C(t)) < \mu_2(t) + \mu_1(t) \end{cases} \quad (7)$$

$$\dot{\mu}_1 - \delta\mu_1 = -\tilde{H}_X = 0 \quad (8)$$

$$\dot{\mu}_2 - \delta\mu_2 = -\tilde{H}_C = -P_S'(C) \cdot S \quad (9)$$

The transversality condition for the stock of suitable land for sequestering carbon requires $\mu_2(T) = 0$. That is, having any sequestration capacity left at time T has no value in terms

[17] See Theorem 4.2 p.81 (and Theorem 12.1 p.318) in Caputo (2005) for more details on necessary conditions (and Theorem 21.1 p.318 for the equivalent necessary conditions in current value form).

of emissions reductions[18]. There is no transversality condition for the atmospheric CO_2 stock state variable. That is to say, the fixed end value B provides the needed condition.

The decision rule for carbon abatement (6) asserts that if the marginal cost of an additional ton of CO_2 abatement is greater than the current value shadow cost of an additional ton of CO_2 removed from the atmosphere, then the social planner should save this reduction strategy for future deployment. Similarly, if the marginal cost of an additional ton of CO_2 abatement is less than the current value shadow cost of an additional ton of CO_2 removed from the atmosphere, then the social planner should use all the abatement capacity.

Equation (7) states the decision rule for carbon sequestration. It asserts that if the marginal cost of sequestering another ton of CO_2 is greater than the sum of the current value shadow cost of an additional ton of CO_2 removed from the atmosphere (μ_1) plus the current value shadow cost of converting another unit of land into forest use (μ_2), then sequestration should not take place. Likewise, if the marginal cost of sequestering another ton of CO_2 is less than the sum of the current value shadow cost of an additional ton of CO_2 removed from the atmosphere (μ_1) plus the current value shadow cost of converting another unit of land into forest use (μ_2), then sequestration should take place at the maximum rate.

The current value shadow cost of an additional ton of CO_2 removed from the atmosphere, $\mu_1(t)$, is non-negative $\forall t \in [0, T]$. This is because the optimal value of the

[18] Note that $\mu_2(t) \leq 0 \; \forall t \in [T_S, T_{SS}]$. That is, carbon sequestration can still have a positive value with respect to emissions reduction after stabilization where $T_{SS} < T$.

objective function will never decrease when adding an extra unit of CO_2 to the atmospheric stock. From (8), $\mu_1(t)$ is growing at the rate of interest (i.e. the present value shadow cost of an additional ton of CO_2 removed from the atmospheric stock is constant overt time): $\frac{\dot{\mu_1}(t)}{\mu_1(t)} = \delta \;\; \forall t \in [0, T]$. Thus we may write:

$$\mu_1(t) = e^{\delta t} \tag{10}$$ [19]

which means that $\mu_1(t)$ is strictly monotonically increasing $\forall t \in [0, T]$.[20]

The current value shadow cost of converting another unit of land into forest use, $\mu_2(t)$, is non positive $\forall t \in [0, T]$. This is because the optimal value of the objective function will never increase when adding an extra suitable unit of land for forestry use (which is not currently in forest use). The optimal time path of $\mu_2(t)$ can be found from (9):

$$\mu_2(t) = \int_t^T e^{-\delta(s-t)} P_S{}'\big(C(s)\big) \cdot S(s) ds + \mu_2(T) e^{-\delta(T-t)} \tag{11}$$

So, $\mu_2(t)$, which measures the total discounted costs (to period t) of converting another unit of land into forest use, is a strictly monotonically decreasing sum of non positive integrated values $\forall t \in [0, T]$ plus a negative value for time $t = T$ (see appendix A for a detailed derivation of (11)).

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[19] We use the normalization condition $\mu_2(0) = 1$ implying that the constant of integration equals 1.

[20] Equations (10) and (6) are sufficient to determine the optimal time path in a simpler space of this model with only abatement as a tool for controlling CO_2 emissions. Assuming initially that$P_A > e^{\delta t}$ implies that $P_A > e^{\delta t}$for some finite period of time at the beginning of the planning horizon, $P_A = e^{\delta t}$only for an instant, say at $t = \tau$, the switching time, and $P_A < e^{\delta t}$for some finite period of time at the end of the planning horizon. This means that the optimal control policy is bang-bang, with no reduction in the first time interval and the maximum rate of reduction in the second.

We can rule out an interior solution for $A(t)$. This is, $A(t)$ is either equal to zero or to $E(t)$ (i.e., $A(t)$ has only corner solutions). Assume not, then $\mu_1(t)$ is constant and equal to P_A. But from (10), $\mu_1(t)$ is increasing at the rate of interest. Thus $\mu_1(t) \neq P_A$ and $A(t)$ does not have an interior solution.

Interior solutions for carbon sequestration, however, cannot be ruled out. Assuming an interior solution, equation (7) has to hold with equality. When carbon sequestration is the only reduction strategy activated prior to stabilization of the atmospheric stock (i.e., $P_A > \mu_1$) we require the total cost of carbon sequestration (the sum of the price of carbon sequestration and the current value shadow cost of converting another unit of land into forest use (recall $\mu_2(t) < 0$)) to be smaller than the price of carbon abatement.

$$P_S\big(C(t)\big) - \mu_2(t) \; < P_A \qquad (12)$$

Condition (12) reveals that the attractiveness of carbon sequestration, relative to carbon abatement, decreases as t increases due to the increase of the left-hand side of (12) (the price of sequestration increases as we keep converting more units of land to forestland and from (11) we know that $\mu_2(t)$ is monotonically decreasing as t increases). The inequality on condition (12) switches for the case where both abatement and sequestration are activated prior to the stabilization of the atmospheric stock (i.e., $P_A < \mu_1$). Here, even though the total cost of carbon sequestration is greater than the price of carbon abatement, carbon sequestration is the only way to reduce the atmospheric stock towards the stabilizing level and therefore has to be activated in spite of its relatively high costs.

Characterization of the Stabilization Point and the Long Run Steady State

We assume the existence of a stabilization point which occurs at $t = T_S$. Stabilization can be thought of as a reaching a target level of the atmospheric stock (say B ppm). Once reaching that level, there is no reason to divert from it (i.e. $\dot{X} = 0 \ \forall t \in [T_S, T]$)[21]. Furthermore, we assume the existence of a steady state at time $t = T$ (i.e., $\dot{X} = \dot{C} = 0$). In a steady state, all emissions reductions are due to only abatement activities (in a steady state: $\dot{C} = -S(t) = 0 \ \forall t \in [T, \infty]$ and $E(t) = A(t) = 0 \ \forall t \in [T, \infty]$). The intuition for the existence of a steady state stems from carbon sequestration being a finite resource which is either exhausted or has no value left to it (with respect to emissions reductions) in the long run[22].

A Steady State Can Only Occur Together with/or After Stabilization Has Occurred.

We show by contradiction that a steady state cannot occur prior to stabilization. Suppose not, then $\exists \ T_\theta < T_S$ such that $\dot{X} = \dot{C} = 0 \ \forall t \in [T_\theta, T]$. But, assuming $X_0 \neq B$ then $\dot{X} \neq 0 \ \forall t \in [0, T_S]$ which is a contradiction. This is an intuitive result as one condition for being in a steady state is a stabilized stock of atmospheric CO_2. The opposite, however, holds. Suppose stabilization has occurred at $t = T_S$. Therefore, $\dot{X} = 0 \ \forall t \in [T_S, T]$. If $P_A < P_S\big(C(t)\big) \ \forall t \in [0, T]$ then upon stabilization $A(t) =$

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[21] Given that we minimize reduction costs to reach the stabilization level and that we have to keep this level of stock in the future, any divert from this level of stock results in higher reduction costs in controlling the stock compared with keeping it at the level of B all the time.

[22] The price of carbon sequestration in our model is dependent on the amount of land converted to forestland. Thus, the price of sequestration is increasing as we shift more land to forestry. Even if we assume that the price of sequestration is less than the constant price of abatement, there exists a finite time at which the price of sequestration reaches the price of abatement. From that moment on, sequestration is less attractive than abatement and thus has no value for further emissions reduction.

$E(t)\ \forall t \in [T_S, T]$ and $S(t) = 0\ \ \forall t \in [T_S, T]$. Steady state and stabilization occur at the same time. However, If $P_A > P_S\big(C(t)\big)\ \forall t \in [0, T_{SS}]$ where $T_S < T_{SS} < T$ (i.e. the stock of suitable land for carbon sequestration is not exhausted upon stabilization at $t = T_{SS}$) then $S(t) > 0\ \ \forall t \in [T_S, T_{SS}]$ and steady state occurs only after stabilization has occurred.

We now turn to characterize all admissible outcomes of the system with respect to the relative prices of abatement and sequestration as well as the relative position of the initial and the targeted stock of CO_2. Specifically, we analyze four different cases. *Case I* involves $X_0 > B$ and, initially, $P_A < P_S(C(t))$. *Case II* involves $X_0 > B$ and, initially, $P_A > P_S(C(t))$. *Case III* involves $X_0 < B$ and, initially, $P_A < P_S(C(t))$. And, *Case IV* involves $X_0 < B$ and initially, $P_A > P_S(C(t))$. We start with the more interesting case in which the initial level of the atmospheric CO_2 stock is higher than the stabilization target (i.e. $X_0 > B\ \ \forall t \in [0, T_S]$. First, we find the minimum time required to hit B. Integrate (2) to obtain $\int_0^{T_S} \dot{X}(t)dt = B - X_0 = \int_0^{T_S} E - A - S(t)dt = (E - A - S) \cdot T_S$ and then solve for T to get:

$$T_S = \frac{B - X_0}{E - A - S} \tag{13}$$

Now, let sequestration and abatement be activated at full capacity, $S(t) = \bar{S}\ and\ A(t) = E(t)\ \forall t \in [0, T_S]$, to get:

$$T_S^m = \frac{B - X_0}{-\bar{S}} \tag{14}$$

Equation (14) defines the minimum time required to hit B when both abatement and sequestration are activated at full capacity prior to stabilization. T_S^m is dependent on the difference between the initial and the desired level of CO_2 atmospheric stock as well as the maximum speed that land converts to forest.[23] T_S^m , however, may not be the optimal path (the path that minimizes reduction costs) for reaching B. For example, let $P_A > P_S(C(t))\ \forall t \in [0, T_S]$. Then, applying abatement before $t = T_S$ might not be cost effective (depending on how large is $\bar{S}$). Clearly, if stabilization is required at $T_S > T_S^m$ it makes sense, economically speaking, to "push" some of the reductions further to the future. This is depicts in Figure 3.1. The dashed line (III) in Figure 3.1 represents the minimum time path for reaching stabilization. The bold solid line and the broken line represent other paths towards stabilization in which some of the reductions are "pushed" further to the future.

*Case I – when initially $P_A < P_S(C(t))$, carbon abatement is activated for all $t \in [0, T_S]$ and carbon sequestration is **fully** activated only for $t \in [T_S - T_S^m, T_S]$. That is, even though sequestration is more expensive than abatement, sequestration is still required to reduce the level of CO_2 towards B. However, its activation is delayed as far as possible into the future.*

Since initially $P_A < P_S(C(t))$ then $A(t) = E(t)\ \forall t \in [0, T_S]$. The intuition is that in order to keep the current value shadow cost of the atmospheric stock from further increasing we have to activate one of the reduction strategies in hand. Abatement is cheaper and thus should be the one to be activated. Because abatement has only corner solutions, its activation means keeping the stock of CO_2 at its initial level, X_0. But, to

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[23] Note that equation (14) is always non-negative because we assume the initial level of the stock is bigger than the targeted level.

reduce the level of the CO_2 stock towards B we have to use sequestration, even though it is more expensive than abatement. The question is when to use sequestration in order to minimize reduction costs? Equation (14) tells us the minimum time for reaching the stabilization level when both reduction strategies are activated. Therefore, to minimize reduction costs, we have to start sequestration at full capacity, $\bar{S}$, when $t = T_S^m$ is the time left for reaching stabilization.

For example, if we would like to stabilize the stock at a level of B ppm 50 years from now and we know that the minimum time for stabilization when both reduction strategies are fully activated is 30 years, then sequestration has to be fully activated 20 years from now to meet the targeted level. In that way we “push” sequestration costs as far as we can to the future (so that its present value costs are the least compared with all other alternatives). This, in turn, is the optimal rate of sequestration (see bold solid line (I) in Figure 3.1). Therefore, according to (14), the optimal rate of sequestration is dependent on the difference between the initial and the desired level of atmospheric stock as well as on the time of stabilization.[24] Upon reaching B, sequestration is either exhausted or has no value left in terms of emissions reductions and abatement is the only activated reduction strategy for all $t \in [T_S, T]$.

Case II – when initially $P_A > P_S(C(t))$, carbon sequestration is activated at first but might be inactivate for a certain period of time prior to stabilization whereas carbon

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[24] We assume here that the capacity of land available for sequestration is enough to derive the atmospheric stock of CO_2 back to point B. If this is not true, then we are stuck somewhere above the stabilization level without any way to get to B.

abatement can be activated prior, exactly at, or after stabilization has occurred, according to equation (12).

Because sequestration is cheaper than abatement, it is the only strategy that is activated initially. Equation (2) reduces to $\dot{X} = E(t) - S(t)\ \forall t \in [0, T^{\tau}]$ where $T^{\tau}$is the optimal time for the activation of carbon abatement according to equation (12). From (13) and given that $A(t) = 0\ \ \forall t \in [0, T^{\tau}]$ we get the optimal rate of sequestration

$$S^{*} = E + \frac{X_0 - B}{T_S} \qquad (15)$$

Note that since by definition $X_0 - B > 0$, then $S^{*} > E$. That is, the rate of sequestration is greater than the rate of carbon emissions released to the atmosphere so that the CO_2 stock can be driven downward towards B. As mentioned above, there is a finite time period $t = T^{\tau}$ where equation (12) holds with equality. Here we have to distinguish among three different alternatives according to the occurrence of T^{τ} and T_S. If $T^{\tau} > T_S$ then sequestration is the only activated reduction strategy prior to stabilization whereas abatement will be engaged at full capacity only after stabilization has occurred such that$E(t) = A(t)\ \forall t \in [T^{\tau}, T]$. If $T^{\tau} = T_S$, then abatement is engaged at full capacity exactly upon stabilization such that $E(t) = A(t)\ \forall t \in [T^{\tau} = T_S, T]$. The more interesting case, however, is where $T^{\tau} < T_S$. Then, abatement becomes attractive, relative to sequestration, before stabilization has occurred. Under this alternative, at $t = T^{\tau}$ the level of the atmospheric CO_2 stock is below X_0 but above B. Denote this level of the stock as X_{φ} where $B < X_{\varphi} < X_0$. Thus, $A(t) = E(t)\ \forall t \in [T^{\tau}, T]$ whereas sequestration is shut down at $t = T^{\tau}$ and is reengaged at full capacity only when $t = T_S^{m(X_{\varphi})}$in a similar fashion as shown in case I, where $T_S^{m(X_\varphi)}$ is the minimum time that is required to reach stabilization when both sequestration and abatement are fully activated. (See broken line (II) in Figure 3.1).

Finally, we note that when $X_0 > B$ the solution $S(t) = A(t) = 0 \;\; \forall t \in [0, T_S]$ is ruled out. This is because when both reduction strategies are inactive prior to stabilization, the stock of CO_2 keeps on accumulating in the atmosphere which in turn results in an additional use of sequestration capacity to drive the stock towards the stabilization point. In addition, given that $X_0 > B$ it is not optimal to drive the stock below the level of B at any point in time. It simply does not make any economic sense to invest money in reducing the stock to a level from which it will have to increase towards stabilization in latter periods.

We turn to analyze the two cases where the initial level of the atmospheric CO_2 stock is smaller than the stabilization level ($X_0 < B$) and relative prices of sequestration and abatement differs.

*Case III – when initially $P_A < P_S(C(t))$, carbon abatement is **fully** activated at $t = T^\theta$, where T^θ is the time when the stock of CO_2 reaches the targeted level (i.e., B) . Carbon sequestration will not be activated at all in this case.*

Because the initial stock of CO_2 is less than the targeted level we let the stock accumulate in the atmosphere until it reaches the targeted level (say, at time $t = T^\theta$) and then use carbon abatement (the cheapest reduction strategy). That is, abatement is engaged at full capacity at T^{θ} $\forall t \in [T^{\theta}, T]$. Sequestration, on the other hand, is inactive throughout the planning horizon (i.e. $S(t) = 0 \;\; \forall t \in [0, T]$.

Case IV – when initially $P_A > P_S(C(t))$, carbon sequestration is activated at $t = T^{\theta}$, where T^{θ} is the time when the stock of CO_2 reaches the targeted level (i.e., B) . Carbon abatement can be activated prior to, exactly at, or after stabilization has occurred, according to equation (12).

As in *case III*, we let the stock accumulate in the atmosphere until it reaches the targeted level (at time $t = T^{\theta}$) and then use carbon sequestration so that $E(t) = S(t) \;\; \forall t \in [T^{\theta}, T_{SS}]$ where $t = T_{SS}$ is the time where condition (12) holds with equality. At this point, abatement is engaged at full capacity such that $E(t) = A(t) \; \forall t \in [T_{SS}, T]$. Condition (12) asserts that sequestration is no longer attractive relative to abatement.

3.4. Stochastic Model

In the previous section we assumed the planner has complete information about the desired stabilization level of the atmospheric CO_2 stock. Climate change, however, entails large uncertainties that need to be taken into account in formulating optimal strategies. As already mentioned above, today we are unsure about the amount of warming expected at different atmospheric CO_2 concentrations. However, as time progresses, society's understanding of the severity of climate impacts is likely to increase.

The following modifications are made to the above deterministic model to incorporate uncertainly regarding the desired level of stabilization. First, the model is reduced to a two period sequential decision-making model,[25] where $t = 0,1$. Second, the decision about how much to control the stock with carbon abatement is restricted to the first period only. That is, the planner chooses the optimal rate of carbon abatement for both periods in the first period only. Thus, the decision about how much to abate in the first period can be viewed as an investment in abatement technology which yields benefits not only at the current time but also in the future. This simplification reduces the complexity of choosing optimal reduction programs for two control variables in the second period while keeping some of the tension between the two reduction strategies present in the first period's decision. Lastly, we allow the marginal cost of sequestration to vary within a period. That is to say, the price of carbon sequestration is now dependent not only on the capacity of land suitable for sequestering carbon within each period but on the rate of sequestration at each period as well. The modification is necessary given that our model involves discrete rather than continuous time. Total costs of carbon sequestration in a given period t can be written as $TC_t^C = \int_0^{S_t} P_S(C_t - u)du$.

The objective of a central planner is to minimize the expected present discounted costs of sequestration while stabilizing the atmospheric stock at the level of B_1 ppm at the end of the second period. The planner is uncertain about the desired stabilization level of the atmospheric stock, B_1, when making the decision about how much to control the

[25] Such a model enables us to understand the general effect on the period 1 decision that would be obtained from a model with more decision periods.

stock in the first period. This uncertainty is due to the limited information on the severity of climate impacts that is available to the planner in the first period.[26] We assume the planner knows the mean of the desired stabilization level, denoted $\bar{B}$, but is uncertain about the variability around the mean, denoted σ, when making reduction decisions in the first period. We consider only two possible states of the world at the end of the second period, B_H and B_L, each with an equal probability of occurrence. If state of world B_H prevails, the desired level of stabilization is $B_H = \bar{B} + \sigma$ and if state of world B_L prevails, the desired level of stabilization is $B_L = \bar{B} - \sigma$.

Information regarding the actual desired stabilization level of the stock is revealed prior to when the decision about how much to control the stock in the second period is made. Thus, the decision about how much to control the stock in the second period is deterministic.

We apply backwards induction starting with the optimization problem for the second period for each one of the two possible states of the world. In particular, we solve for S_1 given a state of world B_L and a state of world B_H. As already noted, sequestration is the only decision variable available for the planner in the second period. The minimization problem for the second period is thus:

$$\min_{S_1} \int_0^{S_1} P_S(C_1 - u)du$$

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[26] To make the story more realistic let the first period represent the current world reflecting reduction decisions in the next few decades (say 40 years) and the second period as the future world, one when uncertainty from climate change is reduced (say 80 years). The proposed length of the two periods enables the introduction of activities such as afforestration and reforestation which can be fully implemented within each one of the periods.

subject to:

$$B_1 = X_1 + E - A_0^* - S_1 \qquad X_1 \text{ is given} \qquad A_0^* \text{ is given} \tag{16}$$

$$0 \leq S_1 \leq C_1 \qquad C_1 \text{ is given} \tag{17}$$

This is a deterministic optimization problem with a fixed end point and a single decision variable. Because the planner is forced to meet the desired stabilization level and has only one way of getting there (i.e. by sequestering more carbon) optimal rates of sequestration are derived from constraint (16) as:

$$S_1^*(B_L) = \begin{cases} X_1 + E - A_0^* - B_L, & X_1 + E - A_0^* - B_L > 0 \\ 0 \quad , & otherwise \end{cases} \tag{18}$$

$$S_1^*(B_H) = \begin{cases} X_1 + E - A_0^* - B_H, & X_1 + E - A_0^* - B_H > 0 \\ 0 \quad , & otherwise \end{cases} \tag{19}$$

In addition, sequestration must bind the solution when the state of world is B_L. In that case all sequestration capacity may be exploited and then (17) holds with equality (i.e. $S_1 = C_1$). Substituting $S_1 = C_1$ into (16) one can form the relationship between X_1 (levels of the CO_2 stock when entering the second period) and C_1 (sequestration capacity when entering the second period). This relationship is reflected in Figure 3.2. The upward sloping line represents the allowed tradeoff between X_1 and C_1 while still meeting the targeted stock, B_L. The area beneath the line (including the line) represents the feasible region for the solution in the sense that if we entered the second period with a combination(C_1, X_1), B_L can be reached if needed.

Having found optimal rates of sequestration in the second period for both states of the world we then move backward to solve for the optimal rates of sequestration and abatement in the first period. Recall that in the first period the planner is uncertain whether state of world B_L or state of world B_H will prevail. Equation (20) is a Bellman equation for the minimization problem in the first period given the expected optimized value function for the second period where ρ denotes the discount factor[27] between the two periods:

$$V(S_0, A_0, 0) = \min_{A_0, S_0} P_A A_0 + \int_0^{S_0} P_S(C_0 - u)du + (1/2)\rho \int_0^{S_1^*(B_H)} P_S(C_0 - S_0 - u)du + (1/2)\rho \int_0^{S_1^*(B_L)} P_S(C_0 - S_0 - u)du \quad (20)$$

Subject to:

$$C_0^* \geq X_0 + 2(E - A_0) - B_L \quad (21)$$

$$X_1 = X_0 + E - A_0 - S_0 \qquad X_0 \; is \; given \quad (22)$$

$$0 \leq A_0 \leq E \qquad 0 \leq S_0 \leq C_0 \qquad C_0 \; is \; given \quad (23)$$

Where C_0^* is the critical capacity of sequestration required to meet B_L expressed in terms of the first period's CO_2 stock level and sequestration capacity. The expected optimal value function for the second period is weighted according to the two states of world. The transition equation of the CO_2 stock in the first period is described in equation (22) and the constraints on the optimal rates of abatement and sequestration are given in equation (23).

Taking the partial derivatives with respect to S_0 and A_0, rearranging[28] and, assuming interior solutions[29] for both conditions, we obtain the following first order conditions:

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[27] $\rho = 1/(1 + \delta)$ where δ is the periodic discount rate.
[28] We also divide both sides of condition (24) by 1/2.

$$\frac{1}{2}P_A = (1/2)\rho[P_S(C_0 - S_0 - S_1^*(B_H) + P_S(C_0 - S_0 - S_1^*(B_L)] \quad (24)$$

$$(1+\rho)P_S(C_0 - S_0) = \rho[P_S(C_0 - S_0 - S_1^*(B_H) + P_S(C_0 - S_0 - S_1^*(B_L)] \quad (25)$$

Condition (24) simply states that present value expected marginal cost of sequestration should be equalized to half the marginal cost of abatement. Condition (25) recognizes the cross period dependency in the marginal cost of sequestration. That is to say, sequestration in the second period is determined according to how much is sequestered in the first period.

Substitute (24) into (25) and rearrange to obtain:

$$\left(\frac{1}{1+\rho}\right)P_A = P_S(C_0 - S_0) \quad (26)$$

Equation (26) is the key to the first period solution. According to (26), sequestration is always cheaper than abatement. This is because the discount factor is restricted to values between zero and one. Hence, the marginal cost of abatement is always less than the marginal cost of sequestration. Furthermore, the optimal rate of sequestration in the first period is uniquely determined by (26) and is dependent on the discount factor, per unit cost of abatement, initial sequestration capacity as well as the functional form of the marginal cost of sequestration. The geometric representation of equation (26) is depicted in Figure 3.3. The optimal rate of sequestration in the first period is represented in terms of how much sequestration capacity is being used. Deployment of more sequestration in the first period is represented by a movement on the horizontal axis towards the origin.

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[29] Corner solutions will be treated below

The optimal rate of abatement can be found by substituting (18) and (19) into (24):

$$(1/2)P_A = (1/2)\rho[P_S(C_0 - X_0 - 2(E - A_0) + B_L) + P_S(C_0 - X_0 - 2(E - A_0) + B_H)] \tag{27}$$

The optimal rate of abatement in the first period is determined at the point where the expected present value marginal cost of sequestration equals one-half the unit cost of abatement. Note that the only difference in the two marginal costs of sequestration on the right-hand side of (27) is due to the variability of climate impacts. This is depicted in Figure 3.3 as the range (2σ) of the expected marginal cost of sequestration for the two states of world. The planner will always keep sequestration capacity in the size of σ at least for future deployment in case the realization is B_L and we need to further reduce the level of the atmospheric stock to meet our reduction target. Also, note that the constraint on the critical capacity appears in equation (27). The term inside the marginal cost of sequestration when the state of world is B_L can also be written as $C_0 - C_0^*$. Since the marginal cost of sequestration admits only non-negative values, the constraint on the critical capacity is always satisfied.

When the future is not discounted (discount factor equals one) the left-hand side of equations (26) and (27) are the same. In this case the equality of equation (26) implies the inequality of equation (27). This is due to the convexity of the marginal sequestration cost function. The optimal rate of sequestration is determined by equation (26). However, the optimal rate of abatement in the first period cannot be determined from (26) because of the inequality. That is, the inequality of equation (26) does not yield a unique solution for the optimal rate of abatement. Note that when the future is not discounted, abatement is twice as expensive as sequestration. Thus, the cost of abating one ton of CO_2 today (which leads to an additional ton of CO_2 abated in the future) equals the cost of sequestering one ton of CO_2 today plus another one in the future. Thus, to find the optimal rate of abatement we have to minimize the total costs of sequestration in the second period when sequestration is binding the solution (i.e., when the state of world is B_L[30]) and the total costs of abatement in the first period with respect to A_0. The minimization problem is thus:

$$\min_{A_0} \int_0^{s_1^*(B_L)(A_0)} P_S(C_1 - u)du + P_A A_0$$

Taking the partial derivative with respect to A_0, rearranging and, assuming an interior solution, we obtain the following first order condition which determines the optimal rate of abatement in the first period:

$$P_S(C_0 - X_0 - 2(E - A_0) + B_L) = (\frac{3}{2})P_A \quad (28)$$

Condition (28) simply states that the optimal rate of abatement in the first period when the future is not discounted is at the point where the marginal cost of sequestration when the state of world is $B_L$equals three-half the unit cost of abatement (see appendix B for a detailed derivation of (28)).

This is depicted in Figure 3.4. The optimal rate of sequestration in the first period equals one-half the unit cost of abatement. Furthermore, the realization of B_L in terms of

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[30] Otherwise we would not be able to meet our target if $B_L$is indeed the realization.

sequestration capacity is to the left of the optimal rate of sequestration in the first period but the realization of B_H is to the right representing the fact that less capacity of sequestration should be used given that we end of in B_H. Equation (26) holds with equality, determining the optimal rate of sequestration in the first period. Equation (27) holds with inequality where the average of the expected marginal cost of sequestration is very close to the optimal rate of sequestration in the first period. Equation (28) is depicted to the left of equations (26) and (27) in figure 3.4 reflecting the fact that the optimal rate of abatement in the first period when the future is not discounted is found where the marginal cost of sequestration in the second period when the state of world is B_L equals to three-half the unit cost of abatement.

As the discount rate increases (i.e. discount factor decreases) optimal rates of sequestration in both periods increase whereas the optimal rate of abatement decreases. This is because according to equation (26) abatement becomes less and less attractive as the future is further discounted. This is depicted in Figure 3.3 by a movement of both equations (26) and (27) towards the origin. That is, the increase in the use of sequestration decreases the available capacity and thus results in the movement towards the origin.

Substitute the mean and variability of the stabilization level into equation (27) to obtain:

$$(1/2)P_A = (1/2)\rho[P_S\big(C_0 - X_0 - 2(E - A_0) + (\bar{B} - \sigma)\big) + P_S\big(C_0 - X_0 - 2(E - A_0) + (\bar{B} - \sigma)\big)] \qquad (29)$$

From equation (29) it is easy to see that an increase in the variability in climate impacts will increase the optimal rate of abatement in the first period[31]. This is because as the variability of climate impacts increases the expected marginal cost of sequestration in equation (29) changes. This is represented in figure 3.4 by a movement to the right of the marginal cost of sequestration given that the realization is B_H and a movement to the left of the marginal cost of sequestration given that the realization is B_L. Furthermore, due to the convexity of the marginal sequestration cost function, the average increases and we need to decrease the expected marginal cost of sequestration for (29) hold. This can only be done by abating more emissions, relative to before. The optimal rate of sequestration in the first is not affected by an increase in the variability of climate impacts in our model as it is uniquely determined by (26). A decrease in the mean of the stabilization level will also result in an increase in the optimal rate of abatement in the first period for similar reasons. Once all units emitted are abated (the constraint on abatement is binding) we will sequester more in the second period, if needed, so that the critical capacity constraint is met.

So far we dealt with interior solutions to the first period minimization problem. However, it may be the case that the optimal solution lies at a corner. If one-half the per unit cost of abatement is less than the expected cost of sequestration and equation (25) holds with equality then it is always cheaper to abate than to sequester (i.e. $\left(\frac{1}{1+\rho}\right) P_A < P_S(C_0 - S_0)$). In that case abatement is fully deployed (i.e. $A_0^* = E$) and no sequestration

[31] Given that all other parameters are fixed.

takes place in the first period. On the other hand, if one-half the per unit cost of abatement is greater than the expected cost of sequestration and equation (25) holds with equality then sequestration is cheaper than abatement initially but the price of sequestration is increasing as we keep sequestering until equation (26) holds with equality. Then we are back at an interior solution. Placing the inequality on equation (25) will lead to similar results.

3.4.1 Adding a Penalty Function to the Model

So far, the planner is forced to meet a specific targeted level of CO_2 stock at the end of the planning horizon. In reality, though, it may well be the case that society fails to meet the desired level of the stock. This could be due to the lack of cooperation among countries regarding specific levels of reductions and how to measure reductions, among many others reasons. Forcing the planner to meet a specific targeted CO_2 level implies an infinite large penalty for not meeting this target. Next, we relax this assumption by introducing a penalty function to the above stochastic model. Let $\varphi(X_2 - B_1)$ represents the penalty function. We assume $\varphi(\cdot)$ is convex and twice differentiable with both $\varphi'_{(X_2-B_1)}(\cdot) > 0$ and$\varphi''_{(X_2-B_1)}(\cdot) > 0$. Furthermore, X_2 is the level of the CO_2 stock in the atmosphere results from the reduction decision made in the second period.

The minimization problem for the second period is now:

$$\min_{S_1} \int_0^{S_1} P_S(C_1 - u)du + \varphi(X_2 - B_1)$$

subject to:

$$X_2 = X_1 + E - A_0^* - S_1 \qquad X_1 \text{ is given} \qquad A_0^* \text{ is given} \tag{30}$$

$$0 \leq S_1 \leq C_1 \qquad C_1 \text{ is given} \tag{31}$$

Substituting (30) to the minimization problem and solving for the decision variable (i.e., the optimal rate of sequestration in the second period) yields the following condition:

$$\frac{\partial L}{\partial S_1} = P_S(C_1 - S_1) - \varphi'(X_1 + E - A_0^* - S_1 - B_1) \lesseqgtr 0 \qquad (32)$$

According to condition (32) the optimal rate of sequestration in the second period is achieved when marginal cost of sequestration is equal to the marginal penalty imposed on each excessive ton of CO_2 in the atmospheric stock[32]. The decision rule for carbon sequestration in the second period in both states of the world is, thus, depends on the relation between these two functions.

If sequestration admits an interior solution in the second period then the optimal rate of sequestration can only be given implicitly by:

$$G^*(S_1; X_1, C_1, B_1) = P_S(C_1 - S_1) - \varphi'(X_1 + E - A_0^* - S_1 - B_1) = 0 \qquad (33)$$

Applying the Implicit Function Theorem (IFT) one can show that $\frac{\partial S_1}{\partial C_1} > 0$ and that $\frac{\partial S_1}{\partial X_1} > 0$. That is, an increase in sequestration capacity and/or in the level of the atmospheric stock at the beginning of the second period will increase the optimal rate of sequestration in the second period.

As before, having found optimal rates of sequestration in the second period for both states of the world we then move backward to solve for the optimal rates of sequestration and abatement in the first period (see Appendix C for a detailed derivation

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[32] If $X_2 - B_1 \leq 0$ then the marginal penalty is zero and we sequester as long as the marginal cost of sequestration is greater than zero.

of the Bellman equation). The two equivalent conditions to conditions (26) and (27) are given in (34) and (35), respectively:

$$(1+\rho)P_S(C_0-S_0)=\left(\frac{1}{2}\right)\rho(((P_S\big(C_0-S_0-S_1^*(B_H)\big)-\varphi'(B_H))\cdot\left(\frac{\partial S_1^*(B_H)}{\partial C_1}\right)+$$

$$+((P_S\big(C_0-S_0-S_1^*(B_L)\big)-\varphi'(B_L))\cdot\left(\frac{\partial S_1^*(B_L)}{\partial C_1}\right))+\left(\frac{1}{2}\right)\rho((P_S\big(C_0-S_0-S_1^*(B_H)\big)+$$

$$+(P_S\big(C_0-S_0-S_1^*(B_L)\big))+P_A \tag{34}$$

$$\left(\frac{1}{2}\right)P_A=\left(\frac{1}{2}\right)\rho(((P_S\big(C_0-S_0-S_1^*(B_H)\big)-\varphi'(B_H))\cdot\left(\frac{\partial S_1^*(B_H)}{\partial X_1}\right)+$$

$$+(P_S\big(C_0-S_0-S_1^*(B_L)\big)-\varphi'(B_L))\cdot\left(\frac{\partial S_1^*(B_L)}{\partial X_1}\right)) \tag{35}$$

We first note that if we let the penalty functions to be zero, $\left(\frac{\partial S_1^*(B_L)}{\partial X_1}\right)=1$ and $\left(\frac{\partial S_1^*(B_L)}{\partial C_1}\right)=0$ conditions (34) and (35) collapse to exactly conditions (26) and (27), respectively. That is, the previous sub-section deals with a special case of the more general form of the model where the penalty for not meeting the targeted level of the stock is infinitely large (i.e., $\varphi'(B_H)=\varphi'(B_L)=0$).

Condition (35) states that present value expected optimal rate of sequestration in the second period multiplied by the change in the optimal rate of sequestration in the second period that is resulted from a change in the level of the atmospheric stock at the beginning of the second period, should be equalized to half the marginal cost of abatement. Condition (34) is similar to condition (26) from above only that once the penalty function is included in the model, the optimal rate of sequestration in the first period is determined not only according to the initial capacity of sequestration, the discount factor, the per unit cost of abatement and the functional form of the marginal cost of sequestration but also according to the present value expected marginal cost of sequestration in the second period as well as the present value expected optimal rate of sequestration in the second period multiplied by the change in the optimal rates of sequestration in the second period that is resulted from a change in sequestration capacity at the beginning of the second period. Consequently, the optimal rate of sequestration in the first period is not determined uniquely by (34). Furthermore, the optimal rate of abatement is not determined uniquely by (35). Instead, the system of two equations should be solved simultaneously to find optimal rates of sequestration and abatement in the first period.

3.5. Discussion

We explore the optimal time path of carbon sequestration and carbon abatement for stabilizing the level of carbon dioxide in the atmosphere. We question the conventional wisdom that carbon sequestration should be used as a near-term strategy by recognizing the fact that sequestration, unlike abatement, can actually remove CO_2 from the atmosphere.

Consistent with previous studies (WG III, IPCC, 2007; Richards and Stokes, 2004) both the deterministic and stochastic models suggest sequestration has an important role in climate change mitigation. The deterministic model shows that carbon sequestration may play an important role as a reduction strategy towards reaching the stabilization target. This is because the optimal paths of carbon sequestration and carbon abatement in the deterministic model are determined not only according to their relative prices but also according to the relative position of the initial and the targeted stock of CO_2. In fact, when the initial level of CO_2 is greater than the targeted one, sequestration is activated even when its marginal cost is higher than the marginal cost of abatement initially (*Case I*). This is because sequestration is the only reduction strategy out of the two that can actually reduce the level of the CO_2 stock. Thus, taking into account the asymmetry between carbon abatement and carbon sequestration we show that it may be the case that sequestration is delayed into the future rather than deployed as early as possible, as suggested by others (Feng et al, 2002).

Furthermore, activation of each of the reduction strategies once reaching stabilization is shown to depend on only their relative prices. In the very long run, there is no role for an additional sequestration of carbon as the marginal cost of sequestration hits the choke price of abatement. This finding is in agreement with Feng et al (2002).

Climate change uncertainty is then introduced into the model. In a two-period sequential decision making model we show analytically that some capacity of sequestration should be saved for future deployment in case climate impacts are large and the CO_2 stock should be further reduced. This result is consistent with previous numerical analysis (Gitz et al, 2006). In addition, increases in the variability of climate impacts and/or a decrease in the mean level of stabilization calls for an increase in the optimal rate of abatement in the first period.[33] That is, an increase in the variability of climate impacts leads us to free more sequestration capacity today in case we will need it in the

[33] This is assuming the constraint on abatement is not binding (i.e. $A_0^* \leq E$).

future (i.e., state of world B_L prevails). This is due to the asymmetry between the two reduction strategies.

Our model suggests that both sequestration and abatement should be deployed in the short term given uncertainty in climate impacts for meeting a long term desired stabilization level. Moreover, the relative share of each reduction strategy is determined according to the discount rate. Investment in abatement becomes less and less attractive as the future is further discounted. This is because the relative price of abatement increases (so abatement is more than twice as expensive as sequestration).

This model focuses on terrestrial carbon sequestration. Other forms of sequestration, however, are available as reduction strategies to limit climate change. One example would be subsurface geological sequestration in depleted oil fields or in deep-sea formations. One possible extension to this paper may explore optimal time paths of different sequestration methods relative to abatement activities.

3.6. References

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3.7. Figures

Figure 3.1: The minimum time option and other alternatives for reaching stabilization given that $X_0 > B$but without specifying price ratio between sequestration and abatement.

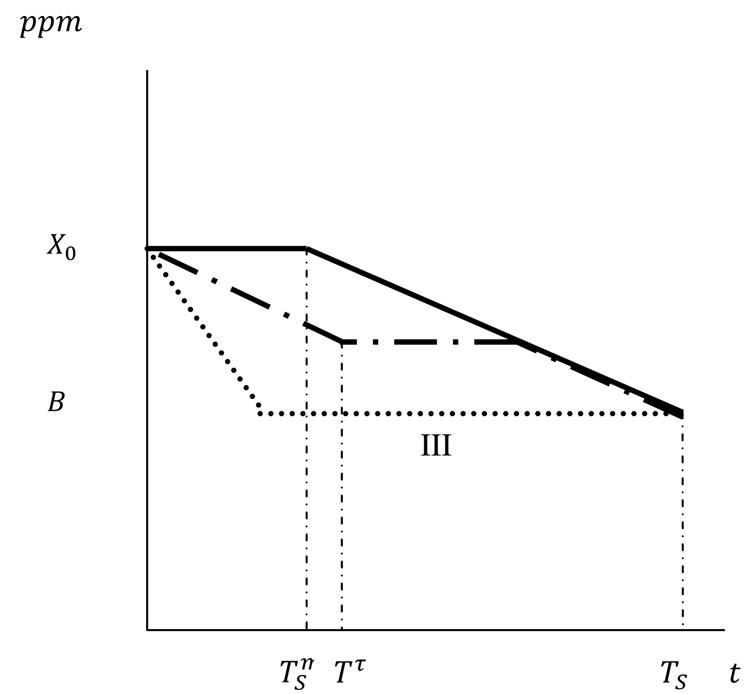


Figure 3.2: Feasibility region in terms of stock of CO_2 and sequestration capacity entering the second period for meeting the desired stabilization when state of world is $\mathbf{B_L}$.

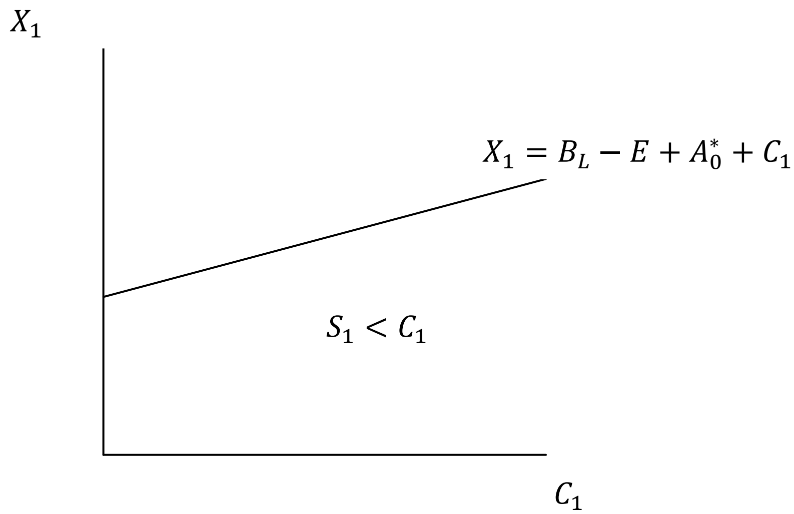


Figure 3.3: Geometric representation of the optimal solution for carbon sequestration and carbon abatement in the first period when $\boldsymbol{\rho} < 1$.

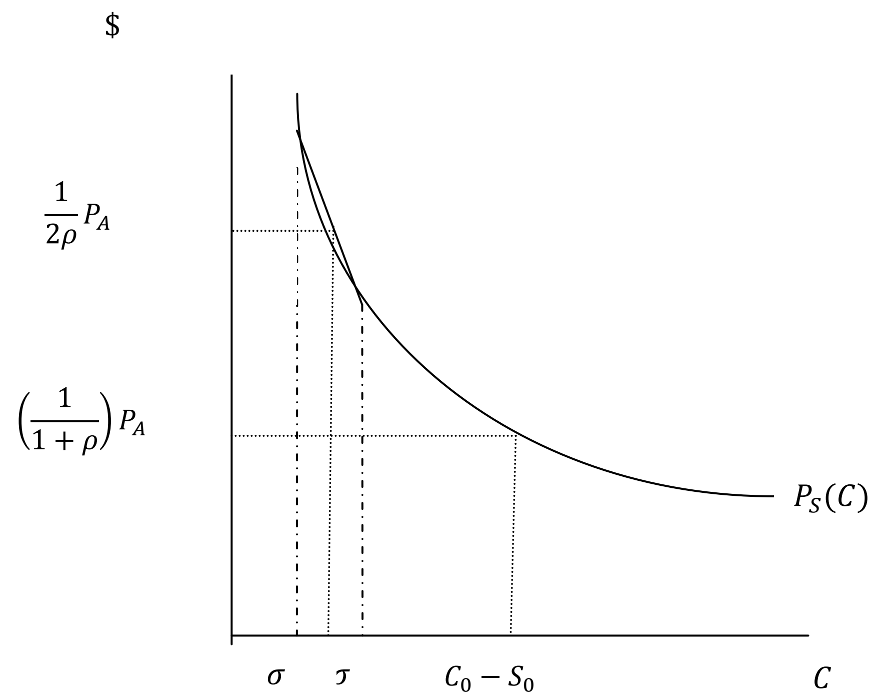
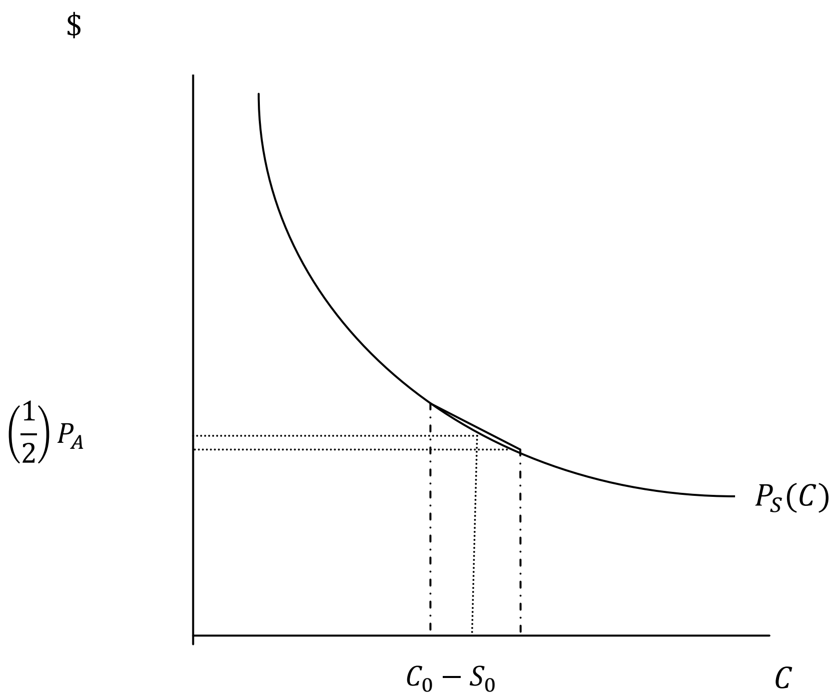


Figure 3.4: Geometric representation of the optimal solution for carbon sequestration and carbon abatement in the first period when $\boldsymbol{\rho = 1}$.



3.8. Appendix A: Derivation of the optimal time path of current value shadow cost of carbon sequestration

Rearrange equation (9):

$$\dot{\mu}_2(t) = \delta\mu_2(t) + f(t) \quad \text{(A1)}$$

Where $f(t) = -P_S{}'(C(t)) \cdot S(t)$.

Set $h(t) = \mu_2(t)e^{-\delta t}$. Then $\dot{h}(t) = e^{-\delta t}(\dot{\mu}_2(t) - \delta\mu_2(t))$. Substitute to (A1) to get:

$$h(t) = e^{-\delta t}f(t) \quad \text{(A2)}$$

Integrate (A2) to get:

$$h(t) = h(T) - \int_t^T e^{-\delta s}f(s)ds \quad \text{(A3)}$$

Use (A3) and (A2) to rewrite (A1):

$$\mu_2(t)e^{-\delta t} = \mu_2(T)e^{-\delta t} - \int_t^T e^{-\delta s}f(s)ds \quad \text{(A4)}$$

Or:

$$\mu_2(t) = \mu_2(T)e^{-\delta(T-t)} + \int_t^T e^{-\delta(s-t)}P_S'C(s)) \cdot S(s)ds \quad \text{(A5)}$$

3.9 Appendix B: Derivation of optimal rate of abatement in the first period when future is not discounted.

Recall the minimization problem

$$\min_{A_0} \int_0^{S_1^*(B_L)(A_0)} P_S(C_1 - u)du + P_A A_0$$

Take the first derivative with respect to A_0 to obtain:

$$-P_S\big(C_1(A_0) - S_1^*(B_L)(A_0)\big) - \int_0^{S_1^*(B_L)(A_0)} \frac{P_S(C_1 - u)du}{du} + P_A = 0 \quad \text{(B1)}$$

Or:

$$-P_S\big(C_1(A_0) - S_1^*(B_L)(A_0)\big) - P_S\big(C_1(A_0) - S_1^*(B_L)(A_0)\big) + P_S\big(C_1(A_0)\big) + P_A = 0 \quad \text{(B2)}$$

Rearrange (B2) to get:

$$2P_S\big(C_1(A_0) - S_1^*(B_L)(A_0)\big) = P_S\big(C_1(A_0)\big) + P_A \quad \text{(B3)}$$

Since C_1 is not affected by A_0 we can substitute $C_1 = C_0 - S_0$. In addition, substitute (18) to obtain:

$$2P_S(C_0 - X_0 - 2(E - A_0) + B_L) = P_S(C_0 - S_0) + P_A \quad \text{(B4)}$$

Finally, substitute equation (26) when $\rho = 1$ to obtain:

$$2P_S(C_0 - X_0 - 2(E - A_0) + B_L) = (\tfrac{3}{2})P_A \quad \text{(B5)}$$

3.10 Appendix C: Derivation of the Bellman equation when the model includes penalty functions

Equation (C1) is a Bellman equation for the minimization problem in the first period given the expected optimized value function for the second period where ρ denotes the discount factor between the two periods:

$$\min_{A_o,S_0} P_A A_0$$

$$+\int_0^{S_0} P_S(C_0-u)du+\left(\frac{1}{2}\right)\rho\{\int_0^{S_1^*(B_H)} P_S(C_0-S_0-u)du+\varphi(X_0+2(E-A_0)-$$

$$-S_0-S_1^*(B_H)-B_H)\}+\left(\frac{1}{2}\right)\rho\{\int_0^{S_1^*(B_L)} P_S(C_0-S_0-u)du+\varphi(X_0-2(E-A_0)-S_0-$$

$$S_1^*(B_L)-B_L)\} \qquad \text{(C1)}$$

Taking the partial derivatives with respect to S_0 and A_0, rearranging and, assuming interior solutions for both conditions, we obtain the following first order conditions:

$$P_A+\left(\frac{1}{2}\right)\rho\{(2\varphi'(B_H)-2P_S(C_0-S_0-S_1^*(B_H)))\cdot\left(\frac{\partial S_1^*(B_H)}{\partial X_1}\right)+$$

$$+(2\varphi'(B_L)-2P_S(C_0-S_0-S_1^*(B_L)))\cdot\left(\frac{\partial S_1^*(B_L)}{\partial X_1}\right)\}=0 \qquad \text{(C2)}$$

$$(1+\rho)P_S(C_0-S_0)+\left(\frac{1}{2}\right)\rho\{(\varphi'(B_H)-(P_S\big(C_0-S_0-S_1^*(B_H)\big))\cdot\left(\frac{\partial S_1^*(B_H)}{\partial X_1}+\frac{\partial S_1^*(B_H)}{\partial C_1}\right)+$$

$$+(\varphi'(B_L)-(P_S\big(C_0-S_0-S_1^*(B_L)\big))\cdot\left(\frac{\partial S_1^*(B_L)}{\partial X_1}+\frac{\partial S_1^*(B_L)}{\partial C_1}\right)-P_S\big(C_0-S_0-S_1^*(B_H)\big)-$$

$$-P_S(C_0-S_0-S_1^*(B_L))\}=0 \qquad \text{(C3)}$$

Substitute (C2) into (C3) and rearrange to obtain condition (34).

CHAPTER FOUR

CLIMATE CHANGE AND FUTURE URBAN DEVELOPMENT: AN ECONOMETRIC ANALYSIS OF THE DEMAND AND SUPPLY OF URBAN LAND

4.1 Introduction

Recent land use trends in the United States reveal a substantial increase in urban land use. Developed land increased by about 50%, around 35 million acres, from 1982 to 2003. Land in major uses such as forestland, cropland and pasture, has declined to accommodate this extensive increase in developed land (U.S Department of Agriculture, Natural Resources Conservation Service 2003). Urban and other developed areas are projected to continue to grow considerably during the 21th century in conjunction with projected increases in U.S. population and income. Alig et al (2010), based on scenarios for the 2010 RPA Assessment that are linked to the 4th Intergovernmental Panel on Climate Change (IPCC) storylines, project the area of urban land to more than double by 2062, relative to 2002, reaching 176 million acres.

Climate change has direct and indirect effects on urban development. Climate change may induce human migration (e.g., people may leave hotter and drier areas), affecting the demand for urban land. Furthermore, climate change may alter the supply of urban land (e.g., loss of land in coastal areas due to sea-level rise). Climate change also can have indirect effects through markets. Changes in the prices for agricultural and forestry commodities or the availability of water for irrigation create incentives for landowners to reallocate their land to more profitable uses, such as urban ones. Urban development, on the other hand, contributes to climate change mostly by affecting precipitation and temperature patterns.

Compensating differential studies find that climate has a significant effect on the quality of life in urban areas (Blomquist et al, 1988; Gyourko and Tracy, 1991). These studies use hedonic models to estimate reduced-form equations for wages and housing prices which are based on microeconomic theory of producer and consumer behavior. Others suggest that domestic migration in the United States to places with nice weather (e.g., migration for warm winters or cooler, less humid summers) is a result of increased valuation of nice weather as a consumption amenity (Rappaport, 2006).

A structural model of the demand for and the supply of urban land is estimated in this chapter. Price elasticities for demand and supply are calculated at the national as well as regional levels. The contribution of different climatic variables in determining the demand for and the supply of urban land is then investigated by estimation of a hierarchical linear model. The structural approach, in contrast to the reduced form, enables us to recover different affects of the examined variables on the demand side and the supply side of the market. Moreover, structural estimation of demand and supply allows us to evaluate non-marginal changes in demand and supply due to shifts in one of the time-varying variables. The model is estimated with panel data on 3032 counties in the contiguous United States for four time periods: 1982, 1987, 1992 and, 1997. A two-step estimation procedure is applied. In the first step, fixed effects and time-varying variables are used to estimate the structural system of demand and supply equations via

Two-Stage Least Squares (2SLS) procedure. This yields consistent estimates of the structural equations' parameters. The model is then extended to a hierarchical linear model. The contribution of observed time-invariant variables in explaining counties fixed effects is investigated. Among these variables are climatic and geographical variables which are assumed to affect both the supply and the demand for urban land, though in potentially different ways.

Two different approaches to estimate the price elasticities of supply and demand for urban land have emerged in the urban economic literature. Muth (1964) views urban land as an input to the production of a house. He finds that demand for urban land in the U.S. is relatively inelastic (a price elasticity of about -0.8). That is, a one percent increase in the price of urban land will reduce the quantity demanded by 0.8 percent. In addition, he finds the supply of urban land in the U.S. to be elastic (price elasticity between 10 and 15). Similar results for the price elasticity of demand for urban land for 32 urban areas in the U.S. for the time period between 1966 and 1978, are found by Kau and Sirmans (1981) using the same approach as Muth (1964). The authors also find that the price elasticity of demand for urban land increased over the examined time period, and was significantly lower in the Western cities and was significantly lower in larger cities.

Unlike Muth, Alonzo (1964) considers urban land as a composite of many attributes such as the location of the lot, the consumer's income and tastes, and commuting costs to the center of the city. That is, the consumer values urban land because of its different attributes and not only as an input into the production of a house. Similarly, he views the supply of urban land in terms of its opportunity cost (e.g., agricultural profitability). Voith (2001), applying Alonso's approach and using an instrumental variables technique in his econometric analysis, finds a more elastic price elasticity of demand for urban land (-1.6) compared with Muth. (1964). However, Voith uses data on housing sales from only one county (Montgomery County) in Philadelphia and, thus, it is unlikely that one can extrapolate his results to other areas in the U.S.

Many studies that are focused on the supply side of the urban land market investigate the effects of restrictive development regulations on housing prices using indices of regulatory stringency. The use of this approach yields mixed results ranging from significant price effects from greater regulatory restrictiveness to little or no effect on price (Quigley and Rosenthal, 2005; Saiz, 2007). In addition, the use of data on land regulations in estimating the price elasticity of supply for urban land has been criticized by several authors. Among the reasons[34] are the failure of most studies to account for the endogeneity of regulations (Quigley and Rosenthal, 2005; Ihlanfeldt, 2007: Saiz, 2007) as well as the complexity of local policymaking and regulatory behavior (Quigley and Rosenthal, 2005). More recent studies explore land topography (e.g., slopes, water bodies) as a factor that may restrict the supply of urban land (Saiz, 2007; Saiz 2010) or use quasi-experimental designs to estimate effects of land-use regulations on property values (Grout et al 2011).

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[34] See Quigley and Rosenthal, (2005) and Ihlanfeldt, (2006) for a complete discussion on the limitations of using regulations in estimating the price elasticity of supply of urban land.

To our knowledge, the proposed study is the first one to estimate the price elasticity of demand and the price elasticity of supply of urban land at the county-level in the United States. All previous work has focused on either specific locations (e.g., cities in a specific state) or metropolitan areas in the U.S. Price elasticity estimations at the county-level are an important extension in the context of climate change research. A key finding in the first essay of this dissertation is that future land-use patterns in the U.S. will be shaped largely by urbanization. This result, however, assumes a perfectly elastic demand for urban land across the nation. This, in turn, may lead us to over predict urban land expansion because, as we know from economic theory, as the price of urban land increases its quantity should fall and less additional land should be provided. Incorporating price elasticity estimates of the demand for urban land as well as the supply of urban land in such projections will result in a better understanding of future land use in the United States. Furthermore, we sort out the effects of climate variables on demand for and supply of urban land separately. At the present time we are unaware of a study that quantifies such effects on the demand for and the supply of urban land.

The paper is organized as follows. A simple model of supply and demand is presented in the next section. The empirical model is presented in the third section, including a discussion of the identification of the supply and demand equations. A description of the proposed econometric estimation procedure closes the third section. The fourth section deals with data collection. Section five presents the results and section six concludes.

4.2. The Model

A simple model of urban land demand and urban land supply is presented. Let $q_{i,t}$ and $p_{i,t}$ denote the quantity and price of urban land, respectively, in county i at time t in the U.S. where $i = 1,..,I$ and $t = 1,..,T$. In addition, let $x_{i,t}^{d}$ and $x_{i,t}^{s}$ denote vectors of exogenous variables characterizing the demand for and the supply of urban land, respectively. For each county at each time, the market demand function, $q_{i,t}^{d}(p_{i,t}, x_{i,t})$, represents the amount of urban land that price taking consumers are willing to purchase at a given price. Likewise, the market supply function, $q_{i,t}^{s}(p_{i,t}, x_{i,t})$, represents the amount of urban land that price taking sellers are willing to offer as a function of price for each county at each time.

Markets are assumed to clear, which means that there is a price-quantity pair at which the quantity demanded is equal to the quantity supplied. In other words, for all counties i and times t there is a price, $p_{i,t}$, that equates demand and supply $q_{i,t}^{d}(p_{i,t}, x_{i,t}) = q_{i,t}^{s}(p_{i,t}, x_{i,t})$.

The simultaneous system of supply and demand and the equilibrium condition can be expressed as follows:

Demand: $$q_{i,t}^{d} = f(p_{i,t}; x_{i,t}^{d})$$

Supply: $$q_{i,t}^{s} = g(p_{i,t}; x_{i,t}^{s})$$

Market clearing: $$q_{i,t}^{d} = q_{i,t}^{s} = q_{i,t}$$

Which simplifies to:

Demand: $q_{i,t} = f(p_{i,t}; x^d_{i,t})$

Supply: $q_{i,t} = g(p_{i,t}; x^s_{i,t})$

The above system of equations is interdependent as both equations (supply and demand) are needed to determine the equilibrium price and quantity (Greene, 2008). That is, the market clearing process feeds prices back into the equations for supply and demand, creating joint determination of the equilibrium quantities. Because the set of regressors in both equations includes the endogenous price variable Ordinary Least Squares (OLS) estimates of the parameters of the equations are inconsistent (Greene, 2008). Thus, other methods of estimation should be employed to obtain consistent and efficient estimates. We now present the proposed empirical model and our estimation procedure.

4.3. Empirical Specification

Consider a panel data model of demand for and supply of urban land which is given in a log-linear specification:

Demand: $\log(q_{it}) = \alpha^d_i + \beta^d_p p_{it} + \beta^d X^d_{it} + \varepsilon^d_{it}$ (1)

Supply: $\log(q_{it}) = \alpha^s_i + \beta^s_p p_{it} + \beta^s X^s_{it} + \varepsilon^s_{i,t}$ (2)

where q_{it} and p_{it} are the equilibrium per acre quantity and per acre annualized price of developed land in county i at time t, respectively. X^d_{it} and X^s_{it} are vectors of exogenous time-varying regressors affecting the demand and the supply, respectively:

$$X^d_{it} = [popden_{it} \quad inc_{it} \quad T1982 \quad T1987 \quad T1992 \quad pcjobscons_{it}]$$

$X_{it}^{s} = [popden_{it} \quad farmearn_{it} \quad T1982 \quad T1987 \quad T1992 \quad pcjobscons_{it}]$

where $popden$ inc $farmearn$ and $pcjobscons$ are population density, per capita income, farm earnings and per capita jobs in construction respectively, in county i at time t. Population density is included in the model to account for the impact that population per acre has on the development of urban land. Per-Capita jobs in constructions controls for future demand expectations. We provide more details on income and farm earning in the identification subsection below. T1982, T1987, and T1992 are dummy variables which capture common time effects on the demand for and the supply of urban land. The dummy variable for 1997 is dropped to avoid perfect collinearity with the constant terms. α_i^d and α_i^s are county-specific constant terms that capture unobserved time-invariant heterogeneity among counties. The idiosyncratic error terms represents all the unexplained variation in the equilibrium quantities and are denoted by ϵ_i^d and ε_i^s, respectively. Finally, β^d, β^s are vectors of parameters to be estimated.

This model is then extended to a hierarchical linear model in which heterogeneity within counties is assumed to be observed so that:

$$\alpha_i^d = \gamma^d Z_i + u_i^d \tag{3}$$

$$\alpha_i^s = \gamma^s Z_i + u_i^s \tag{4}$$

where Z_i is a vector of time-invariant regressors which are assumed to affect both the supply of and the demand for urban land.

$Z_i = [rain_i \quad jantemp_i \quad sun_i \quad jultemp_i \quad prewater_i \quad landsurface_i \quad interstateden_i$

$otherroadsden_i$] where $jantemp,\ jultemp,\ sun,\ rain$ are long average means of temperature for January, temperature for July, hours of sunlight and precipitation in county i, respectively.[35] $prewater$ is the percentage of water area in county i. $landsurface$ is a categorical variable describing land surface with 5 categories ranging from flat plains to high mountains. Four dummy variables are introduced into the model to account for differences in the effect of $landsurface$ on urban land. The omitted category is plains. The variable $interstateden$ is the density of interstate highways in county i. The interstate highway system was largely completed by the 1980s and thus can be treated as a time-invariant exogenous variable in our study. Finally, the variable $otherroadsden$ measures the density of all other roads.[36] Although road density is likely to change over time, due especially to changes in local road systems, there is no time-series data available on local roads at the county level for the time period examined. Because we feel this variable may explain some of the fixed effects variation across counties, we decided to include it in the analysis. u_i^d and u_i^s are the time-invariant error components in the demand and supply equations, respectively. And, γ^d, γ^s are vectors of parameters to be estimated.

Time-invariant variables as well as all time-varying exogenous regressors are assumed to be uncorrelated with the idiosyncratic error terms in both equations (1) and (2):

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[35] Long term averages are for the period 1941-1970. Temperatures are measured in degrees Fahrenheit.
[36] All other roads include major and minor collectors as well as local road systems.

$E\left[\epsilon_{it}^{d}\middle|X^{d}\right] = E[\epsilon_{it}^{s}|X^{s}] = E\left[\epsilon_{it}^{d}\middle|Z\right] = E[\epsilon_{it}^{s}|Z] = 0$

In addition, the idiosyncratic error terms are assumed to be normally distributed with zero mean and constant variances:

$E\left[{\epsilon_{it}^{d}}^{2}\middle|X^{d}\right] = \delta_{\epsilon_d}^{2} \quad , \quad E\left[{\epsilon_{it}^{s}}^{2}\middle|X^{s}\right] = \delta_{\epsilon_s}^{2}$

as well as uncorrelated across counties and over time:

$E\left[\epsilon_{it}^{d}{\epsilon_{js}^{d}}'\middle|X^{d}\right] = 0 \ \ , \ \ E\left[\epsilon_{it}^{s}{\epsilon_{js}^{s}}'\middle|X^{s}\right] = 0 \qquad if\ t \neq s\ or\ i \neq j$

However, the idiosyncratic error terms can be correlated across the two equations in county i at a given time t:

$E\left[\epsilon_{it}^{d}{\epsilon_{js}^{s}}'\middle|X^{d}\right] \neq 0 \qquad if\ t = s\ and\ i = j$

And, lastly, the error terms in the hierarchical model are assumed to be uncorrelated with the time-invariant variables as well as normally distributed and homoscedastic:

$E\left[u_{i}^{d}\middle|Z\right] = E[u_{i}^{s}|Z] = 0, \quad E\left[{u_{i}^{d}}^{2}\middle|Z\right] = \delta_{u_d}^{2} \quad , \quad E\left[{u_{i}^{s}}^{2}\middle|Z\right] = \delta_{u_s}^{2}$

Equations (1) and (2) are the structural equations to be estimated. We expect the demand curve to be downward slopping, $\beta_{p}^{d} < 0$, and the supply curve to be upward sloping, $\beta_{p}^{S} > 0$. In addition, for a solution to exist we require $\beta_{p}^{d} - \beta_{p}^{s} \neq 0$.

4.4. Identification

To obtain supply and demand elasticities, we must estimate the structural form of the simultaneous system of supply and demand equations. This means we must address the well known identification problem. A regression of quantity on price generates estimates that could be estimates of the supply parameters, the demand parameters or some combination of both (Kennedy, 2003).

The solution to the above identification problem requires that we impose restrictions on both equations. For the identification of the demand equation, we require that at least one exogenous variable in the supply function not appear in the demand function (i.e., the parameters of these exogenous variables are restricted to be zero in the demand equation). Only then will demand be identified. An exclusion restriction must also be applied to identify the supply equation.

4.4.1. Identification of Supply

The supply equation is identified using the income variable which is excluded from the supply equation (that is, the coefficient on the income variable equals zero in the supply equation). Determinants of the supply of urban land may include development costs, technology used in development (i.e., machinery and so on) and number of suppliers in the market just to name a few. Income, on the other, is one of the most recognized demand shifters in the economic literature. As per capita income increases, the consumption of urban land rises if urban land is a normal good. We assume here that the supply of urban land is not affected by changes in people’s income levels.

4.4.2. Identification of Demand

The demand equation is identified using the farm earnings variable which is excluded from the demand equation (that is, the coefficient on the farm earnings variable equals zero in the demand equation). Returns to agriculture are related to agricultural land values and can be viewed as an opportunity cost of urban development. Plantinga and

Miller (2001) find that (on average) a 1 dollar increase in annual agricultural rents increases the value of agricultural land by about 5 dollars per acre. Farm earnings are dependent on global agricultural prices as well as changes in agricultural productivity. The latter is constrained by parameters such as soil quality, climate variables, and topography. However, it is unlikely that farm earnings are related to urban demand as this is a supply side phenomenon. It is implausible that consumer's demand for urban land will change for different farm earnings levels.

4.4.3. Estimation Procedure

As mentioned before, estimating the demand (1) and the supply (2) equations separately by OLS will yield neither efficient nor consistent estimates of the structural equation parameters. Inconsistency of the OLS estimates stems from the presence of endogenous variables on the right-hand side of the equations (Greene, 2008). Inefficiency is due to equation by equation estimation of a jointly dependent system (Greene, 2008). In this chapter we address only the consistency issue by applying the 2SLS estimator to simultaneous system of supply and demand. In 2SLS, instruments are used to identify the structural parameters of the system one equation at a time. This method is considered inefficient, though, as it fails to account for cross-equation correlation in the error terms.[37]

The following steps are employed:

[37] An efficient estimation of simultaneous equations system in the context of panel data is a rather complicated task. Since consistency is of our primary interest in estimating price elasticities of demand and supply, we employ 2SLS.

First step: By solving the structural equations (1) and (2) for price as a function of the exogenous variables and the parameters, one obtains the following reduced-form equation for the price of developed land:

$$\mathrm{p_{it}} = \frac{\left(\alpha_i^s - \alpha_i^d\right) + \beta^s X_{i,t}^s - \beta^d X_{i,t}^d + \left(\epsilon_{i,t}^S - \varepsilon_{i.t}^d\right)}{\beta_p^d - \beta_p^s} \tag{5}$$

Equation (5) is simply a regression of the right-hand side endogenous variable on the full set of time-varying instruments. Since all right-hand side variables in (5) are exogenous, OLS estimates are consistent. Note that estimation of (5) is equivalent to a hedonic price regression.

Second step: Fitted values from (5) are used as instruments (W) in the estimation of the coefficients in each of the structural equations (6):[38]

$$\hat{\beta}_{FE(2SLS)} = [(\sum_i W_i' Q_i X_i)(\sum_i X_i' Q_i X_i)^{-1}(\sum_i X_i' Q_i W_i)]^{-1}(\sum_i W_i' Q_i X_i)(\sum_i X_i' Q_i X_i)^{-1}(\sum_i X_i' Q_i y_i) \tag{6}$$

where $Q_i = I_T - j_T(j_T' j_T)^{-1} j_T'$ is a projection matrix that time de-means the data, $y_i = \ln(q_{i\cdot})$ and j_T is a is a T-vector of ones.

[38] the notation for the demand and supply equations is suppressed in the following steps but these steps should be performed for both equations

Third step: $\hat{\beta}_{FE(2SLS)}$ is used to recover estimated county fixed effects for each of the structural equations:

$$\hat{\alpha}_i = \bar{y}_i - \bar{w}_i \hat{\beta}_{FE(2SLS)} \tag{7}$$

where over-bar indicates sample-period mean for county i (e.g., $\bar{y}_i = \frac{1}{T}\sum_t y_{it}$).

Fourth step: The γ in equations (3) and (4) are estimated by using a linear regression of α_i on Z_i[39]. A linear-in-variables model is estimated as well as a quadratic one (except for the categorical variable) in order to detect possible non-linear effects.

4.5. Data

Our panel data model contains observations on 3032 counties in the contiguous U.S. for four time periods: 1982, 1987, 1992 and 1997. County-level data on developed area in the U.S. is available from the four U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) data sets from 1982 to 1997.[40] County-level data on urban net returns are taken from Lubowski (2002). Since no comprehensive county-level data exists on lot prices for developed land, Lubowski (2002) backed out urban net returns using county-level data on single-family home prices (which include both the

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[39] For a large number of observations (n), the sampling variation of $\hat{\beta}_{FE(2SLS)}$ diminishes as it is a consistent estimator of $\beta_{FE(2SLS)}$. Therefore, for estimation of γ, a linear regression of α_i on Z_i, in both the supply of and the demand for urban land will be consistent in n. See Greene (2008, p.230-231) for more details.

[40] NRI were not necessarily developed to provide land use estimates at the county level but there is no other available data.

value of the house and the value of the lot). First, he uses a house price index[41] and median county-level prices for single family homes for the census years 1980 and 1990 to extrapolate yearly data for each year between 1980 and 1999. He then backs out land prices by multiplying the annual estimates of the median single-family home prices in each county by an estimate of the value share of the lot in the total price of a single-family home. Finally, he combines the two estimates (home price and lot share) to get a measure of median lot prices for single-family homes in each county and divides by estimated lot sizes to obtain a per acre measure of developed lot values.[42]

County-level data on population, farm earnings, personal income, land areas, and number of jobs in construction is available from the U.S. Census Bureau. The percentage of water area as well as county level long term averages (1941-1970) of mean temperature for January, mean temperature for July, and mean hours of sunlight are available from the Health Resources and Services Administration, U.S. Department of Health and Human Services. Land surface topography codes at the county level are available from the National Atlas of the United States of America, U.S. Department of Interior. Data on annual average precipitation (in inches) at the county level are available from the HIGH RADON PROJECT.[43] These data represents a "typical meteorological

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[41] House price indices were available only at the state-level and Lubowski had to scale each state trend up and down for each county to fit the change in home prices between 1980 and 1990 from the census (Lubowski 2002).

[42] See section 3.2.4 in Lubowski (2002) for a complete description of the urban net returns estimation procedure.

[43] See HIGH RADON PROJECT website for more details: http://eande.lbl.gov/IEP/high-radon/data/lbnl-met.html

year" and are derived from 30-year climatological data.[44] Data on road lengths by county in the U.S. is taken from the U.S. Department of Transportation website. Lastly, all dollar figures are expressed in constant (1990) dollars. Descriptive statistics for exogenous regressors can be found in Table 4-1.

4.6. Results

Table 4-2 presents estimates of the reduced-form relationship between the price of urban land and all time-varying exogenous regressors. The model coefficients are highly significant ($F(7,9089)=622.18$, $P<0.001$) as are all individual coefficients estimates. In particular, both of the excluded variables (farm earnings in the demand equation and income in the supply equation) are highly significant, indicating a sufficient correlation between the endogenous variable and the instrumental variables (Kennedy, 2003). Furthermore, a Davidson-MacKinnon test of the validity of the instruments finds support for the specification that takes into account the endogeneity of the urban land price[45] (Demand equation: $F(1,9088)= 8.152876$, $P<0.05$; Supply equation: $F(1,9088)=11.2736$, $P<0.001$).

Results for the fixed effects 2SLS regression models for the demand for and the supply of urban land are presented in Table 4-3. County-specific constants differ (Demand equation: $F(3031, 9089)=23.72$, $P<0.001$); Supply equation:

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[44] For more information see Apte et al, (1998).

[45] The Davidson-MacKinnon test examines the null hypothesis of the invalidity of the instruments. The null hypothesis is being rejected both for the demand and the supply equations.

F(3031,9089)=167.19, P<0.001) implying that a linear model with one intercept is inappropriate. In addition, the fraction of variance due to the fixed effects is estimated to be around 98% of the total variance in both equations. Main findings are consistent with theory. For the estimates of demand (supply), price has the expected negative (positive) effect on the quantity of urban land. Indeed, both price coefficients are significant and have the right sign. According to the model, a 10 dollar increase in the price of urban land ($/acre) causes the quantity of urban land demanded to decrease by 0.043 acres and the supplied quantity of urban land to increase by 0.021 acres, all else equal.

Population density, per-capita income and per-capita jobs in construction have a positive and significant effect on the demand for urban land. These findings are consistent with previous findings by Alig et al (2004). A 10 dollar increase in per-capita income, for example, causes the quantity of urban land demanded to increase by 0.0045 acres, all else equal. The negative and significant effect of farm earnings on the supplied urban land is intuitive as this variable represents the opportunity cost of land development. As farm earnings increase we would expect less land to be converted to urban uses, all else equal. The negative and significant effect of population density on the supply of urban land is also rather intuitive. The supply of developed land decreases as areas become denser, reflecting the fact that a big fraction of the land in such areas is already developed. Furthermore, the model suggests that per-capita jobs-in-construction does not affect the supply of urban land. Time has a significant and positive effect on both the demand and supply of urban land. All time dummy variables are highly significant with smaller effect in earlier years.

The price elasticity of demand estimates suggests relatively inelastic demand at the national level (0.44) as well as in all regions but the West region (Table 4-4). The South region exhibits the most inelastic demand (0.28) suggesting that for a one percent change in price of urban land in the South region there is 0.28 percent change in the quantity of urban land in that region, all else equal. As already mentioned, the West region is the only region where the price elasticity of demand for urban land is greater than unity in absolute value (1.64). On the other hand, the supply of urban land is found to be relatively inelastic at both the national and the regional levels (Table 4-4). A change of one percent in the price of urban land causes a change of only about a one-fifth percent change in the quantity of urban land supplied at the national level, all else equal. The South region has the most inelastic supply of urban land (0.14) whereas the West region has the least inelastic supply of urban land (0.81).

Descriptive statistics for the estimated county fixed effects are presented in Table 4-5. Considerable variation in the estimated fixed effects is evident in both the demand and supply equations. The mean is centered around zero and the standard deviation is almost 2.

Effects of time-invariant variables on the position of county-specific intercepts (fixed effects) in the demand and supply equations are presented in Table 4-6. Effects are measured at the average log of urban land area in county i over the four time periods and at the averages of all relevant time-varying regressors in county i over the four time periods. Overall, the estimates of the coefficients in all four specifications are highly significant. For the linear specifications, all climatic variables with the exception of precipitation in the demand equation are significant. Moreover, the signs on the coefficients of all four climatic variables are the same in both equations. Rain in the supply equation and long term average mean temperature in January have positive effects whereas long term average mean hours of sunlight and mean temperature in July have negative effects.

The positive effect of long run average annual mean rainfall and the negative effect of the squared term of this variable in the quadratic specification for the supply equation are significant. This suggests rain has a positive effect on supply which diminishes with further increases in rainfall. This is not true for the demand equation, however. In the quadratic specification, the negative effect of rain on demand is significant but the squared term is not.

The long term average mean temperature in July has a negative and significant effect on demand and supply in the quadratic specification but only the squared term in the supply equation is significantly different than zero. The positive effect of long term average mean temperature in January is significant in both the demand and supply equations in the quadratic specification, but only the squared term in the demand equation has a (positive) significant effect. These results suggest only a second order effect of July (January) temperature on supply (demand).

In agreement with the linear specification, the effect of hours of sunlight (percentage of water bodies) in the quadratic specification is negative (positive) and significant in both equations. Furthermore, the quadratic term of this variable has a positive (negative) and significant effect in both equations. The density of all non-interstate roads (interstate roads) is positive and significant with the exception of the linear (quadratic) specification of the demand equation. The negative (positive) effect of the squared term is significant in both equations.

Lastly, results for the categorical variable, land surface, are in agreement in all four specifications. Plains topography has a positive and significant effect on supply and demand. In addition, the coefficient on the tablelands is negative and significant in all four specifications. Plains with hills or mountains has a positive effect on demand and supply relative to plains topography except in the linear demand equation. Furthermore, only the quadratic specification for the demand equation shows a (positive) significant effect between open hills and mountains and plains topography. Finally, both quadratic specifications show a positive and significant effect between hills and mountains and plains topography.

4.7. Discussion

We estimate a simultaneous equations system of demand and supply using panel data on 3032 counties in the contiguous U.S. over four periods of time to obtain price elasticity estimates for urban land. Furthermore, the role of different climatic and topographic variables in explaining observable variation in demand and supply is examined.

Our findings suggest that results from previous studies which assume a perfectly elastic demand for urban land across the nation (e.g., Haim et al (2011)), are likely to have overestimated future urban development. Our model suggests a relatively inelastic demand for urban land at the national level as well as in most U.S. regions. The West region is the only exception, with a price elasticity greater than unity (in absolute value). According to our findings, while most Americans do not change their consumption of urban land very much as its price increases, Americans in the West region are more likely to do so. This result could be explained by the fact that our elasticity estimates are positively related to average prices of urban land in the different regions. The average price of urban land in the West is considerably higher than in other regions. Our estimates are in agreement with Muth (1964) and Kau and Sirmans (1981) except for the West region. Kau and Sirmans (1981) find that cities in the West tend to have a more inelastic demand for urban land then other regions in the nation while our findings suggest the opposite. This may be due to their inclusion of only seven big cities in the West region,[46] whereas our study includes 133 counties in the West region, most of which are less populated and developed. Another reason may be the different periods of estimation in the two studies. The estimation in Kau and sirmans (1981) are based on the period 1966-1978, while the price of urban land in the West region grew faster than in any other region in the nation (more than three times the rate for the Plains region) between 1982 and 1997.

Price elasticity of supply estimates suggest a relatively inelastic supply of urban land at the national level as well as the regional level. Similar to the demand elasticity, the large variation among regions can be explained by the fact that our estimate depend

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[46] Cities in the West Region included in Ka and Sirmans (1981) are: Los Angeles, Sacramento, San Diego, San Francisco, San Jose, Spokane and, Seattle.

on average prices of urban land in the different regions. Our price elasticity estimates are somewhat lower than those of Saiz (2010). This could be explained by the fact that his estimation is based on metro areas with population greater than 500,000 while we estimate urban land supply for both highly populated and very rural counties. One would expect a relatively inelastic supply in rural areas as a result from higher construction costs or development restrictions to protect natural habitats.

Climatic variables are found to play an important role in the variation of urban land demand and supply across counties in the U.S. Temperature is found to significantly affect urban land demand and supply. Consistent with Rapaport (2006), warmer winter temperatures and cooler summer temperatures increase the demand for and the supply of urban land.

The positive (diminishing) effect of rain on the supply of urban land is perhaps not intuitive. This result suggests that, at least at the national scale, rain is not a limiting factor on agricultural productivity. If the opposite was true, then we would expect that rain would have a negative effect on urban land supply as more rain increases the opportunity cost of land development (i.e., increases the profitability of agricultural land uses). One explanation could be that some of the highest valued agricultural land in the county (e.g., the central valley of California) is actually dependent on irrigation rather than natural precipitation. Schlenker et al (2005) suggest that economic effects of climate change on agriculture should be assessed differently in irrigated and dry-land areas. Our findings suggests that rain does not explain urban land demand in the U.S.

Topography is found to have mixed effects on urban development. In particular, our findings suggest that both consumers and developers of urban land prefer counties that are characterized by plains topography over counties that have tablelands topography. Results for steeper terrains, however, are inconclusive suggesting possibly positive effects of steeper topography on urban land demand and supply. One explanation for the positive effect on the supply of urban land would be that steep land is perhaps less valuable for agriculture and thus is easier to develop. This result, however, is not in agreement with previous studies suggesting steeper landscapes restrict the supply of urban land (Saiz 2007). Positive effects of steeper topography on the demand of urban land may be attributed to beautiful views observed from mountains and hills.

The existence of lakes and streams lead to an increase of urban land demand and supply. This result is in agreement with Wu and Gopinath (2008), who find that natural amenities make a large contribution to spatial variations in housing prices in the U.S. Our findings, however, suggest a non-linear relationship between water bodies and urban land demand and supply with a diminishing effect as water bodies (expressed as a present of the total land in a county) increase.

These results have implications for the design of polices to mitigate climate change effects on urban land use in the U.S. Projected annual warming is greatest in winter in high latitudes (about 5°C) and is greatest in summer in the Southwest US (2 to 3°C). In addition, projections of annual mean precipitation suggest a decrease in the Southwest of the U.S. but an increase in all other regions (IPCC, WG II, 2007). According to our linear specification, demand for urban land is thus expected to decline noticeably in the Southwest region and to increase considerably in northern regions of U.S. as a result of climate change. This is in opposite to recent land use trends in the U.S. (Alig and Ahearn, 2006).

4.8. References

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4.9. Tables

Table 4-1: Descriptive Statistics for exogenous regressors

	Mean	SD
price ($/acre)	2,057	2,330
popden (pop/acre)	0.232	0.954
Income ($)	14,961	3,528
pcjobscons (pop/acre)	0.024	0.019
farmearn ($)	13,600,000	32,500,000
Rain (inch/year)	35.037	14.100
jantemp (Fahrenheit)	32.830	12.131
sun (hours/year)	151.493	33.319
jultemp (Fahrenheit)	75.850	5.393
perwater per cent	4.527	11.175
interstateden (miles/acre)	0.218	0.413
otherroadsden (miles/acre)	1.907	1.648

Table 4-2: Parameter Estimates of Reduced Form Equation

	Reduced form
popden	3785.078***
	(24.65)
farmearn	0.00000432***
	(5.14)
T1982	-694.1935***
	(-24.47)
T1987	-416.2874***
	(-19.24)
T1992	-390.3666***
	(-19.98)
pcjobscons	1838.737**
	(3.32)
inc	0.0699045***
	(10.17)
_cons	406.4374***
	(3.70)
N	12128

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4-3: Parameter Estimates of the Structural Model of the Demand for and the Supply of Urban Land.

	(1)	(2)
	Demand	Supply
price	-0.000212**	0.000105**
	(-2.67)	(2.84)
popden	0.805**	-0.395*
	(2.66)	(-2.46)
inc	0.0000222**	
	(3.26)	
T1982	-0.610***	-0.390***
	(-11.01)	(-11.39)
T1987	-0.409***	-0.277***
	(-12.40)	(-13.39)
T1992	-0.269***	-0.146***
	(-8.65)	(-8.00)
pcjobscons	0.547*	-0.0356
	(2.07)	(-0.15)
farmearn		-1.37e-09***
		(-3.54)
_cons	2.129***	2.000***
	(40.68)	(36.15)
N	12128	12128

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4-4: Price Elasticity of Demand for and Supply of Urban Land in the National and Regional Levels.

	Demand	Supply
National	-0.44	0.22
West	-1.64	0.81
Mountains	-0.78	0.39
Plains	-0.35	0.17
Midwest	-0.33	0.17
Northeast	-0.54	0.26
South	-0.28	0.14

Table 4-5: Descriptive Statistics of Counties Fixed-Effects for Demand and Supply Equations.

	Demand	Supply
Obs	3032	3032
Mean	-2.39e-09	-2.12e-09
Std. Dev.	1.93	1.92
Min	-14.04	-8.52
Max	6.32	9.56

Table 4-6: Parameter Estimates of Counties Fixed-Effects Regression on Time-Invariant Variables.

	(1) Demand (Linear)	(2) Demand (Quadratic)	(3) Supply (Linear)	(4) Supply (quadratic)
rain	0.00336	-0.0143*	0.0148***	0.0288***
	(1.48)	(-2.33)	(9.71)	(4.98)
jantemp	0.0570***	0.0488***	0.0358***	0.0255***
	(14.24)	(6.48)	(16.78)	(3.67)
sun	-0.00478***	-0.0129***	-0.00358***	-0.0167***
	(-6.63)	(-3.35)	(-6.09)	(-4.77)
jultemp	-0.0907***	-0.218**	-0.0437***	-0.266***
	(-10.61)	(-2.68)	(-8.96)	(-3.76)
perwater	0.00737***	0.0688***	0.0143***	0.0572***
	(4.13)	(15.17)	(12.75)	(18.37)
topo_table	-0.332***	-0.213**	-0.231**	-0.168*
	(-3.75)	(-2.80)	(-3.16)	(-2.37)
topo_plains_hm	0.0621	0.295***	0.141*	0.264***
	(0.79)	(4.11)	(2.11)	(4.12)
topo_open_hm	-0.0913	0.151***	-0.0744	0.0678
	(-1.93)	(3.72)	(-1.92)	(1.78)
topo_hm	0.0231	0.351***	0.0159	0.201***
	(0.39)	(6.38)	(0.31)	(4.09)
interstateden	4.902**	-1.038	6.980***	7.495***
	(3.22)	(-1.20)	(5.03)	(11.82)
roadsden	0.0652	1.065***	0.427***	0.856***
	(1.59)	(23.14)	(19.51)	(28.09)
rainsq		0.0000434		-0.000252***
		(0.58)		(-3.43)
jantempsq		0.000210*		0.0001000

		(2.03)		(1.05)
sunsq		0.0000371**		0.0000504***
		(2.88)		(4.25)
jultempsq		0.000823		0.00153**
		(1.47)		(3.12)
perwatersq		-0.00109***		-0.000775***
		(-13.69)		(-14.49)
interstatedensq		50.50***		11.64***
		(8.55)		(4.09)
roadsdensq		-0.0853***		-0.0355***
		(-14.90)		(-11.90)
_cons	5.384***	9.595**	1.152***	9.295***
	(10.22)	(3.27)	(3.41)	(3.62)
N	12128	12128	12128	12128

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