Climate Change Economics, Vol. 2, No. 1 (2011) 27–51
© World Scientific Publishing Company
DOI: 10.1142/S2010007811000218

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

DAVID HAIM*, RALPH J. ALIG†, ANDREW J. PLANTINGA*,§
and BRENT SOHNGEN‡

Department of Agricultural and Resource Economics
Oregon State University

†*U.S. Department of Agriculture, Forest Service*
Pacific Northwest Research Station

‡*Department of Agricultural, Environmental*
and Development Economics, The Ohio State University
§*plantinga@oregonstate.edu*

An econometric land-use model is used to project regional and national land-use changes in the United States under two IPCC emissions 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.

Keywords: Econometric models; land-use; climate change; regional analysis.

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 can also 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.

§Corresponding author.

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 *et al.*, 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.

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 Sec. 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 Sec. 5, and Sec. 6 concludes.

[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.

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) found smaller impacts on U.S. agriculture compared with earlier studies, and in some cases, their results indicated 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 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 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 six 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.

3. IPCC and Baseline Scenarios

Two scenarios (out of four alternative scenario families) from the IPCC 4$^{\text{th}}$ 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 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% larger population by 2060 relative to the A1 scenarios. The A1 scenario has higher personal income, which by 2060 is 44% larger than for the A2 scenario.

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

Scenario	Year						
	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

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). 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 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.

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

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

Table 3. Percentage change in NPP and aboveground carbon relative to 2010 averaged for the entire U.S.

			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%

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

[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).

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.

4.1. *Land-use projection model*

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 *et al.*, 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 6 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

[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.

(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, 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:

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

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 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:

$$P_{ijkt} = P(\hat{\beta}_{jk}, NR_{it}, LQ_i), \tag{2}$$

[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.

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

$$A_{ijt+1} = \sum_{k} P_{ikjt} \cdot A_{ikt}. \tag{3}$$

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.

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 (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 1. The South region is the largest in terms of population, having 29% of the population in the contiguous United States. The Mountain and the Plains regions are the smallest, with a share of almost 10% 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 3063 counties and 16 years (1982–1997). 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 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% 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

Table 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

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 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 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

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

Scenario	Region	Year					
		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

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

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% under A1 and between 74% and 108% under A2.

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. 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 Eq. (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.

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 U.S. 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 on 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 found 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 Eq. (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 Figs. 1–4. 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

[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.

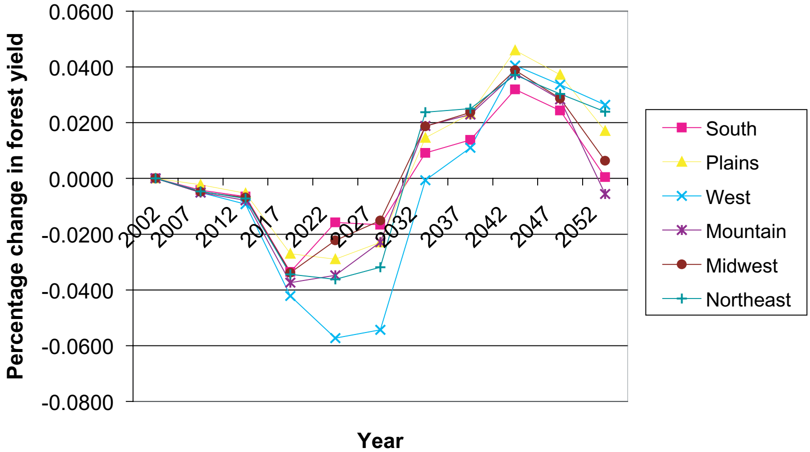

Figure 1. Average percentage changes in forest yields, by region and time period, under the A1 scenario

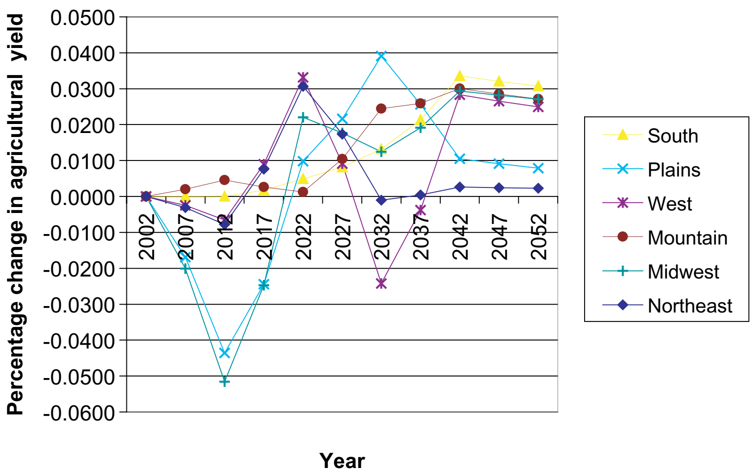

Figure 2. Average percentage changes in agricultural yields, by region and time period, under the A1 scenario

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 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.

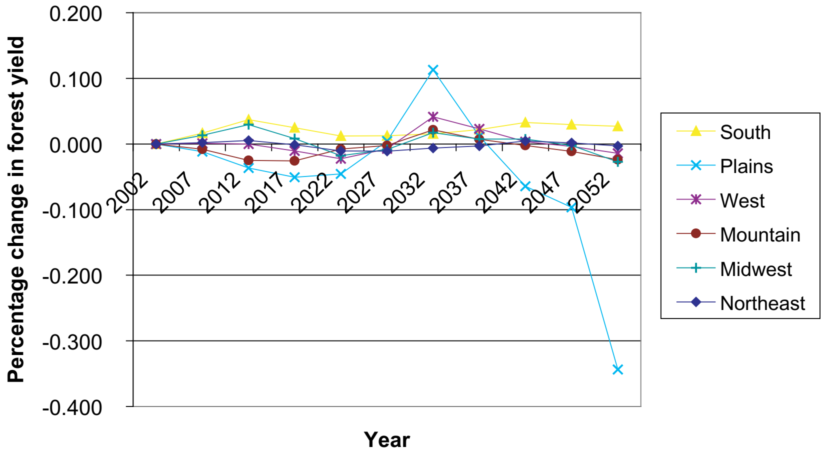

Figure 3. Average percentage changes in forest yields, by region and time period, under the A2 scenario

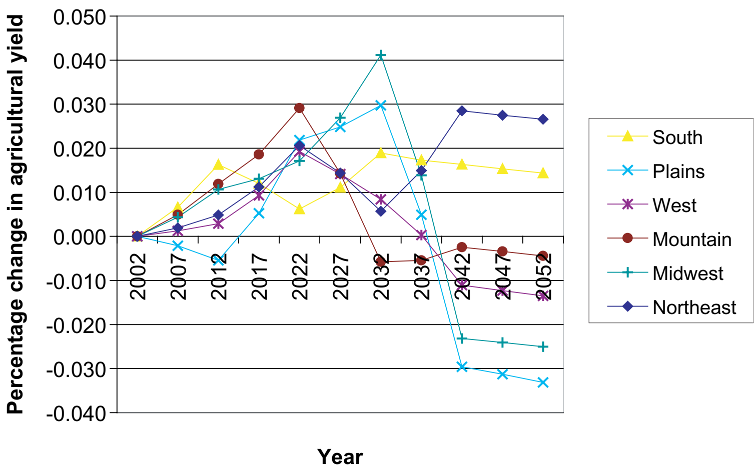

Figure 4. Average percentage changes in agricultural yields, by region and time period, under the A2 scenario

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

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

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.

5. Results

Tables 6 and 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 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 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

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

Regions	Crop	Pasture	Forest	Urban	Range	Total
Area by land-use in 2002						
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						
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						
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 7. Projection of land-use areas to 2052 under the IPCC A2 scenario, by region, in million acres.

Regions	Crop	Pasture	Forest	Urban	Range	Total
Area by land-use in 2002						
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						
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						
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	

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 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 two regions, while declining in the others. The Plains region is the largest of the six 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 (Tables 5–7) mask the variation in changes occurring at county scales within the model. 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 six regions.

Projections for the baseline scenario with no climate change effects on agricultural prices and agricultural and forest yields are presented in Tables 8 and 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

[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.

Table 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.

Regions	Crop	Pasture	Forest	Urban	Range	Total
Climate change (A1 scenario)						
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						
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						
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.

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 affects 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 regions, but lower in

Table 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.

Regions	Crop	Pasture	Forest	Urban	Range	Total
Climate change (A2 scenario)						
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						
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						
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.

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.

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 non-Federal land base in our study in 2002. By 2052, urban land is projected to occupy 16% of the non-Federal 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 (Figs. 1–4). 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 four 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 6), 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.

References

Alig, RJ, DM Adams and B McCarl (2002). Projecting impacts of global climate change on the U.S. forest and agriculture sectors and carbon budgets. *Forest Ecology and Management*, 169, 3–14.

Alig, RJ, AJ Plantinga, D Haim and M Todd (2010). Area changes in U.S. forests and other major land uses, 1982 to 2002, with projections to 2062. *Gen. Tech. Rep.* PNW-GTR-815. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 98 p.

Bachelet, D, RP Neilson, JM Lenihan and RJ Drapek (2004). Regional differences in the carbon source-sink potential of natural vegetation in the U.S. *Environmental Management*, 33 (Supp. 1), S23–S43.

Capozza, DR and RW Helsley (1989). The fundamentals of land prices and urban growth. *Journal of Urban Economics*, 26, 295–306.

Ciais, PH, M Reichstein, N Viovy, A Granier, J Ogee, V Allard, M Aubinet, N Buchmann, CHR Bernhofer, A Carrara, F Chevallier, N De Noblet, AD Friend, P Friedlingstein, T Grunwald, B Heinesch, P Keronen, A Knohl, G Krinner, D Loustau, G Manca, G Matteucci, F Miglietta, JM Ourcival, D Papale, K Pilegaard, S Rambal, G Seufert, JF Soussana, MJ Sanz, ED Schulze, T Vesala and R Valentini (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, 437, 529–533.

[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.

[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).

Deschenes, O and M Greenstone (2007). The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *American Economic Review*, 97(1), 354–385.

Fischer, G, M Shah and V Velthuizen (2002). Climate change and agricultural vulnerability. International Institute for Applied System Analysis. Report prepared UN institutional contract agreement 1113 for World Summit on Sustainable Development. Laxenburg, Austria.

Haberl, H, HK Erb, F Krausmann, V Gaube, A Bondeau, C Plutzar, S Gingrich, W Lucht and M Fisher-Kowalski (2007). Quantifying and mapping the human appropriation of net primary productivity in earth's terrestrial ecosystems. *PNAS*, 104(31), 12942–12947.

Imhoff, ML, L Bounoua, T Ricketts, C Loucks, R Harris and WT Lawrence (2004). Global patterns in human consumption of net primary productivity. *Nature*, 429, 870–873.

Intergovernmental Panel on Climate Change, Working Group I (IPCC-WGI) (2007). Climate change 2007. The Fourth Assessment Report. The Scientific Basis. Cambridge, Cambridge University Press.

Joyce, LA, JR Mills, LS Heath, AD McGuire, RW Haynes and RA Birdsey (1995). Forest sector impacts from changes in forest productivity under climate change. *Journal of Biogeography*, 22, 703–713.

Joyce, LA, J Aber, S McNulty, VH Dale, A Hansen, LC Irland, RP Neilson and K Skog (2000). Potential consequences of climate variability and change for the forests of the United States. In: National Assessment Synthesis Team, comps. Climate change impacts on the United States: The potential consequences of climate variability and change: Foundation. Cambridge, UK: Cambridge University Press, pp. 489–522.

Kurukulasuriya, P and IM Ajwad (2007). Application of the Ricardian technique to estimate the impact of climate change on smallholder farming in Sri Lanka. *Climatic Change*, 81, 39–59.

Kurukulasuriya, P and R Mendelsohn (2007). A Ricardian analysis of the impact of climate change on African agriculture. Policy Research Working Paper 4305, World Bank, Washington, DC.

Langner, L (2010). Basic assumptions for the 2010 Resources Planning Act (RPA) Assessment. Supporting document by the RPA Management Group, Washington, DC. 33 p. Draft report. On file with: Linda Langner, USDA Forest Service, Research and Development, 4th floor RPC, 1601 North Kent Street, Arlington, VA 22209.

Lobell, DB, KG Cassman and C Field (2009). Crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, 34, 179–204.

Lubowski, RN (2002). Determinants of land-use transitions in the United States: Econometric analysis of changes among the major land use categories. Cambridge, MA: Harvard University. 172 p. (plus appendices). PhD dissertation.

Lubowski, RN, AJ Plantinga and RN Stavins (2006). Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function. *Journal of Environmental Economics and Management*, 51(2), 135–152.

Mendelsohn, R, WD Nordhaus and D Shaw (1994). The impact of global warming on agriculture: A Ricardian analysis. *American Economic Review*, 84, 754–771.

Mendelsohn, R, WD Nordhaus and D Shaw (1999). The impact of climate variation on U.S. agriculture. In Mendelsohn R and JE Neumann (eds.), *The Impact of Climate Change on the United States Economy*. Cambridge, Cambridge University Press, pp. 55–74.

Perez-Garcia, J, AL Joyce, AD McGuire and X Xiao (2002). Impacts of climate change on the global forest sector. *Climatic Change*, 54, 439–461.

Plantinga, A, R Alig, H Eichman and D Lewis (2007). Linking land-use projections and forest fragmentation analysis. Res. Pap. PNW-RP-570. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Station. 41 p.

Prince, SD, J Haskett, M Steininger, H Strand and R Wright (2001). Net primary production of US midwest croplands from agricultural harvest yield data. *Ecological Applications*, 11(4), 1194–1205.

Schatzki, T (2003). Options, uncertainty and sunk costs: An empirical analysis of land-use change. *Journal of Environmental Economics and Management*, 46(1), 86–105.

Schlenker, W, WM Hanemann and AC Fisher (2005). Will U.S. agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. *American Economic Review*, 95(1), 395–406.

Schlenker, W, WM Hanemann and AC Fisher (2006). The impact of global warming on U.S. agriculture: An econometric analysis of optimal growing conditions. *Review of Economics and Statistics*, 88(1), 113–125.

Schlenker, W and MJ Roberts (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106(37), 15594–15598.

Segerson, K, AJ Plantinga and EG Irwin (2006). Theoretical background. In Bell KP, KJ Boyle and J Rubin (eds.), *Economics of Rural Land-Use Change*, Burlington, VT: Ashgate Publishing Company. Ch. 6, pp. 79–112.

Shugart, H, R Sedjo and B Sohngen (2003). Forests and global climate change. Potential impacts on U.S. Forest Resources. Arlington, VA: Pew Center on Global Climate Change.

Sohngen, B and R Mendelsohn (1998). Valuing the impact of large-scale ecological change in a market: The effect of climate change on U.S. timber. *American Economic Review*, 88(4), 686–710.

Sohngen, B, R Mendelsohn and R Sedjo (2001). A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics*, 26(2), 326–343.

Sohngen, B and R Sedjo (2005). Impacts of climate change on forest product markets: Implications for North American producers. *Forest Chronicle*, 81(5), 669–674.

Stavins, R and K Richards (2005). The cost of U.S. forest based carbon sequestration. Prepared for the Pew Center for Global Climate Change.

Train, KE (2003). *Discrete Choice Methods with Simulation*. Cambridge, UK: Cambridge University Press.

Tweeten, L and SR Thompson (2008). Long-term global agricultural output supply-demand balance and real farm and food prices. Department of Agricultural, Environmental, and Development Economics, The Ohio State University, Working Paper AEDE-WP 0044-08.

Woods & Poole Economics Inc. (2006). The 2006 complete economic and demographic data source (CEDDS), Washington, DC. http://www.woodsandpoole.com.

Zarnoch, S (2010). Analysis for 2010 Resources Planning Act (RPA) Assessment. Supporting document maintained by the RPA Management Group, Washington, DC. 28 p. Draft report. On file with: Linda Langner, USDA Forest Service, Research and Development, 4th floor RPC, 1601 North Kent Street, Arlington, VA 22209.