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Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets

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Abstract

A multiperiod, regional, mathematical programming model is used to evaluate the potential economic impacts of global climatic change scenarios on the US forest and agricultural sectors, including impacts on forest carbon inventories. Four scenarios of the biological response of forests to climate change (reflected by changes in forest growth rates) are drawn from a national assessment of climate change and are based on combinations of global circulation and ecological process models. These scenarios are simulated in tile the forest and agricultural sector model and results are summarized to characterize broad impacts of climate change on the sectors. We find that less cropland is projected to be converted to forests, forest inventories generally increase, and that aggregate economic impacts (across all consumers and producers in the sector) are relatively small. Producers' income is most at risk, and impacts of global climate change on the two sectors vary over the 100-year projection period. The forest sector is found to have adjustment mechanisms that mitigate climate change impacts, including interregional migration of production, substitution in consumption, and altered stand management.

Keywords: Land-use; Forest sector; Economics

1. Introduction

Global climate change induced by anthropogenic release of greenhouse gases, mainly CO_2, is perceived by some as one of the greatest environmental challenges the world faces today. The specter of possible deleterious effects of climate change on agricultural and forest productivity has been raised, and there is much debate on how to reduce or offset the greenhouse gases released into the atmosphere by industrial production and land management practices. Sequestration of carbon in the biomass of forests has emerged as one significant carbon sink. Since global climate change may modify the growth and geographic distribution of forests, the biological effects of climate change on forests must be considered in any analysis of the impacts of global change on the forest sector. This study offers estimates of the potential economic impacts within the US forest and agricultural sectors due to changes in forest growth under different scenarios of global climate change,[1] including producer and consumer welfare, prices, and land-use changes.

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[1] This analysis was part of the National Climate Change Assessment by the US government and cooperators. The national assessment examined impacts of possible climate change by sector and region of the United States (e.g., see overall, forest, and agriculture-related web sites, respectively: http://www.nacc.usgcrp.gov, http://www.nacc.usgcrp.gov/sectors/forests/, and http://www.nacc.usgcrp.gov/sectors/agriculture/draft-report/).

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We employ a dynamic linked model of the US forest and agriculture sectors (Forest and Agricultural Sector Optimization Model (FASOM) as described in Adams et al. (1996, 1997) and Alig et al. (1998)) that simulates timber and agricultural market behavior and resource management responses in both sectors. Given the considerable uncertainty about the biological impact of global change on forests (e.g., Sohngen and Mendelsohn, 1998), we examine four alternative scenarios based on combinations of projections from global circulation and ecological process models. This study differs from earlier work in that a linked model of the forest and agriculture sectors is used, along with more recent climatological and ecological inputs, to examine possible impacts of climate change on land use shifts between the sectors, among other possible adjustments. The following sections of this paper describe problem background, prior studies, methods employed to estimate the impacts on forestry and agriculture, and then results and discussion. Throughout, emphasis is given to forest sector results. Details on the agricultural sector can be found at the Website noted in footnote 1.

2. Forest resource and product market impacts of climate change

Shifts in global climatic conditions would affect crop and tree growing conditions, but the nature of the altered climate could vary substantially by region. The ecological and economic importance of forests varies across the nation, as do growing conditions and the importance of agriculture. Further, because climate change is global in nature and a considerable portion of US softwood timber consumption is produced in Canada (30% of softwoods), the implications of climate change for harvest in Canada must also be recognized.

In addition to ecological and economic considerations, forests and soils are important carbon sinks. Impacts on agriculture and forests arise from increases in atmospheric CO_2 concentration, change in temperature regimes, and variations in patterns of rainfall over the year. Such shifts could alter basic physiological processes in crops, trees, and soils, influencing growth and the yield of commercial products over time. The actual time pattern of change will be complex, owing to lags between atmospheric changes, climate effects, and biological responses. Economic impacts resulting from growth changes will be further delayed due to the length of forestry rotations, generally involving two or more decades.[2] Thus, an examination of the effects of climate change on agriculture and forests needs to consider forest rotation decisions as well as lags between the onset of climate change and resulting biological impacts. These dynamic aspects of climate-induced changes in yields need to be addressed with a model that recognizes the temporal characteristics of both product markets and the agriculture and forest resources.

Climate change may alter the quantities of agricultural and forest products harvested in a substantial fashion. This will necessitate some resource management changes and may stimulate social and economic processes of adaptation. Differential impacts of climate change on the two sectors could lead to land use shifts as one possible adaptation strategy. For example, if climate-influenced growth impacts result in relatively higher agricultural productivity per hectare, some hectares may be converted from forests to agricultural use. In regions where climatic effects reduce timber growth, smaller timber volumes will be available for harvest in both existing forest stands and in those replanted after harvest in the future. The reverse would be true in regions experiencing increased timber growth. Such changes would alter the supply of products to national and international markets, changing the prices of forest products and the economic well-being of both consumers and producers of these products. Consumers, in turn, will shift their patterns of consumption between forest and non-forest products. Producers will change both the types of management they practice (planting, thinning, and other cultural treatments) and the ages at which they harvest trees in various ways, depending on the nature of the owner (private or public).

The difference between climate change effects on existing trees and trees planted in the future bears further emphasis. Existing trees will be affected only in their incremental growth from the current period to harvest age as climate change occurs. Trees planted in the future will grow entirely in an environment with altered climate. Thus, growth rate responses may

[2] A forest "rotation age" is the length of time that trees are grown from natural regeneration or planting to final harvest.

differ for existing and future trees. For existing trees, current volume will remain unchanged[3] but future incremental growth may vary. For new trees, the entire future time path of volume growth and product yield may be altered. Landowner options to shift land uses also brings in temporal differences between the forest and agriculture sectors with respect to lead time required to respond and shift production. With agricultural rotations typically of one to several years, that provides more flexibility relative to forestry. This affects the likely mix of afforestation, reforestation, and deforestation under different global climate change scenarios for forest industry and non-industrial private owners who tend to have notably different land management objectives (Alig et al., 1990).

3. Past studies of the terrestrial effects of climate change

Several studies have explored climate change implications for the agricultural sector (e.g., Adams et al., 1990, 1999; Kane et al., 1992; or others as reviewed in Adams et al., 1998a,b; Lewandrowski and Schimmelpfennig, 1999). In forestry, longer rotation lengths complicate development of data on biological responses to global warming (Sohngen and Alig, 2000). Comprehensive long-term experiments have not been completed on how trees behave when exposed to alternative climates or CO_2 levels, nor can analyses of existing forests be used with confidence because CO_2 levels associated with future climate change have not been observed. Also little is known about how experimental results on individual trees generalize to stand, forest, and regional levels.

Investigators have simulated climate effects on the distribution and productivity of forests using three different types of models.

1. *Biogeochemistry models* that simulate the gain, loss, and internal cycling of carbon, nutrients, and water. With these models, the impact of changes in temperature, precipitation, soil moisture, atmospheric carbon dioxide, and other climate-related factors can be examined for their influence on such processes as ecosystem productivity and carbon storage.
2. *Biogeographic models* that examine the influence of climate on the geographic distribution of plant species or plant types such as trees, grasses, and shrubs.
3. *Dynamic global vegetation models* that integrate biogeochemical processes with dynamic changes in vegetation composition and distribution.

One limitation of most earlier work is that the models predicted only steady-state conditions. An earlier analysis using biogeochemistry models and four climate scenarios (different from those in the national climate change assessment) showed increased net primary productivity at the continental scale (VEMAP Participants, 1995). Carbon storage results varied with the assumed sensitivity to changes in water availability.

Experimental and simulation evidence indicates that forest productivity increases with the fertilizing effect of atmospheric carbon dioxide (Korner, 1993). Across a wide range of scenarios, it is plausible that modest warming could result in carbon storage gains in most forest ecosystems in the conterminous United States. Yet, under some warming scenarios, it is possible that drought-induced losses of carbon would occur in certain forests, notably in the Southeast and the Northwest (US Forest Sector Team, 2000). The extent of these potential gains and losses of carbon will be affected by changing land-use patterns, such as the conversion of forests to other uses, and the reversion of other lands to forests.

Economics studies have examined potential impacts of climate change on the forest sector. van Kooten and Arthur (1989) concluded that the overall implications of climate change for economic welfare may be negative for Canada.[4] Later, van Kooten (1990) examined 5 and 7.5% increases in Canadian harvests together with positive and negative changes of similar magnitudes for US harvests concluding that consumers in both countries would benefit, but that producers would lose. He also concluded that the

[3] Forest fire risk may increase in some areas according to some studies (e.g., Sohngen and Haynes, 1997).

[4] Economic welfare refers to the combination of producer profits and consumer well-being measured in monetary terms which results from the interaction of supply and demand in a market. Forces that shift demand and supply influence the overall level of welfare in the market and the distribution of welfare between producers and consumers.

overall Canadian impact would be positive only if US harvests declined. Perez-Garcia et al. (1997) assumed that climate change would stimulate increased net primary production and examined climate change effects on the world forest economy using a model that did not change land management patterns. They found increased timber supplies, falling timber prices, and rising consumption. Also major timber producers such as Canada realized a positive, but small, economic gain, while the United States benefited under all scenarios examined.

Sohngen and Mendelsohn (1998) linked a dynamic model of US timber markets with a large-scale biogeographic model. This application provided more information on the dynamic adjustment of markets and resources than the Perez-Garcia et al. (1997) study, although it also assumed a doubling of CO_2 to an equilibrium level that leads to steady-state biogeographical results. Similar to Perez-Garcia et al. (1997), Sohngen and Mendelsohn found that climate change expanded long run timber supply under all scenarios. Economic welfare effects were relatively small. The analysis suggests that human actions in markets can mitigate, and even reverse, resource production shifts induced by climate change (Sohngen et al., 1998).

Rather than drawing directly on growth change estimates derived from ecological models, Burton et al. (1994, 1998) considered what appeared to be extremes (relative to reports in the literature at the time) in the potential range of forest response to global change. Their study used the FASOM model to look at three scenarios of change in forest growth: a 50% increase in decadal growth rates on timberland in both the US North and South; a 50% decrease in both regions; and a 50% increase in the North and a 50% decrease in the South. Simulation results indicated that producers' impacts exceed those on consumers and that Southern producers are affected more than producers in other regions.

McCarl et al. (2000) expanded the approach of Burton et al. (1994) to develop a set of *response functions* predicting climate change implications across a broad range of possible forest growth effects. Results using the FASOM model indicated that aggregate sectoral welfare effects (consumers' savings plus producers' profits) are relatively limited even under extreme scenarios. There are more marked economic welfare shifts between producers and consumers. Yield increases induced by climate change were found to benefit consumers but not producers, while yield decreases have the opposite effect. The forest sector was also found to have adaptive adjustment characteristics, including regional (e.g., northerly) migration of production, substitution in consumption between wood and non-wood products and between sawtimber and pulpwood, and the ability to alter the intensity of forest management (rotation age and timber management regime) among owners and regions.

McCarl et al. (2000) study was based on a model of the forest sector alone. In contrast, the current study uses a linked model of the forest and agriculture sectors. This allows explicit consideration of possible land use shifts between forestry and agriculture arising from impacts of climate change, along with other adjustments within the individual sectors.

4. Methods

4.1. BASE model for simulating forest climate change effects

The FASOM model, as documented in Adams et al. (1996, 1997) and Alig et al. (1998), was employed to derive projections of agriculture and forest sector production, prices, and welfare given a climate change scenario. FASOM is a dynamic optimization model of forest and agricultural markets. The FASOM model finds the market equilibrium for each period in a multiperiod time horizon, using nonlinear mathematical programming methods that maximize a measure of economic welfare in the two sectors. FASOM constructs an inter-temporally optimal production/consumption pattern and associated prices for a 100-year projection. Like all inter-temporal optimization models, FASOM's solution process assumes that economic agents correctly foresee all future supply, demand, and resource developments. This "perfect knowledge" assumption allows optimal selection of resource management actions and optimal adjustment to changes in resource conditions (see Adams et al., 1998a,b for further discussion).

In the case of forestry, FASOM depicts the volume removed, area harvested, and forest management investment decisions for industrial and non-industrial private forests, together with the consumption of timber products and market prices in the US forest sector by major forest region. Products comprise fuelwood, sawtimber, and pulpwood for both softwood and hardwood species. Harvests from public lands and the import supply of timber from Canada are assumed to be determined by forces outside the present analysis and are taken as exogenous input, although these volumes are likely to be affected by climate change (see Section 6).

The biological effects of climate change are introduced in the analysis by modifying timber yields in FASOM, drawing upon estimates from the US Forest Sector Team for the national assessment.[5] FASOM yields (volumes per unit area) vary by the age of the forest and an array of conditions that reflect the quality of the growing site. Let the total volume per unit area in a forest stand at the end of year 1 be Y_1, Y_2 in year 2, and Y_t in year t, and suppose we anticipate an *increase* in the growth rate of δ (for $0 \leq \delta \leq 1$) induced by climate change. Total volume in period 1 would be adjusted upward by δ. In all subsequent periods, the volume at the end of the period would be the volume at the beginning of the period times one plus the *altered* growth rate. The altered growth rate is the original growth rate in the yield table, $(Y_t - Y_{t-1})/Y_{t-1}$, times one plus δ. A similar approach was used to treat existing stands. However, for a stand of trees that is $t-1$ years old at the beginning of the analysis, only the formula for a stand at age t is employed, treating Y_{t-1} as a constant and leaving the initial volume unchanged (McCarl et al., 2000).

To reduce the scope of the problem, we differentiate between growth changes in only two broad regions within the United States, North and South, for softwood and hardwood species.[6] Because timber production is limited in the regions outside the southern and northern regions as here defined, we assume that the growth change in these other areas is the average of the changes in the North and South.

Modifications were also made in public timber harvest and Canadian import supply to reflect the impacts of climate change. These supply elements are not modeled in FASOM, nor were direct estimates of climate change impacts on their output available from the National Assessment. Harvests from public lands in US are established through political processes that are not generally sensitive to markets and recognize only selected aspects of resource conditions. This is also true of allowable harvests from provincial lands in Canada, while export supplies to US have been heavily influenced by trade restrictions. Although some of the climate change literature suggests that growth impacts on northern forests, as in Canada, may be larger than in US, it is not clear how these shifts would be translated into export supply. While we believe that the directions of supply changes from these sources would be the same as those from US private lands, the magnitudes are highly uncertain. As a consequence, we have assumed as an approximation that US public and Canadian export supply volumes change by the average percent change in harvest observed in comparable regions on private lands in the US.

4.2. Timber growth scenario projections

To investigate the outcomes under climate change scenarios, we simulate a base case (BASE) developed as a baseline for comparison. The BASE assumptions for the forest sector derive from the USDA Forest Service's 1993 Resources Planning Act Assessment Update (Haynes et al., 1995). Agriculture sector assumptions are discussed by Chang et al. (1992), and McCarl (2000). Essentially all US farm programs are eliminated in the BASE case, reflecting the Freedom to Farm legislation of the 1995 US Farm Bill. By assumption, conversions of forests to urban and developed uses do not vary between the BASE case and the four scenarios, and are primarily driven by the projected addition of more than 200 million people in the United States over the next 100 years (Alig et al., 1999).

The four climate change scenarios are drawn from a national climate change assessment (US Forest Sector

[5] The forest sector team examined the forest productivity, species diversity in forests, potential changes in carbon storage, and changes in water availability to forest systems. The assessment also examined the role of social and economic shifts in changing the character of forests and the effects of changing climate and climate variability on disturbance factors such as pests, fire, and disease within forest ecosystems.

[6] The North region includes the Pacific Northwest, Rocky Mountains, Lake States, Corn Belt, and Northeast. The South comprises the South East and South Central regions. The specific regional definitions are in Adams et al., (1996, 1997).

Team, 2000; Irland et al., 2001). The scenarios represent combinations of climate projections from two global circulation meteorological models (Canadian and Hadley) which in turn are fed into two ecological process models (Century and Terrestrial ecosystem models) to generate net primary productivity estimates (Irland et al., 2000): (1) Canadian-Century; (2) Canadian-TEM, (3) Hadley-Century, and (4) Hadley-TEM. The analyses used an equilibrium climate scenario based on the transient Canadian and transient Hadley scenarios (US Forest Sector Team, 2000). The baseline scenario was the average climate for the 1961–1990 period, and the "climate change" scenario was the average of the projected climate for 2070–2100. Results from the global circulation and ecological models provided inputs into the FASOM model to evaluate the range of possible projected changes in forest land area, timber markets, and related consumer/producer impacts associated with climate change.

The two biogeochemical models—TEM and Century—simulate the impacts of climate on forest productivity. Both models simulate the influence of environmental factors such as temperature, precipitation, and soil texture on the cycles of carbon, nutrients (e.g., nitrogen), and water in forest ecosystems at a grid cell scale of 0.5° longitude (VEMAP Participants, 1995). For the two climate scenarios that the biogeochemical models were both run under, the climate scenarios suggest a generally more productive environment. The biogeochemical models project increases in total vegetation carbon storage under the Hadley and Canadian climate scenarios (US Forest Sector Team, 2000). Compared to the Hadley climate scenario, the Canadian climate scenario is much warmer and generally drier, with some current forest area projected to have a drought-induced loss of carbon. Changes in vegetation carbon varied by each region as a function of the regional climate and the changes in climate projected by the Hadley and Canadian climate scenarios (Irland et al., 2001). For example, in the Northeast region, the oak–hickory type has the largest change among types—about a 0.3% increase in growth rate per year by 2100. Such changes in vegetation carbon by forest type were mapped into hardwood and softwood types and were used to change timber growth for 11 regions modeled in the FASOM model.

Timber growth of hardwoods and softwoods increases under all four cases in most regions for most decades, with growth increases over 10-year periods relatively small (Irland et al., 2001).

Measures of the economic impacts in the FASOM model include the net present value of economic welfare accruing to producers, consumers, foreign interests, and the total market (see, e.g. McCarl et al., 2000). The producers here are the private owners of forests in all regions of the United States who harvest timber for commercial products. Their economic welfare is measured by their profits in the sale of timber beyond their costs of growing the trees and of foregone interest involved in waiting until they are mature. Consumers comprise all users of harvested timber (for housing, manufacturing, shipping, paper and board, etc.). Their welfare or benefit from the market transaction is measured as the difference between their expenditures if forced to pay the highest price they would be willing to pay to still consume timber and their actual payments at the equilibrium market price. This difference represents a "savings" or "surplus" to consumers. Foreign interests are exporters (suppliers) of timber to, and importers (consumers) of timber from, the United States. Their welfare arising from this trade is measured in essentially the same way as for domestic producers and consumers. The total market welfare is the sum of gains and losses realized by all the market participants (plus adjustments for receipts by public timber sellers and the costs of transporting timber from sources to users). Carbon values were not included in the FASOM objective function in this study; however, the FASOM model estimates forest ecosystem carbon and the pool of carbon in forest products (Adams et al., 1997).

The ASM model used in the National Climate Change Assessment for the agricultural sector analysis is the basis for the FASOM agriculture sector modeling in this study, and more than 200 production possibilities are specified for agricultural production. The large number of agricultural activities facilitates examining possible adjustment mechanisms in response to any climate change. For example, in agriculture, eight principal direct effects of climate change were considered: crop yields, irrigated crop water use, irrigation water supply, livestock performance, grazing/pasture supply, pesticide use, and international trade. Adjustments included, for example, simulating migration of crop areas north in response to productivity shifts, earlier planting, crop mix change, irrigation change, livestock feeding change, and consumption mix change. A complex suite of agricultural models was used to in modeling such biophysical effects, including Century (e.g., grassland and hay production), EPIC (e.g., soil–climate–management combinations), and DSSAT (e.g., wheat, corn, tomatoes, and other crops, vegetables, and fruits) (see footnote 1). The agricultural results do vary across crops, regions, time periods, and climate scenarios but some broad patterns emerged: even without adaptation, yield impacts for crops grown under dryland conditions across US are generally positive with climate change. The Assessment combined those biophysical effects of climate change in an economic model (ASM) that determines the new set of price, consumption, regional production, and resource use levels that clear markets. These include major field crop production, livestock production, fruits and other tree production, and vegetable production, with scores of both primary and secondary agricultural commodities that are modeled (McCarl, 2000). The use of a linked forest and agriculture model in this study is an important difference from other studies, such as the McCarl et al. (2000) study that used a forest-only sector model.

5. Results

5.1. Economic welfare

Economic analyses for several different climate scenarios indicate that an overall increase in forest productivity in the United States is likely to increase long-term timber inventory (Fig. 1), subject to other external forces. With more potential forest inventory, timber harvests in most scenarios rise over the next 100 years (Fig. 2), lowering timber prices (Fig. 3), and reducing costs of wood and paper products to consumers and returns to owners of timberland. Total economic welfare is higher than in the BASE case for all the climate change scenarios (Table 1).

The net effect on the economic welfare of participants in both timber and agricultural markets was projected to increase between 0.4 and 0.7% above the BASE projections (Table 1). Land would likely shift between forestry and agricultural uses as these economic sectors adjust to climate-induced changes in production (Table 2). Although US total forest production generally is projected to increase in these analyses, hardwood output is higher in all scenarios while softwood output increases only under scenarios with moderate warming (Fig. 2). The extent of these changes varies by region and future decade. For example, while timber output is projected to increase

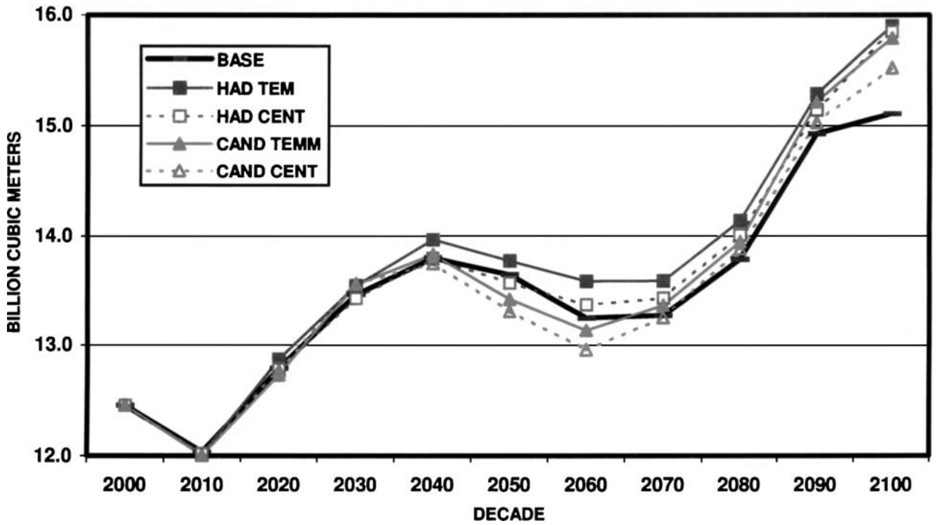

Fig. 1. Projected US total timber inventory by scenario, 2000–2100 (billion cubic meters).

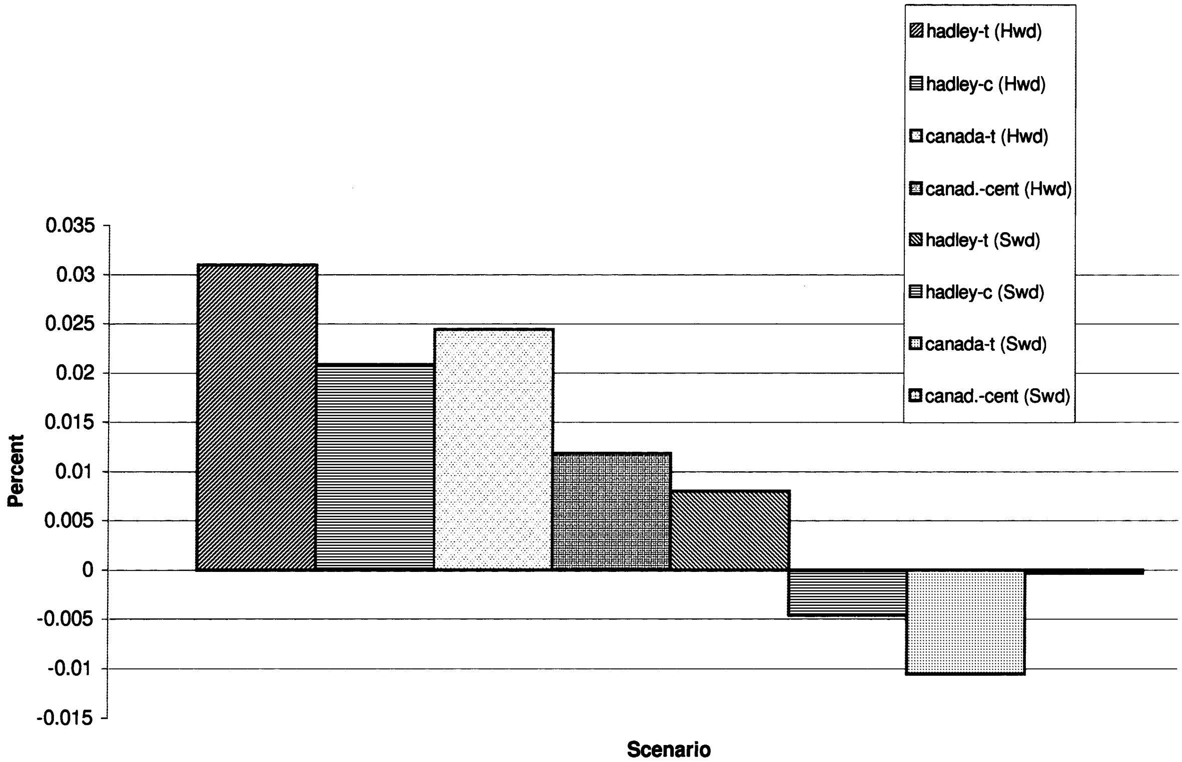

Fig. 2. Projected changes in total harvest volumes over next 100 years, as percentage change from BASE Case.

in the North relative to the South over the next decade, this is projected to reverse over the subsequent five decades so that timber output could increase more in the South. Further, sawtimber volume is projected to rise more than pulpwood.

5.2. Area changes

The four climate change scenarios are projected to lead to less forest area than under the BASE case as less agricultural land is converted to forest (Table 2).

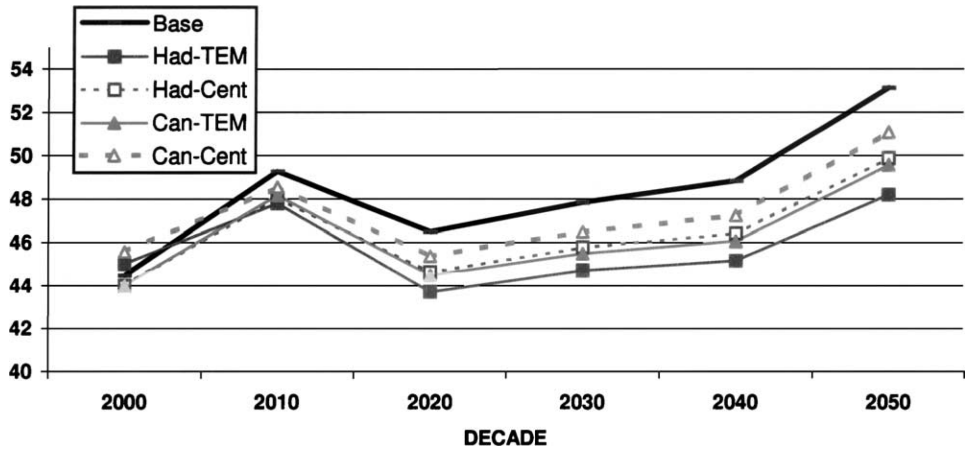

Fig. 3. Projected US average stumpage prices across scenarios, 2000–2050 (1990 US$ per cubic meter).

Table 1
Impacts on economic welfare estimates from climate change scenarios, as percentage changes from the BASE case, for 100-year time horizon (CS: consumers' surplus, PS: producers' surplus)

Measure	Hadley-TEM	Hadley-VEMAP	Canadian-TEM	Canadian-VEMAP
Domestic forestry CS	+1.3	+0.9	+1.0	+0.5
Domestic forestry PS	−7.1	−5.1	−5.5	−3.1
Domestic Ag. CS	+2.0	+2.0	+1.0	+1.0
Domestic Ag. PS	−15.9	−15.9	−7.6	−7.6
Total welfare for both sectors	+0.7	+0.7	+0.4	+0.4

Table 2
Impacts on timberland area from climate change scenarios, as area difference (million hectares) from the BASE case, for first 50 years of projection

Timberland area	BASE[a]	Hadley-TEM	Hadley-VEMAP	Canadian-TEM	Canadian-VEMAP
Forest to crop	1.1	0.0	−0.1	0.0	−0.1
Forest to pasture	2.4	−0.1	−0.1	−0.1	−0.1
Crop to forest	2.7	−2.7	−2.7	−0.8	−0.7
Pasture to forest	1.7	+0.2	+0.2	+0.3	+0.4
Net Ag. to forest transfers	0.9	−2.4	−2.3	−0.4	−0.2

[a] BASE column presents projected total land conversions without climate change, and area difference accounting in other columns is from stance of agriculture to forest transfers.

Under the BASE case, the projected net land exchange from agriculture to forests is about 1 million ha over the next 50 years. With global warming scenarios, the FASOM model has less cropland converted to forests, while more pasture land than under the BASE case is converted to forests. Climate change could lead to increases in overall agricultural crop production and exports, with decreases in crop prices (see footnote 1). Projected changes for livestock production and prices depend on the climate change scenario, with some variation also over regions and time. Given the projected changes in forest and agricultural productivity and returns to land management, the Hadley climate change scenarios have larger land-use impacts at a national scale, with less net agricultural land projected to be converted to forests (Table 2).

Positive forest productivity impacts on the existing forest base due to global climate change lower future prospective returns to new forest hectares and lessen the economic attractiveness of afforestation on cropland. Opportunity costs of land use differ compared to the BASE case. The reverse case of conversion of forests to agricultural use is impacted significantly less than the afforestation pathways (Table 2). Some existing owners of forestland could see the value of land decline as a further manifestation of producer losses.

5.3. Carbon storage

Impacts of the global change scenarios on carbon storage in US forests varies over the projection period. Over the next 20 years, changes are small and variable in sign ranging from +0.1 to −0.2% across the four scenarios, relative to BASE levels. Between 2020 and 2050, carbon inventories decline across all scenarios in a range from −1.0 to −1.7%. This is largely a reflection of higher harvests (Fig. 2) relative to BASE levels. Beyond 2050, carbon storage increases relative to the BASE levels, as harvests fall below growth and forest inventories by 2100 under all scenarios rise above the BASE (Fig. 1).

6. Discussion

Our results are generally similar to findings in other studies. Relatively small impacts are also consistent with the fact that the existing variation in climate and yields across the United States as a whole far exceeds the likely variation caused by climate change. Research in the agricultural sector (Adams et al., 1990, 1998a,b, 1999; Lewandrowski and Schimmelpfennig, 1999) has reached similar conclusions, suggesting that production shifts across regions and between producers and consumers may act to contain the aggregate impacts. In the present analysis, aggregate forest production appears to "migrate" from the North to the South across all scenarios, forest rotations are generally lengthened in the North and little changed in the South, the average intensity of management rises slightly in all regions (despite lower prices), and there is a shift in the concentration of inventory from softwoods to hardwoods. Adaptation is also seen in changing product mixes, with sawtimber use gaining at the expense of pulpwood output.

Small aggregate change does not mean there would be no "distributional impacts", i.e., shifts in economic well-being or welfare among the various groups participating in the market. Shifts between consumers and producers may be substantial, with effects for consumers' and producers' welfare that are uniformly opposing. Producers' welfare sensitivity is roughly 10 times (in percentage terms) that of consumers' welfare, which in turn is roughly five times in percentage terms that of total societal welfare. When yields are reduced, producers' welfare shows gains while consumers' welfare shows losses. When yields increase, the opposite occurs. This is not surprising given that the demand for forest products is fairly inelastic (insensitive to price). In such circumstances (as has been found in agricultural markets), small percentage increases in output lead to larger percentage reductions in prices, which lowers producers' welfare (profits) but increases consumers' welfare (they can consume more at a lower price). Climate change may portend some major dislocations for producers causing widespread structural adjustment, if it stimulates higher yields. These findings are also generally consistent with results from earlier studies to the extent that they are comparable. For example, van Kooten (1990) found that the impacts on producers from yield increases were likely to be negative, while consumers were likely to benefit.

Economic welfare impacts over time may also be important. Both consumers' and producers' impacts expand over time as the growth changes persist (recall the compounding effects of growth change on yields), resulting in variable patterns of change in the aggregate. However, further in the future assumptions about changes in population, land use, trade in wood products, consumption of wood products, recreation patterns and human values become highly uncertain. For example, if human needs from forests increase over the next 100 years and imports are limited, the socioeconomic impacts of climate change on forests would be greater than if needs are low or products can be imported from areas where climate may increase forest growth. Thus, assumptions about change in human needs in the United States and overseas, and about climate change effects in other parts of the world, are likely to have some effect on socioeconomic impacts on the United States.

One general conclusion from this and earlier studies is that timber and wood product markets will adjust and adapt to climate change in ways that act to limit economic effects. The FASOM model used in this study suggests that several forms of adaptation may be used in the forest sector, including changes in: (a) land-use choice, (b) timber management intensity, (c) hardwood/softwood species mix, (d) timber growth and harvesting patterns within and between regions, (e) rotation ages, and (f) consumers' use of wood versus other products (i.e., substitution of non-wood product in consumption based on relative price). Changes in climate and consequent impact on forests are likely to change market incentives to harvest and plant trees and shift land uses between agriculture and forestry. Adaptation to productivity increases induced by climate change could include less afforestation than under the BASE case, as adjustments in agriculture and forestry land market equilibria are prompted by perceived higher present values of economic returns in one land use versus the other.

In addition to land markets, the timber growing and processing portions of the forest sector also have options for responding to market-based incentives from climate-induced changes. Here the forest sector may see interregional migration of production, substitution in consumption, and altered forest stand management. The latter instance could include changes in rotation length and intensity or level of investment in forest practices, such as types of site preparation and planting stock, fertilization, thinning, and salvage of dead or dying trees. However, patterns of some of these changes may vary over space and time. For example, producers may act to change rotation lengths over time periods in response to climate change, with some shifts towards softwood sawtimber in the South relative to pulpwood production between 2020 and 2050. Impacts on forest carbon may likewise vary over time and involve changes in both forest ecosystem and wood products pools.

At a more detailed level, adaptation of human systems has proven to be an important factor in the assessment of climate change impacts. First, human influences on landscapes across the United States are substantial, as humans have and will continue to modify the quality, amount, and spatial configuration of habitats. A number of natural community types now cover less than 2% of their pre-settlement ranges (Noss et al., 1994). Forest changes caused by human use of forests could exceed those from climate change. More broadly, the area involved in land use shifts can dwarf the land area involved in natural forest disturbances. For example, the area of harvested cropland went from 118 million ha in 1964 to 140 million ha in 1982, and then down to 119 million ha in 1987. A second aspect of human adaptation is the modification of production methods. Studies in agriculture suggest that shifts in crop varieties, crop mixes, and other factors may reduce climate change impacts by as much as 50% relative to estimates that ignore adaptation (Adams et al., 1999).

7. Conclusion

Projecting impacts of global climate change on US forest and agricultural sectors and carbon budgets helps to place in context concerns about economic shifts associated with climate change and the importance of human actions in adaptation and mitigation. Based on the magnitude of changes in forest and agricultural yields from climate change estimated by ecological models, projection results point to relatively small aggregate economic impacts and carbon budget impacts. At present, however, estimates of impacts of climate change on forest yields have a wide range of uncertainty (Sohngen and Mendelsohn, 1998). As new findings on climatic effects arise, the scenarios of climate change from the national assessment (see footnote 1, US Forest Sector Team, 2000) should be re-evaluated.

Results from the FASOM model indicate that although aggregate sectoral welfare effects (consumers' savings plus producers' profits) are relatively limited, there are marked economic welfare shifts between producers and consumers. The overall yield increases induced by climate change were found to benefit consumers but not producers. The forest sector was also found to have adaptive adjustment characteristics, including land market adjustments, substitution in consumption between wood and non-wood products (reflected in overall growth in wood products use) and between sawtimber and pulpwood, the ability to alter the intensity of forest management and rotation age among owners and regions, and to change harvesting patterns. Such findings challenge modelers and policy analysts to be explicit regarding the size, location, and timing of various impacts, to consider the transition from current vegetation and forest stocks, and to gauge the trade-offs between short-term policy concerns and long-term ecological impacts.

Future research could include investigating the importance of the assumption of "perfect foresight" as in FASOM and related models. It may be that the "perfect foresight" condition overstates the adaptability of actual market and management systems and hence precipitates an understatement of the economic impacts. Economic modeling will also benefit from companion advances in climate and ecological modeling, such as dynamic biogeographic and vegetation modeling (e.g., improved transient forest and agriculture crop) that could provide more realistic inputs. Work on enhanced capabilities to simulate vegetation and product yields under climate change scenarios should be integrated with research to improve baseline estimates of carbon sequestration in forestry and agriculture, including attention to both land management and product options and policies (Sohngen and Alig, 2000). Improved information on possible impacts on forest and agricultural yields in other parts of the world would also enhance future US sector analyses. Feedback within the system (global circulation and climate, terrestrial ecology and forest growth, and human activities) also warrants more attention in future work.

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