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What are the Impacts of Global Warming on U.S. Forests, Regions, and the U.S. Timber Industry?

by

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What are the Impacts of Global Warming on U.S. Forests, Regions, and the U.S. Timber Industry?

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This paper addresses the question of the impacts of global warming on forests for the U.S. and other specific regions. The focus will be two-fold. First, what are the issues related to understanding the likely effects of warming on forests generally? Second, what are the effects of the changes on forests on the production of one important commodity: industrial wood? Our background is that of an economist; therefore, some of the discussion on biology and ecology might be a bit crude. However, having been involved in forests for over two decades and climate for well over a decade, we presume that we have learned a bit about biology and ecology over that period.

Parts of this paper are drawn from the paper "Forests and Global Climate Change: Potential Impacts on U.S. Forest Resources," which is going to be published shortly as part of the climate series from the Pew Center for Climate Change.[1] However, the views expressed here today are those of the authors and not necessarily those of our coauthor or of Pew Center.

Introduction

This paper explores the potential effects of climate change on natural and managed forested ecosystems, and the consequent economic impacts on timber markets. Most forests within the U.S. are, or have been, managed at some time. However, large areas of forests receive minimal direct human management and, thus, are considered natural forests for the purposes of this study. Managed forests, in turn, receive significant

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1. HERMAN SHUGART ET AL., PEW CENTER ON GLOBAL CLIMATE CHANGE, "FORESTS & GLOBAL CLIMATE CHANGE: POTENTIAL IMPACTS ON U.S. FOREST RESOURCES," Feb. 2003.

amounts of human intervention in the form of planting, thinning, or other management activities. Both natural and managed forests are important for the range of attributes society values from forests. Further, the ecological changes caused by climate change could have large implications both for non-marketed attributes (e.g. biodiversity), and for other economic sectors associated with forests (e.g. recreation and water supply). The economic analysis in this paper, however, focuses strictly on the impacts on the timber market.

Climate change is expected to have far-reaching consequences for forests and timber production in the U.S. Although studies have shown that forests have adapted to 2-3° C changes in the past, these changes occurred over thousands of years. Current climate predictions suggest that average global mean temperatures could rise 1.5-6.0° C over this century alone. Such rapid climate changes could affect forests significantly. Understanding how climate change will affect future forests and markets, however, is a complex task. Ecological and economic processes are exceptionally complicated and understanding how integrated ecological and economic systems will respond to changing climate conditions remains a challenge. In spite of a number of remaining uncertainties, this paper describes some of the many important insights into this process developed over the last ten to twenty years of research.

Some Issues of Climate Change Impact on Forests

It is important to consider how climate change could affect the productivity of forests (i.e. annual growth in forests). Some locations will almost surely experience higher productivity while other locations will experience lower productivity. Existing studies, based on the relationship between temperature and moisture, often show both positive and negative impacts on overall productivity, depending on the climate scenarios. For example, if the southern U.S. becomes drier, as some General Circulation Models (GCM) predict, productivity is more likely to decline in species that are generally more sensitive to the effects of drying, while productivity is generally predicted to rise in the northern United States. However, other GCMs predict less drying in the southern U.S. with average annual growth. In addition, there are some issues that relate to the effect on productivity and growth associated with the other aspects of climate change.

The first issue is forest dieback. A 1987 paper incorporates some of Solomon's earlier work and examines the consequences of global warming on forests, assuming that the forest die back will be fairly rapid and that its replacement by new vegetation and new forests will be very gradual.[2] In this context, forest dieback would become a dominant feature of many landscapes. Literature exists to support this view through examinations of the rate of species migration during past warming including the period since the ice age when temperatures are said to have risen by about 2 ° C. In some of the literature, this issue seems to be a race between dieback and restoration. More generally, however, one could always posit a rate of dieback that would overwhelm migration. But, at some rates of climate change, most types of vegetative migrations will be able to keep pace. This issue is still debated and is discussed in the PEW paper.

Second, is the relationship between warming and precipitation. A very simple rule that appears to be approximately correct is that "warming with sufficient increased precipitation will generally be positive for forests over the longer term, while warming and drying will generally have a negative effect." There might be some exceptions to this rule in parts of the hot tropics but it will generally hold, especially in the eastern and southeastern U.S.

Also, the species mix may change in response to the change in the temperature/precipitation mix. In the MINK study undertaken by Resources for the Future the temperature/precipitation mix seemed to determine where the interface between the prairie and the forest would occur.[3] And the question of trees versus grasses seemed to be largely determined by precipitation levels.[4] As discussed in issue three, a warming in climate generally needs to be slightly offset by increased moisture, but moisture seems to be the key factor.

Third is the effect of increased atmospheric carbon dioxide on plant growth. Plants appear to use water more efficiently in an atmosphere with increased carbon dioxide. If there is more CO2 in the air outside the leaf, then the diffusion of water molecules inward appears to be is greater. This theory has the potential to allow plants to growth better under drier atmospheric conditions. Thus, it appears that increased atmospheric carbon dioxide may offset some of the negative effects associated with a drier climate.

Fourth is the critical issue of carbon dioxide fertilization. This is an important issue and much of the overall improvement in global forests that is projected is driven by the assumption that the effects of CO_2 fertilization are positive and significant. It is well know that the growth of

2. R. A. Sedjo & A. M. Solomon, *Resources for the Future, Climate and Forests, in* GREENHOUSE WARMING: ABATEMENT AND ADAPTATION 105-19 (Norman J. Rosenberg et al. eds., 1989).

3. *See*, Norman J. Rosenberg et al., *The MINK Methodology: Background and Baseline,* 24 CLIMATIC CHANGE, June 1993, at 7.

4. *See id.*

certain types of plants responds very positively to an increase in carbon dioxide in the atmosphere. It is clear that this is also true for tree seedlings. In greenhouse studies involving single-potted agricultural species, grown under well-watered conditions with adequate nutrients and light and with an ambient CO_2 concentration (about 660 parts per million or double the current CO_2 concentration), plant growth increases about 40% across a variety of young plants and about 26% for tree seedlings and mature plants. What is somewhat less clear is how this effect applies to mature trees, although some evidence suggests the effects are reduced. Overall, CO2 fertilization is likely to increase tree growth on an individual level. However, the real question we are addressing relates not to individual trees, but to an entire forest or ecosystem. Do the growth advantages of carbon fertilization cancel out? Do some tree species prosper while the wood biomass of the entire system remains roughly unchanged? One might argue that there is a presumption that carbon fertilization will increase the growth of the whole forest unless one can make a compelling argument that CO_2 fertilization is fundamentally different from other fertilization, e.g., organic or chemical. Clearly chemical and organic fertilization benefit the growth of the forest, as well as individual trees, so why should CO_2 fertilization be different?

Frankly, it is a bit of a surprise that this question remains unresolved. Scientists have been working on it for over a decade. A number of experiments have been conducted, often with older forests, where not only individual trees but also a parcel of natural forest, e.g., one-tenth of a hectare, has received a steady diet of high carbon dioxide atmosphere. Nevertheless this issue is still unresolved in many of its aspects.[5]

There are certainly other issues related to the impact of climate change on forests that this paper has not addressed. Certainly, the species composition of forests is likely to change. The process of climate change and forest adjustment, in location and composition, is likely to have implications for biodiversity. Endemic species and species with very slow migration potential appear at the greatest risk.

General Circulations Models (GCMs) and Forest Modeling

Species-level Approaches — In the face of evidence of large changes in the makeup of vegetation (albeit at a more detailed level), there has been an interest in resolving the changes at a more detailed (often species) level. Iverson and his colleagues have recently completed an extremely detailed analysis of the expected distribution and importance

5. SHUGART, *supra* note 3, at 43.

of eighty major eastern U.S. trees.[6] As an example of this approach, Figure 1 shows the distribution of Loblolly Pine (*Pinus teada*), the principal forestry species in the U.S. Iverson estimates shifts in the range of Loblolly Pine under five different GCM scenarios for climate change in the eastern U. S. (lower section Figure 2). By estimating shifts in distributions of all eighty tree taxa, they were able to estimate the changes in forest types across the eastern U. S. These evaluations are significant. This example evaluation essentially depicts the major timber species of the South being displaced into what is now a cereal grain producing agricultural region. It also predicts a major shifting and reconstitution of the forest communities of the eastern U. S.

The estimations of Iverson and his colleagues are based primarily on a statistical evaluation of a large amount of survey data on the distribution of tree species. Other approaches that use a more descriptive approach to the factors controlling the distribution of species provide relatively similar results (at least in their broad patterns). One such analysis (Figure 3) identifies forest types that appear particularly vulnerable to climatic change across the U.S., such as high elevation forests in several locations, and drier and older forests in the Northwest and South.[7]

Ecological Forest Models

The ongoing VEMAP (1995) model comparison exercise compares six different models for ecological conditions of doubled CO_2 and several different climatic change scenarios for the United States.[8] The input requirements for the six ecological models vary significantly, but include several homogeneous landscape models, particularly in the parts of the project oriented toward dynamic responses. Perhaps not unexpectedly, given the differences in model formulation and resolution, the six models produced rather different results when subjected to large changes in the environment. For example, three of the models simulate change in vegetation structure across landscapes. These three models produce, a substantial increase in forest area under climatic warming scenarios (MAPSS model), a relatively slight change in forest cover (DOLY model), and a significant decrease in forest area (the BIOME2 model).

There is a similar variation in the net primary productivity and bio-

6. L.R. IVERSON ET AL., NORTHEASTERN RESEARCH STATION, USDA FOREST SERVICE, AN ATLAS OF CURRENT AND POTENTIAL FUTURE DISTRIBUTIONS OF COMMON TREES OF THE EASTERN UNITED STATES, GENERAL TECHNICAL REPORT NE-265 (1999).

7. R.P. NEILSON, *A Model for Predicting Continental Scale Vegetation Distribution and Water Balance*, 5 ECOLOGICAL APPLICATIONS 362-85 (1995).

8. *See* J.R. MALCON ET AL., PEW CENTER ON GLOBAL CLIMATE CHANGE, ECOSYSTEMS & GLOBAL CLIMATE CHANGE: A REVIEW OF POTENTIAL IMPACTS ON U.S. TERRESTRIAL ECOSYSTEMS AND BIODIVERSITY (Dec. 2000).

mass predicted by the homogeneous landscape models in the comparison (BIOME-BGC, CENTURY, and TEM). Depending on the model and climate change scenario considered, the climate change effects produce a range of net primary production changes from -6.5% to +17.0% of the baseline and the total carbon storage changes from between -37.6% and +4.3% when CO_2 fertilization is not included or set to zero in the model simulations. When CO_2 effects are incorporated in the model responses, the simultaneous effects of climate change and direct CO_2 effects ranged from +1.7% to +34.6% for net primary productivity and -32.7% to +14.6% for total carbon storage (again, depending on model and scenario). The variation in the performance of the models in all cases indicates a need for further model development.

The following describes the current understanding of the potential impacts of climate change on U.S. forests and timber markets as stated in the Pew Study:

- *Tree species are expected to migrate northward or upward on mountain slopes*. While species may adapt over time by moving from one region to another, differential rates of change may cause significant differences in the types of natural stands in the future. Rates will depend critically on how fast seeds migrate into new regions that are climatically suitable for a species after a climate change, changes in the spread of insect disease, the spread of wildfire in different climates, and conscience human interventions to promote species migration.
- *The effect of climate change on forest productivity and forest area is uncertain*. Forests could become more or less productive depending on: how much climate changes, whether mortality rates change, how forests respond to higher carbon concentrations in the atmosphere, and whether disturbance induced dieback increases or decreases. Many of these factors are expected to vary from region to region, making impacts difficult to estimate.
- *The effect of additional carbon dioxide in the atmosphere on forested ecosystems (so-called "carbon fertilization") is uncertain, but it has large implications for understanding how forest productivity will change*. Most studies suggest that forest area and productivity will decline if carbon fertilization does not occur, but that they are likely to increase if carbon fertilization enhances forest growth. It is important to continue developing a better understanding of the effects of carbon fertilization.
- *The role of forest disturbance is important, but uncertain*.

Forest disturbance can have negative consequences for the structure of forests, but its impact in markets can be mitigated by salvage. In the short term, disturbances can increase timber supply and reduce prices. While disturbances have negative effects on landowners, salvage ameliorates the impacts that landowners would otherwise experience.

- *Climate change is estimated to have relatively small effects on timber markets when measured at the national level*. Most studies suggest that the economic impacts on the U. S. range from small negative to positive changes, although the result is more negative if CO_2 fertilization is absent. Higher forest yield translates into increased timber inventory, increased supply, and lower prices. Lower prices generate overall net benefits, although primarily generating consumer benefits at the expense of potentially harming landowners. Lower forest yield has the opposite effect.
- *Regional impacts of climate change on timber markets could be large*. Southern markets are most susceptible to climate change because southern species are sensitive to potential drying effects caused by climate change. Additionally, the northward migration of species reduces the comparative advantage for timber production that is currently enjoyed by southern producers. Northern markets, on the other hand, could gain substantially from climate change.

Forests, Management and Timber

It is important to note that the issues of what is happening to forests generally and what is happening to economic timber supply are more loosely connected than most would suppose. As recently as a few decades ago, the vast majority of industrial forests came from wild, natural forests. This fact is much less true today and it will almost surely be even less true thirty years from now in both the U.S. and worldwide.

Increasingly, industrial wood is the product of a planted and intensively managed forest system, very similar to agricultural cropping systems. Thus, just as it has been shown that agricultural production has the capacity to adapt and adjust to changing climate, managed and particularly planted forests have that same capability. This trend has been underway for decades, but has accelerated in the past ten years since the Forest Service dramatically reduced timber harvests from National Forests. The major wood basket of the U.S. is now the Southeast, supplemented by timber from other areas of the country. The harvests from the Southeast are increasingly being drawn from planted forests.

Table 1. Estimated Global Harvests by Forest Management Condition Circa 1995[9]

Old-growth	22
Second-growth, minimal management	14
Indigenous second-growth, managed	30
Industrial plantations, indigenous	24
Industrial plantations, exotic	10

Notes: Old-growth includes: Canada, Russia, Indonesia/Malaysia.
Adjusted for harvest declines after the demise of the Soviet Union.
Second-growth, minimal management: parts of the U.S. and Canada, Russia
Indigenous second growth, managed:
Industrial plantations, indigenous: Nordic, most of Europe, a large but minor portion of U.S., Japan, and some from China and India.
Industrial exotic plantations
Second-growth, minimal management: the residual

With intensive management, a relatively small area of forest can produce large volumes of timber. This timber is typically of relatively short harvest rotations, a couple of decades. So, for most reasonable rates of warming, at least one or two rotations of twenty to thirty years could be generated from a site. Should conditions permit; these same sites might be used for additional planting of different species. New planting could also be introduced elsewhere should the current sites become unusable. In addition, the physical timber stock of the U.S. is much larger than needed to meet likely timber demand. In the case of forest dieback, timber salvage operations could capture the mortality and damaged trees. In fact, the planting of different species, which are more suitable to the modified climatic conditions, could follow salvage operations. In summary, adequate timber supply today is less dependent upon the extent and conditions of natural forests than on the productivity of industrial forests and the flexibility of tree growers and planted forests. This is likely to be increasingly the case in the 21st century.

A number of studies have attempted to assess the impact of climate warming on timber production.[10] Most of these have concluded that overall, global warming is likely to increase the availability of timber.[11] This result is not surprising in that the focus has been largely on what

9. Roger A. Sedjo, *Potential of High-Yield Plantation Forestry for Meeting Timber Needs*, 17 PLANTED FORESTS: CONTRIBUTION TO THE QUEST FOR SUSTAINABLE SOCIETIES (J.R. Boyle et al. eds., 1999).

10. *See* Table 2.

11. *See generally* Table 2.

warming would do to forest biological productivity. Since productivity usually rises during climate warming; forest growth and timber volumes are projected to increase. It should be noted that most of these studies have incorporated a carbon fertilization effect.

A number of economists have used results from the ecological models to assess how timber markets might respond to climate change.[12] These studies provide a number of insights into the scale of potential changes markets may face, including timber prices, changes in future availability of timber, location of timber production, and profits for landowners and mills. To date, economists have introduced three types of ecological impacts into their estimates of future timber production: yield effects, dieback effects, and species migration.[13]

Yield effects measure the impact of climate change on the annual growth of trees. Changes in the annual growth of timber ultimately alter timber supply and prices by changing the quantity of timber available on each hectare of forestland. Because ecological models make different predictions about the rate, size, and direction of the climate change impact on forests, economists have used a range of the results available from ecological studies to determine potential changes in the annual growth of timber.

One of the difficulties with predicting how forest growth will change involves translating results from ecological models into estimates that can be used by economic models, namely, estimates of change in annual growth. The effects on merchantable timber species are the most important for market analysis. To date, economic studies have used a variety of indicators from ecological models to determine how climate change affects timber yields. Although some studies have used different indicators, most economic studies have assumed that changes in annual growth are proportional to predicted changes in net primary productivity (NPP; see Box 2).

In addition to considering changes in timber yield, some ecologists have suggested that trees could be affected by dieback and species migration.[14] Estimates of potential changes in the geographic distribution of species are drawn from biogeographical models. These studies suggest that some stocks of existing timber become ill-suited for their current range when climate changes. In these areas, existing timber species are assumed to be unsuccessful in naturally regenerating, whether the ex-

12. *See* Table 2.

13. B. Sohngen, R. Mendelsohn and R. Sedjo, *A Global Model of Climate Change Impacts on Timber Markets*, J. AGRIC. & RESOURCES ECON., 26(2):326-343 (Dec. 2001).

14. *See generally* J.S. Clark, *Why Trees Migrate So Fast: Confounding Theory with Dispersal Biology and the Paleorecord*, 152 AM. NATURALIST 204-224 (1998).

isting trees die back or continue living. If only ecology was considered, species would take many years to migrate from place to place.[15] Economists, however, model human adaptation and adjustment through salvage logging and replanting. Foresters, for example, can adapt by planting new species in new areas when climate changes. The area replanted depends not only on the ecological conditions but also on economic conditions such as the costs of replanting and current and future prices.

For the most part, economic studies have attempted to link results from ecological models to economic models, although some studies have developed sensitivity analyses across a range of assumed effects. The studies that rely on ecological models have mostly used widely available equilibrium ecological results.[16] Equilibrium results assume that both climate and ecosystems stabilize after CO_2 concentrations have doubled (usually assumed to occur around 2060). Although researchers recognize that atmospheric CO_2 will likely increase beyond double current levels,[17] and that climate and ecosystems will continue to change beyond that, the earlier equilibrium estimates were driven by the models available at the time of the research.[18] Thus, economic studies have made a variety of simplifying assumptions about the transient changes, the most important of which appears to be that they often assumed that changes will occur proportionally (often linearly) over the next sixty to seventy years until CO_2 concentrations doubled and will not change thereafter.

The main limitation of these equilibrium studies is that they do not provide information on how forests will change over time. It is possible that the changes could be negative for a period and then positive, or vice-versa. Recently, atmospheric scientists and ecologists have modeled transient changes, and economists have begun adopting these results.[19]

A number of other issues affect the link between ecological and economic effects. First, as discussed in the introduction, most ecological studies focus on non-managed forests, while most economic studies address managed forests. It is not entirely clear what measures from ecological studies should be used to drive yield changes in economic models. For example, some studies have chosen NPP while others have chosen vegetation carbon [see Box 1]. These differences could affect

15. *Id.* at 213.

16. *See* L. A. Joyce et al., *Forest Sector Impacts from Changes in Forest Productivity under Climate Change,* 22 J. BIOGEOGRAPHY 703 (1995).

17. CLIMATE CHANGE 2001: THE SCIENTIFIC BASIS (Interngovernmental Panel on Climate Change, 2001).

18. *See, e.g.*, J. Perez-Garcia et al., *Economic Impacts of Climate Change on the Global Forest Sector: An Integrated Ecological Economic Assessment, in* ECONOMICS OF CARBON SEQUESTRATION FORESTRY: CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY 123 (R.A. Sedjo et al. eds., 1997).

19. B. Sohngen et al., *supra* note 15.

modeled economic outcomes if the ecological models predict differences in how NPP and vegetation carbon respond to climate change. Second, increased CO_2 and changes in climate could change the economically optimal age for cutting trees. There is little research on this theory to date, although changes in rotation ages could have important effects. Third, some of the ecological research discussed above now suggests that the early positive effects of increased CO_2 levels on tree growth could subside or even be reversed in the longer term. We clearly expect that as ecological results continue to explore new hypotheses, economic modelers will develop new estimates based on new ecological results.

Systematic Examinations of Climate Impacts on Timber Supply

A brief review of several U.S. timber market studies is provided in Table 2. Each of the studies in the table is unique, but there are some general similarities and differences among them. First, all of the economic predictions assume the presence of a future steady-state climate and that ecological changes are predicted to move toward an equilibrium effect. Forests have large initial inventories and the largest changes in growth are predicted to occur beyond the year 2050, so all of the models tend to predict small initial impacts, positive or negative, on markets. Even though these impacts become larger as the effects move toward the equilibrium, the studies tend to predict small overall impacts because economists use discounting (which results in near future effects having relatively more "present value" than effects far in the future) to value the future market impacts.

Second, many economic models focus explicitly on growth effects.[20] Among these studies, the modelers have chosen different approaches for linking the predictions of ecological models to growth functions in timber models. These differences provide a wide range of sensitivity of markets to potential effects; although, if the ecological models predict increases in future growth, timber market studies predict that future inventories will increase (vice-versa if future growth is predicted to decrease).

Third, two of the studies have combined changes in growth with potential dieback and species migration.[21] This combination study depicts a

20. L.A. Joyce et al., *supra* note 18; J. Perez-Garcia et al., *supra* note 19; B.A. McCarl et al., *Effects of Global Climate Change on the U.S. Forest Sector: Response Functions Derived from a Dynamic Resource and Market Simulator*, 15 CLIMATE RESEARCH 195 (2000); L. Irland et al., *Assessing Socioeconomic Impacts of Climate Change on U.S. Forest, Wood-Product Markets, and Forest Recreation*, 51 BIOSCIENCE 743 (2001).

21. B. Sohngen & R. Mendelsohn, *Valuing the Market Impact of Large Scale Ecological Change: The Effects of Climate Change on U.S. Timber*, 88 AM. ECON. REV. 689

wider range of potential economic effects. For example, they explore a set of scenarios where forests dieback. Even though the model predicts an increase in growth for individual trees, net growth across some regions declines because the losses from dieback outweigh the gains from higher growth.

Table 2. Comparison of Timber Market Studies.[22]

Study	Market	Method	Results
Joyce et al., 1995	United States	Use changes in net primary productivity from the Terrestrial Ecosystem Model (TEM) to predict changes in timber growth rates, changes in timber inventories, and changes in timber supply	Change in timber growth = +15%, range of -7% to +43% across species
Perez-Garcia et al., 1997	Global	Use changes in net primary productivity from the TEM to predict changes in timber growth rates, changes in timber inventories, and changes in regional timber supply	Changes in timber growth for the United States = +10%, range of 0% to +30% across species
Sohngen and Mendelsohn, 1998	U.S. softwood	Use changes in net primary productivity and changes in distribution of timber species from three different models to predict changes in timber supply; changes in the distribution of species are modeled with a dramatic "dieback" scenario, and through a less dramatic "regeneration" scenario	Change in timber growth = +7%, range of -35% to +50% across species. Range of species loss through dieback = 25 to 46%. Range of change in net softwood area = 6 to 38%.
Sohngen et al., 2001	Global	Use BIOME3 model and ecological assumptions similar to Sohngen and Mendelsohn	Change in U.S. timber growth = 17%, range of -1% to +34% across species, Range of species loss through dieback =0% to 75% . Range of change in net forest area = -2% to -7%.

(1998); B. Sohngen, R. Mendelsohn & R. Sedjo, *supra* note 15.

22. H. SHUGART ET AL., *supra* note 3.

McCarl et al., 2000	United States	Use assumed changes in U.S. and Canadian production to develop range of scenarios of potential changes in future timber yields for important species based on literature review; use timber model to estimate economic impacts of combinations of these changes	Change in long-term annual timber growth = -6.2% to +13% (in northern United States only)
Irland et al., 2001	United States	Use changes in vegetation carbon predicted from two transient climate models and two transient ecological models to predict decadal changes in timber growth rates.	Change in U.S. timber growth = +0.1% to +0.3% by 2100. Some reductions in growth in early periods.

A number of general results from the studies in Table 2 are described below.

1. Higher timber growth increases timber inventories, expands the long-run supply of timber, and reduces prices. Lower timber growth reduces timber inventories and supply, and increases prices.[23]
2. Assuming that species ranges change as suggested by a number of ecological models, adaptation through regeneration of southern species farther to the north can increase timber supply, as faster growing species replace slower growing species over large areas.[24]
3. Economic impacts are predicted to be increasingly sensitive to reductions in southern softwood timber growth.[25] This conclusion supports previous studies that suggest U.S. timber supply is most heavily influenced by how climate change affects growth and yield in the Southern U.S.[26]
4. Each study found that a range of adaptation is possible in timber markets: reducing prices, shifting the mix of species used in the production process, shifting capital from one region to another, and replanting new species when they are

23. *See supra* note 21.

24. See Brent Sohngen & Robert Mendelsohn, Valuing the Impact of Large-Scale Ecological Change in a Market: The Effect of Climate Change on U.S. Timber, 88 AM. ECON. REV. 686-710 (1998).

25. Bruce A. McCarl et. al., Effects of Global Climate Change on the U.S. Forest Sector: Response Functions Derived from a Dynamic Resource and Market Simulator, 15 CLIMATE RESEARCH 195-205 (2000).

26. *See, e.g.,* Joyce, *supra* note 20; D.M. Burton et. al., *Economic Dimensions of Climate Change Impacts on Southern Forests, in* THE PRODUCTIVITY AND SUSTAINABILITY OF SOUTHERN FOREST ECOSYSTEMS IN A CHANGING ENVIRONMENT (Susan A. Fox & Robert A. Mickler eds., 1998).

suited to a new climate. However, the predicted overall capacity to adapt differs dramatically.

5. Rapid, short-term dieback was found not to dramatically reduce timber supply if landowners have salvage possibilities.[27] Dieback signals markets to shift species from one region to another.
6. Climate change impacts in other regions of the world will affect U.S. production, although studies disagree on the direction and size of change. One global timber market model finds that U.S. lumber and plywood production increases, although some scenarios show decreases in pulpwood production.[28] Another model suggests that U.S. production would decline in the short term, due to higher productivity abroad, leading to potential economic losses.[29]

In general, these studies predict that climate changes that include a doubling of CO_2 will increase national timber supply and lower future timber prices. Aggregate economic impacts for U.S. timber markets as a whole are predicted to be positive, ranging from +1% to +12%.[30] Irland predicts significantly smaller economic impacts of less than 1%, although the aggregate results are all positive.[31] McCarl makes no explicit links to ecological models, but they consider increased growth in northern U.S. forests and decreased growth or no change in growth for southern U.S. forests.[32] The range of economic impacts in that study is -4% to +1%. These estimates are less optimistic because they assume that southern forests experience either no growth effect or negative growth effects.

All the studies suggest that consumers gain while producers could be harmed if prices decline. However, producer losses predominately affect existing timberland owners with the most productive forests because domestic prices are lower. For example, the largest losses occur in the southern United States where large investments in forestry have already been made and producers experience either lower prices, lower growth, or both. In contrast, producers in northern regions are expected to gain as productivity in that region increases more than in the south. These gains are predicted to be even larger for northern landowners if

27. Sohngen et al., *supra* note 15.
28. Perez-Garcia, *supra* note 19.
29. Sohngen et al., *supra* note 28.
30. Sohngen et al., *supra* note 25.
31. Lloyd C. Irland et al., *Assessing Socioeconomic Impacts of Climate Change on U.S. Forest, Wood-Product Markets, and Forest Recreation*, BIOSCIENCE, vol. 51, n. 9, Sept. 2001 at 753.
32. McCarl et al., *supra* note 26.

species migration occurs (either naturally or with human intervention) because landowners in the north can plant faster growing forests. Additionally, they could gain forestlands at the expense of less productive grasslands or savannas in the Northern Plains.

Although an economic analysis of forest migration is complicated, the potential for forest migration is important to consider. For example, it is unclear whether forestland will expand at the expense of agriculture. Much of the prime agricultural land in this country was originally derived from cleared forests. Many of these regions could still be suitable for different tree species altogether. For the most part, economic studies assume that forestland will not expand into these prime agricultural regions. Our understanding on this issue is incomplete because forestry may move into areas where forest productivity increases and agricultural productivity decreases. Whether or not markets allow this expansion will depend on price and relative differences in productivity effects between timber and agriculture. To date, researchers have not developed models to explore ecological and economic effects of climate change in both markets.

Migration also can affect the predicted timing of economic impacts. Because dieback and species migration potentially have near-term impacts on forests, studies that investigate these possibilities suggest larger near-term consequences for markets (see Box 4). Researchers who consider only growth effects in their studies tend to assume that the largest effects occur far into the future.[33] This consideration has the effect of reducing the estimates of impacts in markets because most measures of economic impacts involve financial discounting.

One concern with most economic studies is that they use ecological results that include carbon fertilization effects.[34] If the carbon fertilization effect turns out not to have positive impacts on forest growth and area, economic impact studies would show broader reductions in forest inventories, reductions in timber supply, and higher prices (see discussion on CO_2 fertilization above). It is difficult to assess how different assumptions about CO_2 fertilization would affect the overall results, but the studies that do predict growth reductions for the south, suggest that market impacts appear to be more sensitive to decreases in timber growth than to gains in timber growth.[35]

While many of the researchers use equilibrium results, more recent

33. *See, e.g.,* Joyce, *supra,* note 18;Perez-Garcia, *supra* note 19; McCarl et al., *supra* note 26.

34. *See, e.g.*, Joyce, *supra* note 18; Perez-Garcia, *supra* note 19; Sohngen et al., *supra* note 25.

35. Burton et al., *supra* note 27; McCarl et al., *supra* note 26.

researchers capture transient changes in their studies. These more recent studies may have important implications for economic estimates. Irland, for example, capture reductions in near-term (2000 – 2040) timber yields in some regions followed by long-term (2040 – 2100) increases in timber yields.[36] Because economic models weigh near-term effects more heavily, that study predicts smaller positive effects than many earlier studies that simply assumed how the changes would occur.

Few studies have explored how a rapidly changing climate may actually affect human adaptation, but existing model results provide some useful information. On the one hand, if growth rates increase rapidly, prices will decline substantially. Although aggregate economic impacts would likely be positive, producer losses could be substantial while consumers gain from lower prices. On the other hand, if rapid climate change leads to very rapid forest losses, such as might be caused by fires or disease, or rapid reductions in forest growth, economic losses could be substantial. One set of studies has explored assumptions about potential dieback, as described in Box 4.

The international aspects of climate change are likely to be important for measuring U.S. forest sector impacts if climate change has large effects elsewhere. These aspects are particularly important because recent research suggests that production from North America is gradually becoming relatively disadvantaged compared to timber production elsewhere in the world because economic forces are driving long-term timber production offshore.[37] If timber growth increases in other regions of the world more than timber growth in the United States, U.S. prices could fall, harming U.S. producers but benefiting consumers.[38] Climate change could put pressure on profits for producers of U.S. timber simply by making other regions of the world more attractive for timber investments. Given that we already import large volumes of timber and industrial wood, global effects are not likely to reduce timber availability in the United States in the absence of an overall global timber supply reduction. While any major changes in trade law are not foreseen, any action that restricts trade would most likely have negative effects on U.S. consumers.

The Mid Atlantic Region (MAR)

In the recent study of the Mid-Atlantic Region, researchers noted

36. Irland, *supra* note 32.
37. R. A. Sedjo & K.S. Lyon, , Discussion Paper, RESOURCES FOR THE FUTURE, TIMBER SUPPLY MODEL 96: A GLOBAL TIMBER SUPPLY MODEL WITH A PULPWOOD COMPONENT 96-15 (1996).
38. Sohngen et al., *supra* note 15.

that the forest area has been relatively stable for the past thirty years while total standing biomass has increased as the forests matured.[39] The Hadley and the CCC model show the climate trend of the region; the CCC model depicts a warming of the region with constant precipitation and the Hadley model depicts an increased precipitation.

One expectation is that the forests composition would shift from the dominance of maple-beech-hickory to one of oak-hickory and to a lesser extent southern pine and mixed oak pine. We might note here that human management could modify that scenario. Sohngen and Mendelsohn show that the Mid Atlantic region would be more conducive to southern pine so that pine plantations could shift into the region from the south and become well established.[40]

What would be the effect of forest management on forestry production? The MAR analysis indicates that forest production would be expected to increase by virtue of the warming. The negative impact could be caused by the increased occurrence of extreme events. From a timber production perspective, the introduction of forest management, such as timber salvage, would coax out greater productivity and could mitigate against losses due to extreme events.

Although it is uncertain as to why this impact is viewed negatively, researchers of the MAR study look at a negative impact due to changing forest composition. In terms of the provision of environmental services such as erosion control, water shed protection, and wildlife habitat, the before and after forests are likely to provide comparable services except, perhaps, for warm water fisheries.

Summary and Conclusions

Recent research suggests that the anticipated global warming is likely to impact the forests of the MAR and U.S. and global forests. Approaches for estimating the impacts include General Circulations Models (GCMs), which provide predictions of future climate changes, and ecological models, which predict the response of ecological systems, including unmanaged forests, to the climate change. Temperature and precipitation play critical roles in determining the nature of the predicted changes. Unfortunately, the various models often have different predictions. Most models predict changes in the species composition of many forests together with areas of forest expansion and contraction. Most models also predict a modest increase in forest productivity and area. However, the research predicts an overall change between a very small

39. A. Fisher et al., PREPARING FOR A CHANGING CLIMATE: MID-ATLANTIC OVERVIEW, A REPORT OF THE MID-ATLANTIC REGIONAL ASSESSMENT TEAM (2000).
40. Sohngen et al., *supra* note 25.

decline to a modest increase in forest productivity and area. This outcome tends to depend upon a fairly robust carbon dioxide fertilization effect. The scientific jury is still out on how significant the carbon fertilization effect might be for trees and forests. Some evidence suggests that its effects may be limited to the early seedling growth and that it will not be very important over the total life of a tree. If the carbon dioxide fertilization effect is small or nonexistent, the likelihood of a forest area and productivity increase is decreased.

The concept of forest die-back is part of the process of a changing forest; however, the relative rates of forest die-back and forest migration are not well understood. Although one could conceive of some sufficiently rapid climate change so that the rate of die-back could exceed the migration rate of substitution species to fill the gaps left by die-back, this appears unlikely. Humans could assist natural forces of regeneration through such interventions as aerial seeding.

Small changes in the overall area and productivity of the natural forest are likely to have small impacts on timber markets. Most studies on the effect of climate change on the industrial wood sector suggest the effects on productivity and production. Furthermore, dead and dying wood can be salvaged for industrial uses. Finally, industrial wood is increasingly being produced on managed plantations, much like an agricultural crop. As in agriculture, management practices can be adjusted should the climate change. More appropriate species might be introduced or the location of the plantations moved in response to climate change. Hence, the likely effect of climate change on industrial wood production and supply is likely to be small to negligible.

Table 3. Models used in the VEMAP (1995) comparison of vegetation change in response to climatic changes and CO_2 increases.

Model (Citation)	Type of Model	Principal Internal Variables Responding to Climatic Change	CO_2-response is obtained from model by:
Prentice, *et al.* (1992), BIOME2	Biogeographical	Biome type (from plant types) based on calibrations to climate variables. Linear relation between gross primary productivity (GPP) and absorbed photosynthetically active radiation (Monteith 1972, 1981a&b). Ratio of actual to potential evapotranspiration and temperature also considered.	Change in GPP. Change in competitive differences in C_3 and C_4 plants.
MAPPS (Neilson 1995)	Biogeographical	Biome type (from plant types) from calibrations to climate variables. Leaf area calculated from water balance considerations	Change in stomatal conductance alters water balance calculations
CENTURY (Parton *et al.* 1987, 1988)	Material Transfer	C, P, N and S dynamics with internal transfers among compartments controlled by calibrations to climatic variables.	Reduction in N content in vegetation. Changes in actual evapotranspiration.
TEM (Raich *et al.* 1991)	Material Transfer	Calibration of rates of transfers of carbon and nitrogen among compartments to existing data with a strong emphasis on C:N ratios.	Modification of GPP. Actual and potential evapotranspiration not changed by elevated CO_2.
BIOME-BGC (Running and Couglan 1988)	Canopy Process	Biophysical responses used as a basis to simulate daily photosynthesis and evapotranspiration.	Reduction in N content in vegetation. Modification of biophysical model parameters (canopy conductance).
DOLY (Woodward *et al.*, 1995)	Canopy Process	Biophysical responses used as a basis to simulate daily photosynthesis and evapotranspiration. Statistical calibrations produce biome types as an output option.	Modification of biophysical model parameters (stomatal conductance).

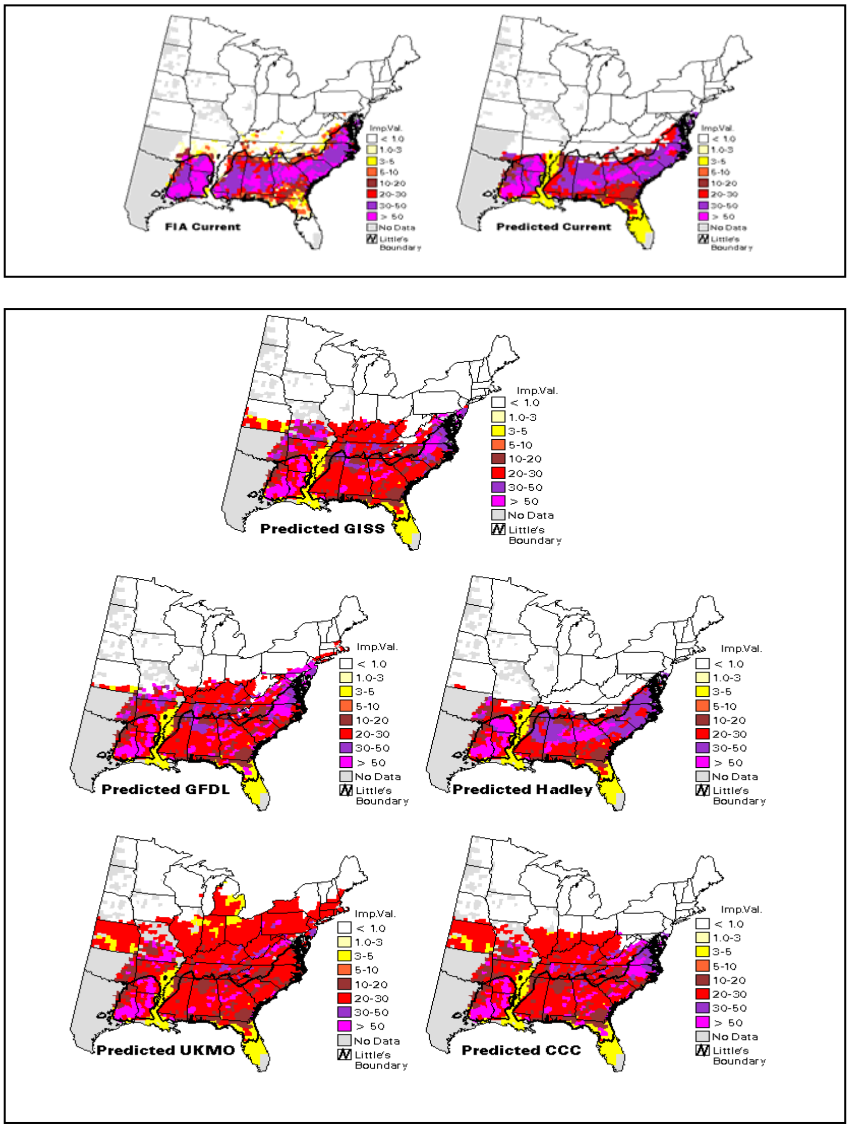

Figure 1. Changes the distribution and abundance of Loblolly Pine (*Pinus teada*) under 5 different General Circulation Models (GCM's). Upper. Initial test on the statistical prediction of the range and abundance of Loblolly Pine and comparison to the present abundance and distribution based on forest inventory (FIA) data. Lower. Predicted distribution and abundance under climate conditions for a doubled CO_2 for five GCM's. From: Iverson *et al*. 1999

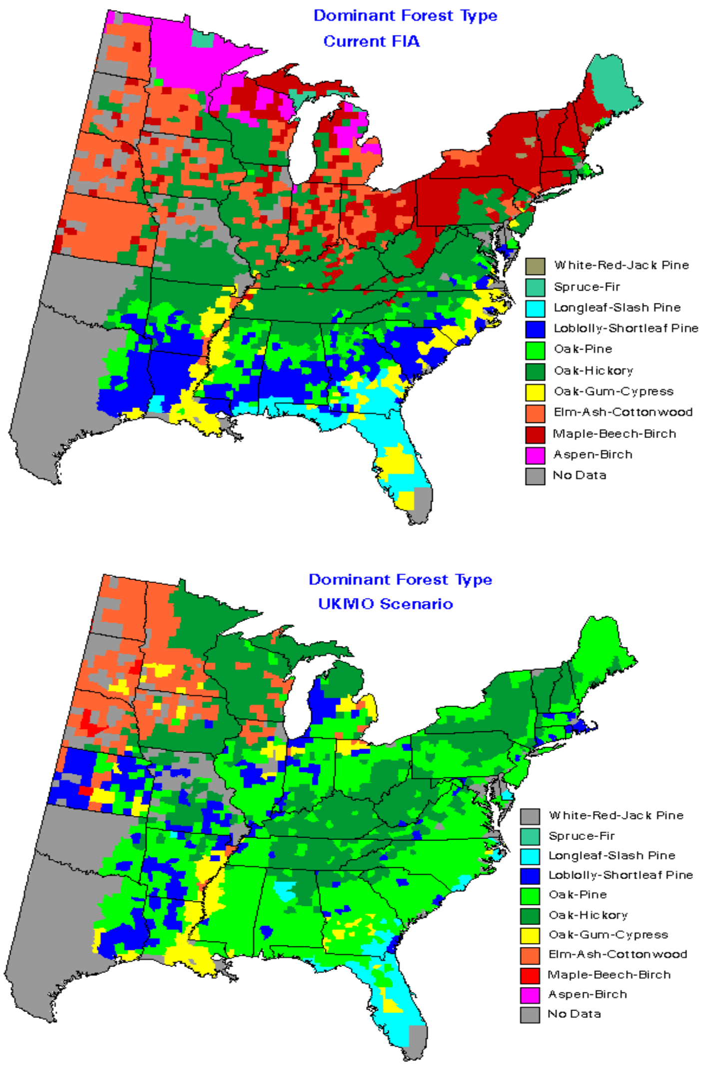

Figure 2. Changes in the dominant forest types across the US east of the 100th meridian. Maps were developed by using all of the 80 species considered by Iverson *et al*. (1999) and then determining the dominant species at points across the eastern US to obtain forest types. Upper. Current distribution of forest types from the curent USDA/Forest Service inventory (FIA) data. Lower. Analogous forest type map generated under the climate conditions predicted by the United Kingdom Meteorological Office for a doubling in atmospheric CO_2.

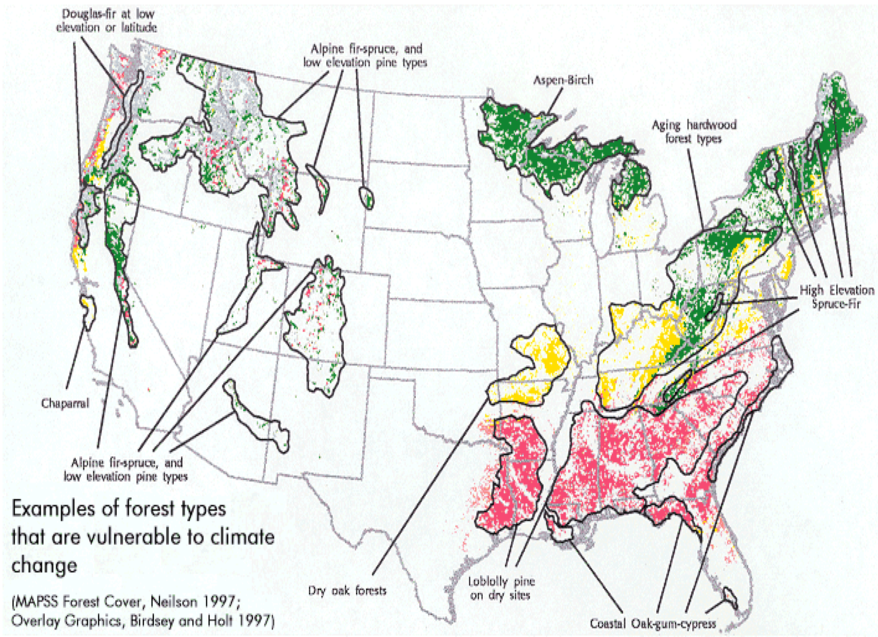

Figure 3. Forest types in the U.S. that are vulnerable to climate change using the MAPPS model (Neilson 1995). Figure prepared by Richard Birdsey and found on the web page of the USDA/Forest Service Southern Research Station, Southern Global Change Program: http://www.sgcp.ncsu.edu/nac/forestsector.htm.