The Economic Effects of Climate Change on U.S. Forests

Final Report

RCG/Hagler Bailly

THE ECONOMIC EFFECTS OF CLIMATE CHANGE ON U.S. FORESTS

Final Report

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PREFACE

Global climate change poses threats to the environment, human welfare, and human health. How the United States will respond to these threats is a challenging public policy decision that will be influenced by a variety of considerations. Among the considerations are the potential damages that may result from climate change, where damages are evaluated using economic concepts of human welfare To advance our knowledge of potential damages, the Climate Change Division of the United States Environmental Protection Agency has conducted and supported a number of studies to examine different categories of climate change effects. *The Economic Effects of Climate Change on U.S. Forests* reports results from one of the studies supported by our office.

The study draws upon previous work on the potential physical responses of forests to changes in climate The study moves our state of knowledge forward by evaluating how these changes may influence the production and consumption of commercial forest products, standing forest stocks, and the economic rewards reaped by producers and consumers of commercial forest products The results provide an indication that the values that are derived by our society from our forests, and that are vulnerable to climate change, are substantial. The magnitudes of the damage estimates for commercial forestry are sufficiently great to warrant concern and further consideration as we formulate strategies to address global climate change

The results of the study should not be interpreted as forecasts of the economic consequences of the effects of climate change on U.S. forests. Information and understanding of how climate may change in different regions, the responses of individual tree species and forest communities to changes in climate, the potential for human responses to adapt forestry practices to a changing climate, and how forestry and forest product markets may evolve in the future in response to other forces are too imperfect to support reliable forecasts at this time Instead, the results provide illustrations of the potential severity of the economic consequences of selected scenarios of climate change impacts.

The study was performed by RCG/Hagler Bailly, under subcontract to ICF Incorporated, for the Environmental Protection Agency. An earlier version of the report was reviewed by EPA staff and by experts from outside the agency Participants in the review process are thanked for their efforts The final report is a report to the EPA and does not necessarily reflect the views or policies of the EPA.

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EXECUTIVE SUMMARY

Global climate change poses risks to the forests of the United States. Rising temperatures, changes in precipitation and soil moisture, and other changes in climate will affect both the growth rates of different tree species and the competition among them for nutrients and sunlight. This will result in changes in the species composition of forest stands and, with this, perhaps wider changes in the distribution of forest types across the United States. The exact character of these effects is uncertain and will be determined both by complex physical and biological processes and by management responses. Some of the studies that have analyzed the effects of climate change on forests suggest that climate change could adversely impact both forest health and productivity in the United States The impacts projected in these studies are most severe in the southeastern and south central states, where the growth rates of plantation and natural pines could be severely reduced, leading to decreases or the disappearance of these species in some areas. Such changes would have adverse consequences on economic well-being in the U.S due to reduced timber supplies and higher wood and paper product prices. These impacts on forests could also have potentially severe environmental consequences in the form of reductions in wildlife habitat, biodiversity, watershed protection, aesthetic values and forest-based recreation.

This study examines one category of potential losses from the effects of climate change on U.S forests, the economic losses associated with the production and consumption of commercial timber products Previous studies have explored the potential effects of climate change on U S forests in physical terms, such as impacts on geographic distributions and physiological effects on photosynthetic rates, leaf area, biomass, and yields. The objective of the present study is to extend the previous research by evaluating the economic consequences of the physical changes in commercial forests on timber markets in the United States

To evaluate the economic consequences of the effects of climate change on commercial forests, scenarios of hypothesized yield changes are developed based on published results of site specific forest responses to climate change The majority of published results relied upon come from studies that use forest gap models to project the potential responses of forested stands to changes in climate Other types of simulation models, such as biogeography and biogeochemistry models, also can and have been used to assess the potential responses of forests to climate change and the results have been found to vary significantly across the various models used in these analyses. However, with a few exceptions, the results from these studies were not published or available until all of the substantive research on this study had been completed. The results now becoming available from these other methodologies indicate that the projections of the forest gap models are within the range of those from other methods, but are nearer to the lower end of the range (i.e., greater losses of forest biomass, or smaller gains, depending upon the species and region).

The projected yield changes used in this study are presented in Table S-1. They vary by region and by wood type—softwood and hardwood. Four scenarios were developed for the analysis. The scenarios differ in the assumed amount of warming and in the inclusion or exclusion of beneficial effects of carbon dioxide on photosynthetic rates and water use efficiency. The four scenarios can be characterized as displaying severe reductions in softwood yields, particularly in the South. Hardwood yield changes are modest in comparison, though still substantial, and range from yield increases in the Northeast and North Central regions to yield decreases in the Southeast and South central regions.

The hypothesized yield changes are used as inputs to FASOM, a model of U.S. stumpage markets. FASOM is a dynamic, nonlinear programming model of the forest sector in the United States. It simulates the production and consumption of sawtimber, pulp, and fuelwood in nine forest regions[1] of the United States. It also projects product prices, forest inventories, and consumer and producer surpluses. Simulations were performed for the four climate change scenarios plus a base case scenario for comparison. FASOM incorporates adaptation to climate change in the sense that it simulates the impacts of reduced yields on the relative profitability of different timber products. Landowners respond by altering a wide range of management decisions related to planting/regeneration, tending of planted stands, and harvesting, consistent with intertemporal profit maximization. Buyers of stumpage optimize by shifting the quantity and mix of forest products purchased in response to price signals. However, adaptations in management practices that would mitigate the yield changes themselves, such as the introduction of heat and drought tolerant species into a region, are not reflected in the analysis.

The analysis was performed, assuming that the yield changes in Table S-1 reflected an equilibrium adjustment by forests to the changes in climate. The yield changes were introduced during the first decade of the model projections, 1990-2000. Thus, the estimates of annualized value of damages are higher than could be expected if, as one would expect, forest yields change at a rate roughly in proportion to the rate of climate change, over time. On the other hand, this approach gives a clearer picture of long-run impacts on welfare, harvest levels and stumpage prices and forest inventory stocks.

The potential welfare impacts of the four scenarios are summarized in Table S-2. They are consistent with the long-run consequences of a 2.5° and 4.0°C warming. The simulations project substantial losses in economic welfare. On an annualized basis, losses vary from $2.5 billion to $12 billion in 1990 dollars across the scenarios, or roughly 4 to 20% of the net value of commercial forests to society The losses are very unevenly distributed across consumers and producers. Consumers, facing prices that are 100 to 250% higher than in the base case scenario, consume 20 to almost 50% less forest products. Consequently, consumer welfare, measured by the change in ordinary consumer surplus, declines by $10 billion to

[1] These regions are the Pacific Northwest-West, The Pacific Northwest-East, the Pacific Southwest, the Rocky Mountains, the Lake States, Corn Belt, Southeast, South central, Northeast.

Table S-1
Percent Changes in Yields by Region and Species for Four Climate Scenarios

Region	Scenarios			
	2.5 with CO_2 Change	2.5 without CO_2 Change	4.0 with CO_2 Change	4.0 without CO_2 Change
Softwood				
Pacific Northwest-West	20	-10	-32	-53
Pacific Northwest-East	20	-10	-32	-53
Northeast	-40	-55	-68	-78
Lakes States	-51	-64	-66	-76
Corn Belt	-51	-64	-66	-76
Southeast	-56	-83	-76	-100
South Central	-75	-87	-76	-100
Rocky Mountains	70	30	79	33
Pacific Southwest	20	-10	-32	-53
Hardwood				
Pacific Northwest-West	0	0	0	0
Pacific Northwest-East	0	0	0	0
Northeast	46	14	71	36
Lakes States	39	11	53	21
Corn Belt	38	11	53	21
Southeast	20	-10	-8	-30
South Central	0	-20	-44	-60
Rocky Mountains	0	0	0	0
Pacific Southwest	0	0	0	0

Table S-2
Annualized Value[1] of Welfare Components for the Base Case and Percent Changes from the Base Case for Four Climate Change Scenarios

Welfare Component	Base ($ Millions)	2.5 with CO_2	2.5 without CO_2	4.0 with CO_2	4.0 without CO_2
Consumer Surplus	56,748	-17.42%	-33.47%	-28.34%	-42.09%
Producer Surplus	3,871	145.67%	237.40%	194.50%	207.69%
Foreign Trade Surplus	324	-21.79%	-39.34%	-35.62%	-50.10%
Terminal Inventory	1,805	-6.13%	-13.89%	-11.33%	-33.13%
Public Cut	2,023	79.56%	159.84%	137.05%	222 87%
Total Surplus	**64,771**	**-4.35%**	**-10.73%**	**-9.42%**	**-18.68%**

[1] Annualized values calculated for 1990-2080 using a discount rate of 4%

$24 billion per year. In contrast, producers benefit from the higher prices, and reap a welfare gain of $6 billion to $8 billion per year despite the reduced volume of marketed harvests. The net effect in all scenarios, however, is to decrease the benefits to society provided by commercial forest harvests by billions of dollars annually

In addition to the welfare losses, the scenario simulations also raise concerns about the sustainability of softwood forest resources in the United States in a warmer climate Projected harvests are typically greater than net growth, causing softwood forest inventories to decline fairly dramatically by 2060. The projected trends also suggest that inventories will continue to decline after 2060 for the most severe scenarios. Sustainable production of softwood forest products would therefore require reductions in harvests that are considerably larger than those projected to occur in response to market price increases under conditions of severe yield decreases.

The results of the study indicate that the economic consequences of climate change for commercial forestry are potentially severe The results, however, are not without qualification. The hypothesized yield changes are based on gap model results for unmanaged forests, which may overestimate the sensitivity of forests to climate change. The omission of forest management adaptations that might mitigate yield losses may result in further overestimation of impacts. Also, the potential effects of elevated carbon dioxide levels on forests are highly uncertain and the speculative yield increases from carbon dioxide included in some scenarios could either overestimate or underestimate these gains. Another limitation of the study is the omission of changes in Canadian forest yields and their potential effects on U.S forest product markets. Increases in softwood yields in Canada could offset domestic supply losses, providing gains to consumers but possible losses to domestic producers. Other limitations include the absence of adjustment in land uses between agricultural, forest, and other uses; uncertainty about the possibilities for substitutions among species, among wood products, and between wood products and other materials; and uncertainty about future technologies. Each of these limitations represents directions in which the work presented in this report might be extended to improve our understanding of the economic consequences of the effects of climate change on commercial forests.

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Climate is a major determinant of the range, type, and density of forests. The northern geographic limit of forests is determined by minimum temperatures, while the southern limit is influenced by such factors as soil moisture and compeuuon from species better adapted to warmer climates (Davis, 1989) Changes in average climate conditions in pre-history, such as the Ice Ages, resulted in large scale shifts in location of forests. Oaks, for example, which are now found all over the eastern United States, only existed in the Deep South at the height of the last Ice Age (Webb, 1992)

Climate change will most likely have a significant effect on the range, type, and density of forests in the United States (VEMAP Participants, submitted; Smith and Shugart, 1993, Westman et al., 1990; Smith and Tirpak, 1989, Shands and Hoffman, 1987) Warmer temperatures may enable forests to grow in higher latitudes and at higher altitudes. Warmer temperatures may also result in drier soils and northward expansion of pests and diseases, which could cause rapid dieback along the current southern and low elevation boundaries of forests (Smith and Shugart, 1993) In addition, warmer adapted species will most likely migrate north or upslope, driving out species better adapted to cooler climates

The literature on climate change impacts on forests contains very different conclusions about whether forest density (i e., biomass) will increase or decrease Neilson (1993), for example, using the MAPPS model found that forest cover in the coterminous United States could decrease by 30 to 94%. Studies of forests in the South using gap models have found that there could be significant reductions in forest biomass, particularly for softwood species (Urban and Shugart, 1989, Solomon, 1986) On the other hand, studies such as Melillo et al (1993), which used a bio-geochemical model found that productivity of many forests in the United States could significantly increase (Many of these studies are discussed in more detail in Chapter 2.) Thus, the future fate of forests in the United States appears to be uncertain.

Forests in the United States produce many different types of market and nonmarket services. The most visible of these is timber supply from public and private lands. There are roughly 740 million acres of forestland[1] in the United States. Of that amount, roughly 490 million

[1] Forestland is any land stocked with at least 10 percent of trees of any kind or size.

acres are in timberland.[2] About 75 percent of all timberland in the United States is privately held, either by industrial or nonindustrial private owners (Waddell et al., 1989). In 1986, the value of timber harvested in the United States was approximately $12.67 billion, with softwoods contributing over 80% of the value before manufacturing (USFS, 1990). Forests also provide a variety of nonmarket services including recreation and aesthetics, wildlife habitat and ecosystem diversity, and the control of surface water runoff. However, the value of these services are more difficult to quantify and value in monetary terms.

Changes in the location, composition, and abundance of forests have the potential to affect timber markets and the welfare of individuals and firms that own timberland, supply inputs for timber harvesting and management and who purchase stumpage for milling and transformation into primary and secondary products. In general, reductions in forest productivity will make it more expensive to supply timber to the market in each period, leading to higher stumpage prices and reduced harvests, while increases in productivity will have the opposite effect. Forest inventories will be affected directly by changes in forest yields, however, adverse impacts due to yield decreases will be choked off to some extent by reductions in harvests. If forest yields decline, as suggested by the studies reviewed in this report, higher prices will always lead to reductions in consumer welfare; however, the welfare of producers may rise if products demands are inelastic and the reductions in inventories is not too severe. If changes in productivity are unevenly distributed across species and regions, the economic impacts will also be uneven. Commercial operations such as milling and primary and secondary processing of wood products may move closer to timber areas that have become relatively more productive Timber and wood product production could even shift to Canada if warmer temperatures have a strong beneficial affect as one moves northward

Climate change almost certainly will affect the nonmarket services provided by forest ecosystems At the very simplest level, climate-induced increases in forest area are likely to enhance such services as wildlife habitat, ecosystem diversity, flood control and carbon storage, while decreases in forest area would, in all probability, adversely impact the ability of forests to supply these and other kinds of nonmarket services. However, our knowledge about the relationship between climate and forest ecosystems and the availability of data and methods for quantifying and valuing these impacts are not well developed enough at this stage to perform national assessments Therefore this study does not include them, nor does it dismiss them as unimportant

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[2] Timberland is forested land that can produce at least 20 cubic feet per year of industrial wood and is not reserved.

1.2 REVIEW OF ECONOMIC STUDIES

To date, no published study has examined the economic effects of climate change on timber markets in the United States based on estimates of yield changes found in the science literature.[3] In that regard, this study appears to be a first. However, there are a handful of published studies that looked at the economic effects of changes in forest yields from air pollution and other undifferentiated sources. This literature provides the background to the current study.

An early study by Callaway et al. (1986) used the TAMM model (Adams and Haynes, 1980) to conduct a sensitivity analysis of the economic impacts of hypothetical reductions in timber yields, ranging from -10% to -20%. The authors speculated that these yield changes could be due to a variety of sources, including acid rain and CO_2-induced changes in temperature. They found that the present value of damages between 1985 and 2030 ranged from $3 4 billion to $5 0 billion ($0 34 to $0 52 billion in annualized terms), depending on the severity of the hypothetical growth reduction. These welfare losses are in the range of 5% to 7% of total welfare in the base case.

A subsequent study by Haynes and Kaiser (1991) used a newer version of the TAMM model to examine the effects of reductions in timber yields due to acidic deposition. These yield loss estimates were based on expert opinions published by de Steigeur and Pye (1988) and were -5% for hardwood species and in the range of -5% (North) to -10% (South) for softwoods Haynes and Kaiser reported annual welfare losses (expressed in future values) ranging from $0.6 billion in 2000 to $3.0 billion in 2040

This study was followed up by one by Callaway (1991) in which he used that newer version of TAMM to estimate the economic impacts of reductions in southern pine yields (planted and natural) in the range of +2% to -10% The annualized welfare impacts associated with these yield reductions ranged from an increase of about +$40 million per year for the +2% case to about -$110 million for the -10% case

All these studies shared two common features They were all sensitivity analyses and the yield changes used in the analyses did not vary much, if at all, from species to species or region to region In addition, all these studies used the TAMM model. TAMM is a spatial price and equilibrium model, and as such it is basically a good tool for examining the economic effects of yield changes from a variety of sources However, TAMM has one important limitation in this regard. Management of the forest inventory, including harvesting, is linked only to current period prices Thus, TAMM does not do a very good job of simulating economic behavior in the market for timberland. This is an important limitation

[3] An unpublished study by Sohngen and Mendlesohn, "Integrating Ecology and Economics: The Timber Market Impacts of Climate Change," was not available until the final revisions to this report were being made This study shows increases in both forest yields and economic welfare due to climate change

because it means that the behavior of landowners in current periods does not anticipate reduced yields in future periods, through the signal of land prices. Thus, producers in TAMM are always in a "reactive" mode, and welfare losses are larger than they would be if timberland owners were able to anticipate the reductions in yields over longer periods.

Recently, Burton et al. (1994) presented a paper under the auspices of the Southern Global Change Program on the economic effects of climate change on Southern forests The paper is important because it relied on the same model being used in this study, FASOM, (Forest and Agricultural Sector Optimization Model) as the vehicle for estimating these impacts. However, like all the previous studies cited above, the yield changes used in this analyses were not based on studies of the effects of changes in climate on forest yields, but were instead framed in the context of a sensitivity analysis. The authors postulated changes of ±5% and ±10% in the annual growth rate of all species in all regions of the United States. Changes in the net present value of welfare ranged from +0.6% (+10% case) to -0.6% (-10% case) This study showed that the market behavior simulated in FASOM could greatly mitigate the effects of reductions in yields, although the authors did not describe in any detail the underlying economic logic for this.

Finally, Cline (1992) estimated economic losses to forests as a result of climate change using a fairly crude, but transparent, top-down approach. He very roughly estimated the annual average value of stumpage at $10 billion He used studies cited by EPA to fix expected reductions in forest productivity at about 40% per year and then reduced the stumpage value accordingly to around $4 billion annually, in the absence of any mitigation. Cline then estimated that forest management costs would have to double or triple to reduce forest losses by one-third. Taking into account all three factors—losses without mitigation, plus the costs of reducing damages through forest management, minus the losses avoided by management measures—Cline estimated that net annual losses would be in the neighborhood of $3 3 billion.

1.3 SCOPE AND OBJECTIVES

The study described in this report differs from previous ones in two distinct ways First, the yield changes used in the analysis are based on results contained in the published literature, based on a fairly sophisticated extrapolation methodology. Second, for the first time, the analysis was performed with a dynamic economic model that simulates land owner behavior in a way that is perfectly consistent with intertemporal optimization.

Accordingly, the objectives of this study were to use the FASOM model to estimate the impacts of these changes in yields on:

- the annualized value and distribution of consumer and producer surplus
- the regional distribution of producer surpluses, over time

- stumpage product prices, over time
- stumpage production, by product, over time
- inventory levels, by species, over time.

In this study, we used published information on climate change impacts on yields of hardwood and softwood species to estimate changes in consumer and producer surplus from commercial use of forests The estimates of changes in yields are based on published results of so-called "gap models." While these models do not represent the entire range of potential changes in forest yields from climate change (see Chapter 2), they are the only set of studies that give species specific results. Based on site specific results from the gap model studies, we estimated changes in hardwood and softwood yields for four scenarios:

- a 2.5°C warming with carbon dioxide fertilization[4]
- a 2.5°C warming without carbon dioxide fertilization
- a 4°C warming with carbon dioxide fertilization
- a 4°C warming without carbon dioxide fertilization.

We then used FASOM (Adams et al , 1994), to evaluate the impact of these changes in forest productivity on welfare, production (i.e., harvests), and forest inventory stocks in stumpage markets in the United States FASOM is an optimization model that simulates the growth, harvesting, and sale of timber products, in nine regions of the coterminous United States. It provides information about the effects of changes in forest yields on inventory volumes and acreage, on timber harvest and stumpage prices for sawtimber pulpwood and fuelwood, and on various components of producer and consumer welfare. A more complete discussion of the model and definitions of the welfare measures used in this report are contained in Chapter 4

The important feature about FASOM that differentiates it from other economic models used to look at the impacts of timber yield changes on stumpage markets is that FASOM is not a static or a myopic economic model It incorporates the future price expectations into the simulated investment behavior of timberland owners. What this means is that timberland owners are able to look into the future and adjust their planting and harvesting decisions, now, based on an understanding of future resource scarcity (or abundance). This allows for greater flexibility in the decision-making behavior that is incorporated into the model and more closely simulates how landowners actually behave. Because FASOM does include this type of mechanism, welfare losses due to lower yields, as projected by FASOM, would be reduced.

This report describes the methods and results from the research. The research was conducted in two phases. In the first phase, we estimated changes in hardwood and softwood yields based on results of studies in the literature. The first phase is described in Chapters 2 and 3.

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[4] The CO_2 effect assumes actual doubling of atmospheric CO_2 levels to about 700 ppm.

Chapter 2 describes the methods used to estimate the impacts of climate change on forest productivity, including the scenarios. Chapter 3 describes how estimates of site specific changes in yields due to climate change were used to estimate changes in hardwood and softwood yields in nine U.S. Forest Service regions.

In the second phase of our analysis, we used the yield changes to estimate changes in timber production and societal welfare. The methods and results from this phase are described in Chapters 4 and 5. Chapter 4 describes the FASOM model, with special reference to the forest sector. This chapter also describes the procedures for introducing the yield changes into the FASOM model and shows how the yields vary by species and region for each scenario. Chapter 5 presents the main economic results of the analysis in tabular and graphic form.

Chapter 6 provides the major conclusions of the study and outlines future research needs to improve the quality of the estimated economic impacts. Appendix A outlines the specific assumptions used to estimate changes in growing stock in the western United States Appendix B contains the tabular information that was used to develop the figures presented in Chapter 5. Lastly, Appendix C contains documentation on the mathematical structure of the forest sector in FASOM.

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CHAPTER 2
SOURCES OF INFORMATION AND METHODS FOR ESTIMATING CHANGES IN FOREST YIELDS

This chapter describes the methods used to estimate changes in yields of commercially important hardwood and softwood forests The estimates are based solely on published scientific literature on the biophysical effects of climate change on forests. The chapter includes discussions on data needs for conducting this analysis, the published studies on biophysical effects of climate change, the climate change scenarios used in those studies, uncertainties about climate change and its effects on forests, and how regional estimates of changes in hardwood and softwood growing stock for different climate change scenarios were derived.

2.1 DATA NEEDS

FASOM requires information on hardwood and softwood yields for the nine U.S Forest Service regions (see Chapter 4). To be useful for this study, information from the literature on climate change effects on forests had to indicate hardwood and softwood yields at the regional level Studies that estimated changes in the range of forests or total forest biomass or only gave information at a national level would not be used for this study. The next section describes the types of studies of climate change effects on vegetation, whether they provide the information needed for this analysis, and results and limitations of the studies we used

2.2 INFORMATION SOURCES

We evaluated the published literature on climate change impacts on forests based on whether it provided information on hardwood and softwood yields in the nine U.S Forest Service regions Three general types of models have been used to examine climate change impacts on forests:

- **biogeography models**, which simulate the dominance of competing forms of vegetation based on ecophysiological and resource constraints

- **biogeochemistry models**, which simulate the cycling of carbon, nutrients and water as influenced by climate and environmental conditions

- **community competition (gap) models**, which simulate competition among tree species in response to changes in temperature and moisture.

Since FASOM requires yield information by species and region, highly aggregated estimates of total forest productivity were not sufficient. Biogeography models (e.g., Smith et al., 1992a) and biogeochemical models (e.g., Melillo et al., 1993) estimate changes in conditions of major forest types, such as cool temperate mixed forests[1] and, do not produce information on changes in yields in hardwoods and softwoods. Although some forest types, such as temperate deciduous forests, are either hardwood or softwoods, many of the classifications contain mixtures of both hardwoods and softwoods. Thus, neither type of model gives sufficient detail about changes in hardwood and softwood yields.

To obtain the information needed for this analysis, we used the results from community competition, or gap models. This class of models derives its name from the fact that they simulate the growth of trees when gaps in a forest canopy are created by the death of a large tree (Shugart, 1987) These also simulate the site specific growth of tree species over time [2] The models are physiologically based and have been used to estimate the effects of climate change on hardwood and softwood trees over much of North America. Table 2-1 lists the gap model studies used in this analysis.

Gap models are considered to be highly credible tools for examining forest response to environmental stress (Dale and Rauscher, 1994) These models have been applied and validated for different forest types around the world (Shugart et al., 1992). Yet there are a number of limitations in using gap models as a basis for estimating how climate change will affect private forests The first is that they have been used to examine only unmanaged forests Gap models have not been used to examine forests that are harvested, thinned, or replanted—that is, forests that are used for timber, among other purposes. Timber forests are the subject of this study [3]

The second limitation is that gap models tend to be very sensitive to changes in temperature. They use an inverse parabola to describe the relationship between temperature and tree species growth (see Figure 2-1). Using this approach, a 4°C warming would translate into an

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[1] See VEMAP Participants, submitted. "Vegetation/Ecosystem Modeling and Analysis Project (VEMAP). Assessing Biogeography and Biogeochemistry Models in a Regional Study of Terrestrial Ecosystem Responses to Climate Change and CO_2 Doubling." Manuscript obtained from J.M Melillo, VEMAP coordinator, The Ecosystem Center, Marine Biological Laboratory, Woods Hole, MA 22903.

[2] This feature also makes gap models useful as in input into FASOM. As is discussed below, most of the gap model results are for static climate change scenarios.

[3] Most studies of climate change impacts on forests have focused on forests or vegetation types unaffected by human activities

Table 2-1
Gap Model Studies

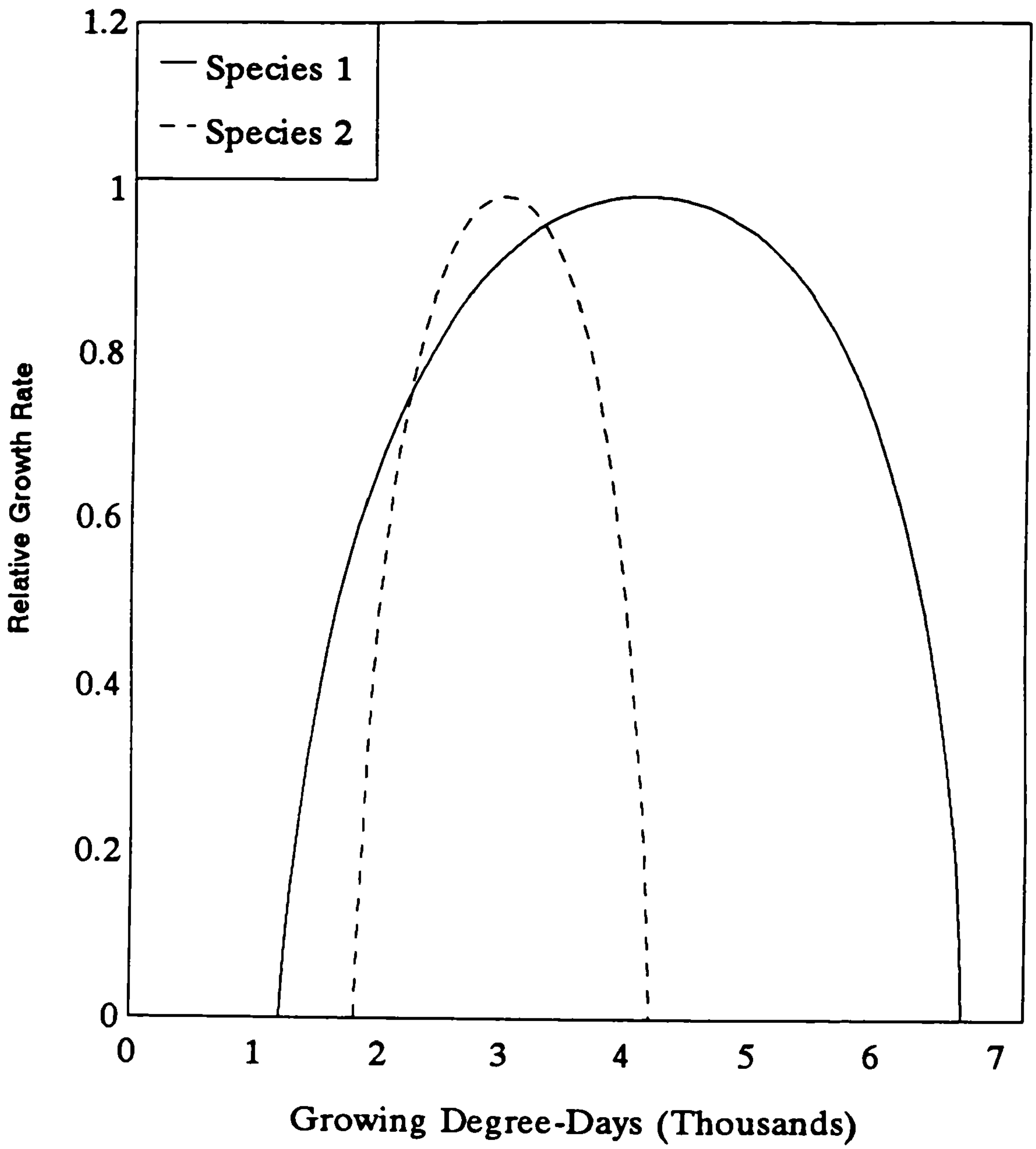
Study	Region	Climate Change Scenarios
Solomon, 1986	Eastern United States	UKMO $2XCO_2$ and $4XCO_2$
Pastor and Post, 1988	Northeast United States	UKMO $2XCO_2$
Botkin et al., 1989	Great Lakes States	GISS, GFDL, OSU, $2XCO_2$, GISS Transient
Urban and Shugart, 1989	Southeast	GISS, GFDL, OSU, $2XCO_2$, GISS Transient
Urban et al , 1993	Pacific Northwest	GISS, OSU, $2XCO_2$
King and Tingey, 1992	Pacific Northwest	GISS, OSU, $2xCO_2$, GISS Transient
Running and Nemani, 1991	Rocky Mountains	+4°C, +10% Precipitation

increase of approximately 1,000 growing degree days, which can result in a dramatic reduction in tree growth (Urban et al , 1993). The specification of the parabola is based on the observed range of tree species, with the temperatures at the northern boundary used to determine the minimum temperature tolerance and the temperatures at the southern boundary used to determine the maximum temperature tolerance Although the northern or upper elevation boundaries of trees are often limited by cold temperatures, the southern or lower elevation limits are often influenced by reduced soil moisture or competition from species better adapted to warmer climates Both soil moisture and the range of competitive species are influenced by temperature. Raising temperatures and leaving precipitation unchanged will most likely result in drier soils Yet, climate change could cause both temperature and precipitation to increase, which could result in wetter soils. Many tree species could survive warmer *and wetter* conditions, and perhaps even prosper, at least until more southern species migrate into the region and outcompete them (Smith et al., 1992b) [4] On the other hand, the gap models do not account for such climate change induced factors as increased wildfires, pests, and pathogens, which could accelerate dieback of forests (Shugart et al., 1992)

On the whole, gap models may overestimate the extent to which forests may die back in response to higher temperatures. This problem is particularly acute in the Southeast. The observed southern boundary of many forest species in that region may be limited by the

[4] This situation could be exacerbated because some gap models may overstate the degree of drought stress (Bugman and Martin, 1995).

Figure 2-1
Typical Gap Model Relationship between Growing Degree Days and Growth



Source: Based on Urban and Shugart, 1989.

presence of the Gulf of Mexico. So it is uncertain whether these forests could survive in hotter conditions (Smith and Tirpak, 1989).

The third limitation is that the gap model studies, for the most part, did not estimate whether heat-and drought-tolerant species not currently found in the subject region would grow under climate change. Forest managers may replant forests with more heat- and drought-tolerant species Thus, the studies may have overestimated the decrease in yields, particularly of the softwood species grown in managed forests One exception to this limitation is Solomon (1986), who found that some northern sites could support southern pines under some scenarios.

The final limitation is that, with the exception of the Running and Nemani (1991), all of the studies used in this analysis did not account for CO_2 fertilization. Increased concentrations of atmospheric CO_2 will, without climate change, increase growth and decrease demand for water by trees (Bazzaz and Fajer, 1992). Most studies on CO_2 fertilization have been conducted in laboratories or under controlled conditions There is significant uncertainty about the degree to which enhanced CO_2 concentrations will affect trees outside the laboratory

Box 2-1 summarizes the results of the studies using gap models and Box 2-2 briefly describes the results of studies using other approaches Generally, the gap models tend to estimate reductions in forest biomass, particularly for softwoods in the Southeast. To be sure, the models estimate that hardwood growth in the north could increase The biogeography and biogeochemical models described in Box 2-2 tend to have more mixed results. Some show significant declines in total national biomass of forests that are of even larger magnitude than those estimated by the gap models (Some also show potentially severe declines in southeastern forests). Others estimate that forest productivity could increase under climate change In fact, the VEMAP study (VEMAP Participants, submitted) found there is no basis to determine which of these biogeography or biogeochemical models is more accurate Thus, the gap models are consistent with results of other studies, but they tend to be on the pessimistic side of the range of all forest studies

2.3 CLIMATE CHANGE SCENARIOS

Since FASOM is a dynamic model, that is it simulates change in forest production over time, it would be desirable to use transient scenarios of climate change. Transient scenarios estimate how climate might change over time as greenhouse gas concentrations in the atmosphere gradually increase. In contrast, equilibrium scenarios estimate static climate conditions based on a specific level of atmospheric greenhouse gases, such as a doubling of carbon dioxide levels (often referred to as $2XCO_2$) In determining how climate change affects forests, we were limited by the choice of climate change scenarios in the gap modeling studies. Table 2-2 lists the changes in global temperatures from the general circulation model GCM runs used in the gap model studies Most studies of climate change impacts on forests

Box 2-1
Results of Gap Model Studies

This table briefly summarizes the results of the studies used as the basis for estimating changes in yields. All studies, except for Running and Nemani (1991), used gap models and assumed no CO_2 fertilization effect.

Solomon (1986) examined effects on vegetation across all of the eastern half of North America. He found that along northern border states, biomass did not change significantly, but composition did. South of those sites, climate change significantly reduced biomass.

Pastor and Post (1988) modeled two areas in the United States, northeastern Minnesota and Maine. They found that biomass would increase on wet soils in Minnesota and decrease on dry soils Biomass in Maine would increase in both types of soils. Softwoods generally disappeared, while hardwoods increased in abundance.

Botkin et al. (1989) modeled a site in northeastern Minnesota and another in south-central Michigan. They found that the climate change scenarios resulted in the replacement of southern boreal species in Minnesota (softwoods and hardwoods) with northern deciduous species (mostly hardwoods). In the Michigan site, the abundance of oaks and maples is significantly reduced.

Urban and Shugart (1989) examined the effects of climate change on softwoods in sites across the Southeast. In Tennessee, the oak-pine forest would shift to a loblolly pine forest, with little change in total biomass. In South Carolina, Georgia, and Mississippi, forest biomass would decline, with the most severe decline in Mississippi.

Urban et al. (1993) studied a site on the western slope of the Cascade Range in central Oregon. They found that forest zones would shift 500 to 1000 meters higher in elevation. Both the OSU and GISS scenarios caused reductions in biomass for forests at 1000 meter elevation.

King and Tingey (1992) examined several sites in Oregon and Washington. Like Urban et al (1993), they also found that a 2°C to 5°C warming would cause vegetation zones to shift 500 to 1000 meters upslope. King and Tingey concluded that forest cover in the Pacific Northwest could be reduced by 5 to 25% Biomass changes were not reported.

Running and Nemani (1991) used the FOREST-BGC model, a biogeochemical model, to examine changes in net primary productivity (NPP) and leaf area index (LAI) for Missoula Montana. We used this study because no gap model results were available for the Rocky Mountain Regions. Assuming a 4°C warming, a 10% increase in precipitation, and a carbon fertilization effect, they estimated that NPP would increase 88% and LAI 10 to 20%

Box 2-2
Simulated Effects of Climate Change Using Biogeography and Biogeochemical Models

Smith et al. (1992a), using a biogeography model, estimated that forest cover over the lower 48 states could be reduced by 1 to 7% in the long run. The extent of wet forest cover would be reduced, and dry forest cover would increase.

Melillo et al. (1993) used the terrestrial ecosystem model (TEM), a biogeochemical model, to estimate climate change effects on global NPP. They found that assuming climate change from four GCMs and CO_2 doubling, global NPP would increase by 19 to 27%. Regional results for the United States were not included in this article.

VEMAP Study (VEMAP Participants, submitted) used common scenarios of climate change and elevated CO_2 in the United States to compare three biogeography (BIOME2, DOLY, and MAPPS) and three biogeochemical models (TEM, CENTURY, and BIOME-BGC). All six models accurately estimate the current distribution of vegetation across the lower 48 states under current climate Yet, their estimates of climate change impacts on vegetation diverge substantially.

- BIOME2 (biogeography model) projected an expansion of forests in North America with CO_2-induced warming.
- MAPPS (biogeography model) showed a significant reduction in forest cover, particularly in the southeast
- TEM (biogeochemical model) projected 12 to 16% increases in biomass due to a doubling of CO_2.
- BIOME-BGC (biogeochemical model) indicated a 9 to 32% reduction in biomass for the same CO_2 doubling.

All three biogeochemical models, however, estimate that doubling CO_2 concentrations without changing climate only increases carbon storage by 2 to 9%. The study also "coupled" biogeographical models to estimate changes in location of vegetation types and biogeochemical models to estimate changes in plant functioning in response to climate change. These couplings produced very widely divergent results, with the combination of BIOME2 and TEM yielding a 32 to 56% increase in carbon storage, while the combination of MAPPS and BIOME-BGC estimated a 8 to 39% reduction in carbon. The main source of the differences among the model results concerns how they respond to increase evaporative demands from higher temperature. The study concluded that there is no basis for determining which model results are most reliable

Table 2-2
GCM Runs Used in Gap Model Studies

Model	Citation	Global ΔT (°C)
UKMO $2XCO_2$	Mitchell, 1983	2.3
UKMO $4XCO_2$	Mitchell and Lupton, 1984[1]	4.6
GISS $2XCO_2$	Hansen et al., 1983	4.2
GFDL $2XCO_2$	Manabe and Wetherald, 1987	4.0
OSU $2XCO_2$	Schlesinger and Zhao, 1989	2.8
GISS Transient	Hansen et al., 1988	0-4.2

[1] We assumed that $4XCO_2$ concentrations in the UKMO model result in double the temperature change from the $2XCO_2$ run using the UKMO model (Mitchell, 1983).

used $2XCO_2$ equilibrium scenarios. Note that the GISS transient was the only transient scenario used in gap model studies and it was used in only three studies.Thus, this study only uses equilibrium climate change scenarios.

The GCM scenarios in Table 2-2 tend to be clustered either around a 2.5°C or a 4°C global warming. Based on this selection of models, we decided to estimate the forest impacts under scenarios a global 2 5°C and 4°C warming These changes in temperature are within the range of increase in global temperatures estimated by the Intergovernmental Panel on Climate Change (Houghton et al., 1992) We used results based on the UKMO $2XCO_2$ and OSU models as representative of a 2.5°C warming and results based on the UKMO $4XCO_2$, GISS and GFDL models as representative of a 4°C warming. The GISS transient provides information about both amounts of climate change. Relative changes in regional temperatures may vary between models.

We also developed scenarios with and without the effects of CO_2 fertilization. The without CO_2 scenarios uses the results directly from all of the gap modeling studies, except for Running and Nemani (1991) (see Chapter 3). The with CO_2 scenarios assumes there is a CO_2 fertilization effect. We assumed a doubling of atmospheric CO_2 levels from approximately 350 ppm to 700 ppm.

The assumption about the CO_2 fertilization effect is our educated guess based on conversations with gap modelers (e.g., Ron Neilson, Corvallis Lab, Corvallis, Oregon; Dean Urban, Colorado State University, Fort Collins; George King, Mantech Inc., Corvallis, Oregon) and a review of the literature on the CO_2. fertilization effect. The literature indicates that a doubling of CO_2 concentrations in the atmosphere could increase plant growth by up to 40% For example, Drake found that elevated CO_2 levels increase plant growth by 30 to 40% (Drake, 1992). Since there is significant uncertainty about the extent to which elevated CO_2 concentrations will enhance forest growth in relatively unmanaged conditions (e.g., Bazzaz and Fajer, 1992; Luxmoore et al., 1993), we assumed that CO_2 increases yields by 25% to 33%

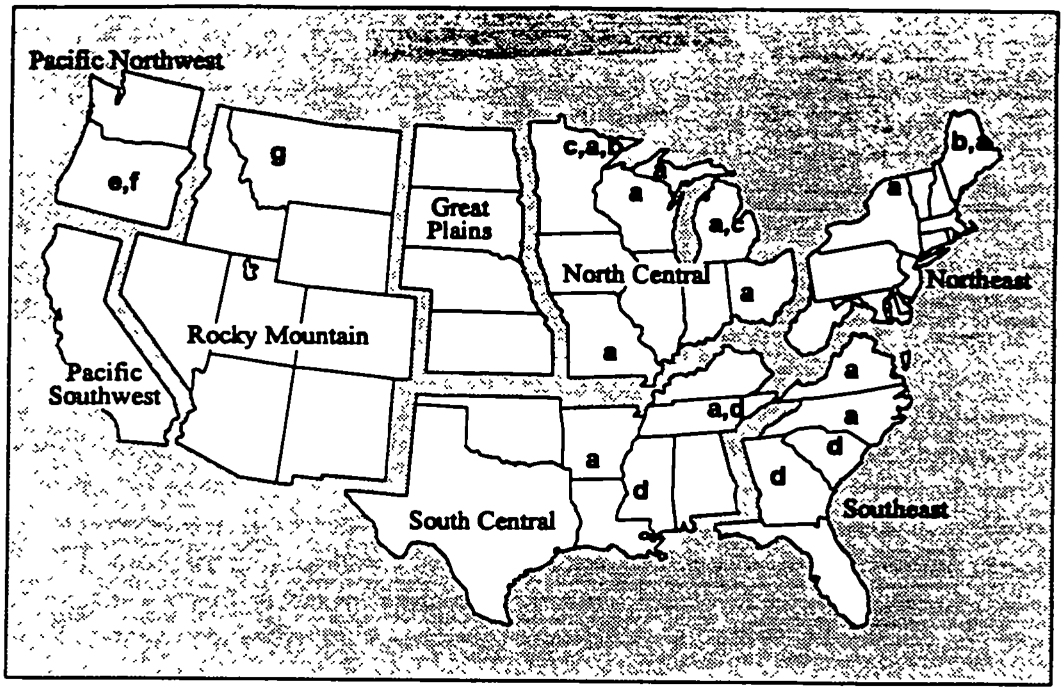
To calculate the CO_2 effect we multiplied the change in biomass under the no CO_2 scenario by 1.25 to 1.33. If, in the no CO_2 scenario, biomass was estimated to be reduced, we assumed that the CO_2 fertilization effect increased yields by one-third. For example, if the no CO_2 scenario had biomass decrease to 30% of no climate change level (i e., a 70% decrease in yield), the with CO_2 case would have biomass decrease to 40% of current level ($1.33 \times 0.3 = 0\ 4$; a 60% decrease in yield). To have a minimum positive CO_2 fertilization effect, in all cases we assumed at least an absolute change of 10%. So if biomass were estimated to decrease by 90% in a no CO_2 case, we assumed that it would decrease by 80% in a with CO_2 case. If in a no CO_2 scenario, biomass is unchanged or increases, we assumed the CO_2 effect increased yields by one-quarter. We assumed a lower positive effect of CO_2 when yields increase to avoid unduly large increases in biomass. So if biomass were estimated to be 200% of current biomass under a no CO_2 case, the CO_2 effect would result in yield of 250% ($1.25 \times 2 = 2\ 50$).

2.4 USING SITE-SPECIFIC INFORMATION TO ESTIMATE REGIONAL CHANGES IN GROWING STOCK

As noted above, gap models were used to estimate changes in growth of trees on specific sites. Figure 2-2 displays the sites modeled by the gap model studies The map also displays the U S Forest Service regions, which are the same regions used in FASOM. There are more modeled sites and more extensive coverage of forests in the eastern half of the United States than in the western half. This section describes how we used site-specific results to develop estimates of changes in hardwood and softwood growing stock for the U.S. Forest Service regions.

We used the results from the gap model studies to develop estimates of changes in hardwood and softwood growing stock Where a study gave estimates for many hardwood or softwood species, we used the change in total biomass for all hardwood or softwood species as indicative of changes in hardwood or softwood biomass. For example, Solomon (1986) reports results for several dozen hardwood and softwood species To determine changes in hardwoods, we summed his estimated biomass changes for all hardwoods at a site. If only a

Figure 2-2
Location of Sites from Published Gap Model Studies



a - Solomon
b - Pastor and Post
c - Botkin et al
d - Urban and Shugart
e - Urban et al
f - King and Tingey
g - Running and Nemani

limited number of species were reported, we used results for commercially important species For example, in the South, Urban and Shugart (1989) report results for loblolly and shortleaf pines. We used those results to develop estimates of changes in softwood production in the Southeast and South Central regions.

If two or more studies had sites in the same area, we averaged their results together to create a composite result. For example, Solomon (1986), Pastor and Post (1988), and Botkin et al. (1989) estimated changes in northern Minnesota forests. The results of all three were averaged to estimate yield changes in Minnesota. In some cases, we gave less weight to studies that appeared to have extreme results. We assumed that each site was representative of the forests in the entire state For example, the results of Urban and Shugart's (1989) study of softwood forests in Macon, Georgia, were assumed to be representative of all Georgia softwoods. We had more than one site in only one state, Michigan, where sites in upper and lower Michigan were modeled separately. In that case, we developed state-wide estimates based on the distributions of hardwoods and softwoods in the state (see Chapter 3).

Shifts in elevation are not relatively important in affecting yield of eastern forests and we did not take them into account in our analysis. In the West such shifts could have significant influence on the habitable area and yield of commercially important species, such as Douglas fir For the West, we assumed that forests would shift upslope with higher temperatures We extrapolated state results to Forest Service regions based on the state's percentage of regional volume of hardwood or softwood growing stock (Waddell et al., 1989). For example, Urban and Shugart estimated change in yields for softwoods in Georgia and South Carolina These states respectively have 33 and 17% of softwood growing stock in the Southeast region We weighted the state changes in softwood by their relative shares, (66%) for Georgia and (34%) for South Carolina, to calculate change in softwood production for the region We describe specific regional extrapolation issues in Chapter 3.

We also calculated the changes in the national growing stock of hardwoods and softwoods These were based on the relative shares of hardwoods and softwoods in each region

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CHAPTER 3
RESULTS: YIELD CHANGES

In this chapter, we discuss regional and national changes in hardwood and softwood yields Only the regional changes were used as inputs into FASOM. The national results were not used in FASOM, but are useful for comparing percentage changes in yields with percentage changes in welfare. State by state results are reported in the discussions on each region. Weighted average results for hardwood and softwood yields by region are displayed in Tables 3-7a and 3-7b at the end of this chapter.

3.1 SOUTHEAST AND SOUTH CENTRAL REGIONS

The Forest Service and FASOM consider the Southeast and South Central regions to be distinct regions Results are reported for both regions because the same gap model studies included sites in both regions The Southeast region consists of Virginia, North Carolina, South Carolina, Georgia, and Florida The South Central region consists of Kentucky, Tennessee, Alabama, Mississippi, Louisiana, Arkansas, Oklahoma, and Texas

We developed estimates of changes in softwood yields based on Urban and Shugart (1989) and for hardwood yields based on Solomon (1986) State results for softwoods and hardwoods are displayed in Tables 3-1 (a and b) and 3-2 (a and b).

Table 3-1a
Change in Southeast Softwood Biomass

Climate Scenario	% Change in Biomass	
	South Carolina	Georgia
2 5°C without CO_2	-90	-80
2 5°C with CO_2	-30	-70
4°C without CO_2	-100	-100
4°C with CO_2	-50	-90

Table 3-1b
Change in Southeast Hardwood Biomass

Climate Scenario	% Change in Biomass	
	Virginia	N. Carolina
2 5°C without CO_2	-10	-10
2.5°C with CO_2	+20	+20
4°C without CO_2	-20	-40
4°C with CO_2	+5	-20

Table 3-2a
Change in South Central Softwood Biomass

Climate Scenario	% Change in Biomass		
	Tennessee	Arkansas	Mississippi
2.5°C without CO_2	0	-100	-100
2 5°C with CO_2	+25	-90	-90
4°C without CO_2	-100	-100	-100
4°C with CO_2	+10	-90	-90

Table 3-2b
Change in South Central Hardwood Biomass

Climate Scenario	% Change in Biomass	
	Tennessee	Arkansas
2.5°C without CO_2	+5	-50
2.5°C with CO_2	+30	-33
4°C without CO_2	-35	-90
4°C with CO_2	-15	-80

Urban and Shugart estimated changes in loblolly and shortleaf pine yields in South Carolina, Georgia, Tennessee, and Mississippi under the GISS, GFDL, and OSU $2XCO_2$ scenarios and the GISS transient scenario. We used the GFDL scenario to estimate the 4°C without CO_2 case and the OSU scenario to estimate the 2.5°C without CO_2 case. To estimate the 4°C and 2 5°C with CO_2 cases, we used the GISS $2XCO_2$ scenario and the GISS transient scenario (combined with the CO_2 fertilization effect). We included the GISS results in the with CO_2 case because the GISS scenario is significantly wetter than the other two scenarios (Smith and Tirpak, 1989). Thus, the without CO_2 scenarios in the South can be thought of as relatively dry scenarios without a CO_2 fertilization effect and the with CO_2 scenarios can be thought of as relatively wet scenarios with a CO_2 fertilization effect.

The results for the with and without CO_2 scenarios for softwoods in Tennessee differ widely This is because there were large differences between GISS, OSU, and GFDL from Urban and Shugart Urban and Shugart estimated that, under the GISS and OSU scenarios, there would be no change in biomass, while under the GFDL scenario, all forests would disappear

Solomon (1986) examined sites in Virginia, North Carolina, Tennessee, and Arkansas He only used two scenarios. UKMO $2XCO_2$ and UKMO $4XCO_2$ The first scenario was used to represent a 2.5°C warming. Solomon reported that all hardwoods in Arkansas would be eliminated under the $4XCO_2$ scenario, which has a 4.6°C warming. To arrive at an estimate for 4 0°C, we interpolated between the 4.6°C and the $2XCO_2$ warming (2.3°C) to arrive at the 90% reduction in biomass. It is quite possible that the threshold for eliminating hardwoods in Arkansas is below 4 6°C and we were too generous in assuming that some hardwoods would survive. If so, the without CO_2 case would have a 100% reduction in biomass.

The results generally show decreases, particularly for softwoods The 4°C without CO_2 scenario eliminates all softwoods in the regions Hardwoods are not as adversely affected The more southerly and westerly sites in the two regions tend to be the most negatively affected by climate change

3.2 NORTH CENTRAL

The North Central region consists of Minnesota, Wisconsin, Michigan, Ohio, Indiana, Illinois, Iowa, and Missouri. We used three studies to develop biomass change estimates for this region: Solomon (1986), Pastor and Post (1988), and Botkin et al. (1989). Solomon had sites in Minnesota, Wisconsin, upper and lower Michigan, Ohio, and Missouri. Pastor only had species-specific results in Minnesota (he estimated changes in total biomass in other sites). Botkin provided estimates for Minnesota and lower Michigan.

As noted above, Solomon used two scenarios, the UKMO $2XCO_2$ and the UKMO $4XCO_2$. Pastor and Post also used the same UKMO $2XCO_2$ scenario That scenario was used to represent the 2 5°C warming, and the UKMO $4XCO_2$ scenario was used (with some interpolation) to represent the 4°C scenario. Botkin et al. used the OSU (2.8°C), GFDL (4.0°C), and GISS (4.2°C) $2XCO_2$ scenarios and the GISS transient (0 to 3.7°C). The OSU and the GISS transient were used to help estimate biomass changes for 2.5°C without CO_2 scenario , and the GFDL GISS $2XCO_2$ and GISS transient results were used to estimate changes for a 4°C warming without CO_2 scenario.

All three studies provided estimates for Minnesota. Botkin et al., however, gave estimates for only one hardwood species, sugar maples. Those estimates showed increases in biomass of 5 to 10 times current levels. Solomon and Pastor and Post had hardwood increases of less than 100% Because they considered more species and were consistent with each other, we gave more weight to Solomon and Pastor and Post than to Botkin et al. for the Minnesota estimates.

Estimates were given for sites in the upper and lower parts of Michigan. Botkin estimated changes for southern Michigan, as did Solomon. We averaged results from both studies to develop a composite estimate for lower Michigan. Solomon also estimated changes in upper Michigan. By examining the distribution of hardwoods and softwoods in the Great Lakes states, we assumed that hardwoods were split evenly between upper and lower Michigan, but that 90% of softwoods are in upper Michigan. We used these assumptions to weight the results from upper and lower Michigan. State results are displayed in Table 3-3 (a and b).

Table 3-3a
Change in North Central Softwood Biomass

Climate Scenario	% Change in Biomass			
	Minnesota	Wisconsin	Michigan	Ohio
2.5°C without CO_2	-75	-70	-60	-10
2.5°C with CO_2	-65	-60	-45	+20
4°C without CO_2	-70	-80	-75	-70
4°C with CO_2	-60	-70	-65	-60

The North Central region presents some interesting differences between northern and southern states in the region. Softwood yields tend to decrease across all the region, although the 2.5°C sensitivities for Ohio have very little change in yield. It is not evident to us why the softwoods in Ohio respond differently to the 2.5°C warming than did softwoods elsewhere in the region. In contrast, hardwood yields increase markedly in the northern states of Minnesota, Wisconsin, and Michigan, but decline in the more southern states of Ohio and Missouri In the more northern states, the larger the temperature increase, the more hardwood yields rise.

Table 3-3b
Change in North Central Hardwood Biomass

Climate Scenario	% Change in Biomass				
	Minnesota	Wisconsin	Michigan	Ohio	Missouri
2.5°C without CO_2	+40	+40	+15	-10	-40
2.5°C with CO_2	+75	+75	+40	+20	-20
4°C without CO_2	+100	+60	+35	-25	-70
4°C with CO_2	+150	+100	+70	0	-60

3.3 NORTHEAST

Estimates of changes in yields from the Northeast regions were based on Solomon (1986) and Pastor and Post (1988). The states in the region are the New England states, New York, Pennsylvania, New Jersey, Delaware, Maryland, and West Virginia. Solomon modeled sites in New York and Maine, and Pastor and Post reported species results only for Maine Both studies used the same UKMO scenarios discussed above, and we used the same procedures to examine the 2 5°C and 4°C scenarios. Both studies showed very similar reductions in softwood biomass. Although both studies estimated that hardwoods would increase in biomass, Solomon estimated a much larger increase than Pastor and Post did In developing the combined estimate of hardwood changes in Maine, we gave slightly greater weight to Pastor and Post's results The results for Maine and New York are displayed in Table 3-4. Since both states are in the northern part of the region, we assumed they are representative of forests in New York and New England

Even though Ohio is not in the region, we used the results for Ohio forests as representative of the other states in the region (Pennsylvania, New Jersey, West Virginia, Maryland, and Delaware) because it was the closest and most representative site

The results differ in sign for hardwoods and softwoods. While hardwood show increasing yields with increasing temperatures, softwoods have decreasing yields with higher temperatures.

Table 3-4
Change in Northeast Biomass

Climate Scenario	% Change in Biomass			
	Softwoods		Hardwoods	
	New York	Maine	New York	Maine
2.5°C without CO_2	-33	-70	0	+100
2.5°C with CO_2	-10	-60	+25	+150
4°C without CO_2	-75	-80	+60	+150
4°C with CO_2	-65	-70	+100	+200

3.4 PACIFIC NORTHWEST AND PACIFIC SOUTHWEST

As is shown in Figure 2-1, only one site in the West Coast states of the United States has been the subject of a gap modeling study. The site, in central Oregon, is approximately in the middle latitudes of the hardwood and softwood range in the region, and thus we assumed that it is representative of the Pacific Northwest and Pacific Southwest regions. These regions consist of Washington, Oregon, and California.

Results are reported in Urban et al (1993) and King and Tingey (1992). Since Urban provided forest yield changes to King and Tingey, for the sake of simplicity, we only cite Urban et al. in the rest of this section Only the OSU and GISS scenarios were used. We used the GISS scenario, which produced yield declines of 90%, to estimate the 4°C without CO_2 sensitivity The OSU scenario resulted in yield declines of 50% and was used to determine the 2 5°C without CO_2 case Urban et al estimated biomass only for softwoods, so no changes in hardwood yields for these regions were developed. Hardwood yields in the West are relatively small so not including changes in yields of those species did not significantly affect results from FASOM

Urban et al estimated changes in yields for softwood forests at current elevations. In the West, the elevation ranges where trees are found will most likely change as a result of climate Although yield could decline at current elevations, warmer temperatures will most likely enable forests to survive at higher elevations.

To estimate the effects of climate change on western forests, we had to develop two set of assumptions The first concerned the changes in habitable area as temperatures and elevations rise The second concerned how yields in the different elevations would change. We used a typical mountain profile of the Cascades to calculate changes in habitable area due to shifts in elevation. We further assumed that for each incremental increase in temperature (current to 2.5°C; 2.5°C to 4.0°C), estimated changes in yields would shift upslope by 500 meters. Both assumptions are discussed in detail in Appendix A.

Results are displayed in Table 3-5 The higher reductions in yields from the 4°C warming scenario appears to substantially offset the increase in elevation for softwoods. For the 2.5°C scenarios, the increase in elevation approximately offsets decrease in yields at current elevations.

Table 3-5
Change in Softwood Biomass in Pacific Northwest and Pacific Southwest

Climate Scenario	% Change in Biomass
2 5°C without CO_2	-10%
2.5°C with CO_2	+20%
4°C without CO_2	-53%
4°C with CO_2	-32%

3.5 ROCKY MOUNTAINS

As is shown in Figure 2-1, the Rocky Mountain region had only one site, located in northwestern Montana This region, however, includes Montana, Idaho, Wyoming, Colorado, Utah, Nevada, Arizona, and New Mexico. We assumed this site is representative of softwoods in the Rocky Mountains region Although almost all of the softwoods are in the northern part of the region, the site still may be too far north to be representative of most softwoods in the region. As can be seen in other regions, the farther north a site, the more likely it is to have less negative or more positive impacts Thus, the Running and Nemani study (1991) may have results that are too positive for the entire Rocky Mountains region.

Running and Nemani used only a single scenario of climate change, a 4°C increase in temperature and a 10% increase in precipitation. Running and Nemani also assumed that photosynthesis increases 30% and stomatal conductance decreases 30% because of CO_2 fertilization. They only estimated changes in softwood yields.

Unlike the other studies, Running and Nemani used a biogeochemical model and estimated changes in leaf area index (LAI), not biomass Since LAI is not the same as biomass, we needed to convert it to biomass to be consistent with the other studies. Based on Carlson (1987), we assumed that increases in biomass are one-third less than increases in LAI. Running and Nemani estimated that LAI would increase 10 to 20% under the 4°C scenario. The midpoint of that estimate is 15%, and a one-third reduction gives an estimate of a 10% increase in biomass.

Since Running and Nemani include CO_2 fertilization, their results were used for the with CO_2 case. Assuming that CO_2 increases growth by 33%, we calculated that without the CO_2 effect, yields would have decreased by 20% in the 4°C low sensitivity case. We assumed that the 2.5°C warming would halve the reduction in yields to 10%. This latter result was used for the high sensitivity case. We increased the biomass by one-third to give the 2.5°C high sensitivity case

As in the West Coast, we accounted for shifts in elevation. We assumed that the relative shifts in area elevation and habitable area for the 2.5 and 4°C warmings are the same as the assumptions used in the Pacific Northwest and Pacific Southwest (George King, personal communication). We also assumed that, for each incremental increase in temperature, yields would shift upslope by 500 meters (see Appendix)

Results are displayed in Table 3-6. Unlike the other regions, yields for softwoods increase under all four scenarios.

Table 3-6
Change in Softwood Biomass in Rocky Mountains

Climate Scenario	% Change in Biomass
2 5°C without CO_2	+30%
2 5°C with CO_2	+70%
4°C without CO_2	+33%
4°C with CO_2	+79%

3.6 NATIONAL RESULTS

Tables 3-7a and 3-7b display, respectively, regional changes in softwood and hardwood growing stock. Table 3-7b does not display results for the western regions because hardwood growing stock is quite small. As discussed in Chapter 2, regional changes for regions with multiple sites from the gap model studies were derived based on the current distribution of growing stock in the region.

Table 3-7a
Regional Changes in Softwood Growing Stock
(Percent Change)

Scenario	Southeast	South Central	Northeast	North Central	Rocky Mountains	Pacific Northwest	Pacific Southwest
2.5°C without CO_2	-83	-87	-55	-64	+30	-10	-10
2.5°C with CO_2	-56	-75	-40	-51	+70	+20	+20
4°C without CO_2	-100	-100	-78	-76	+33	-53	-53
4°C with CO_2	-76	-77	-68	-66	+79	-32	-32

Table 3-7b
Regional Changes in Hardwood Growing Stock
(Percent Change)

Scenario	Southeast	South Central	Northeast	North Central
2.5°C without CO_2	-10	-20	+14	+11
2.5°C with CO_2	+20	-1	+46	+39
4°C without CO_2	-30	-60	+36	+21
4°C with CO_2	-8	-44	+71	+53

Softwoods were estimated to decline in the eastern half of the United States under all four scenarios In some regions such as the South, softwoods were estimated to be completely eliminated under some scenarios. In contrast, softwoods were estimated to increase in western areas in some scenarios. The potential for increase is due in part to higher elevations, allowing the softwood growing area to expand.

Hardwood growing stock also shows mixed results with increases in some regions and decreases in others. In contrast to the softwoods, latitude appears to be a more important factor than longitude in determining whether hardwood growing stock will increase or decrease The northern regions consistently show increased hardwood yields, while the southern regions tend to have decreased hardwood yields.

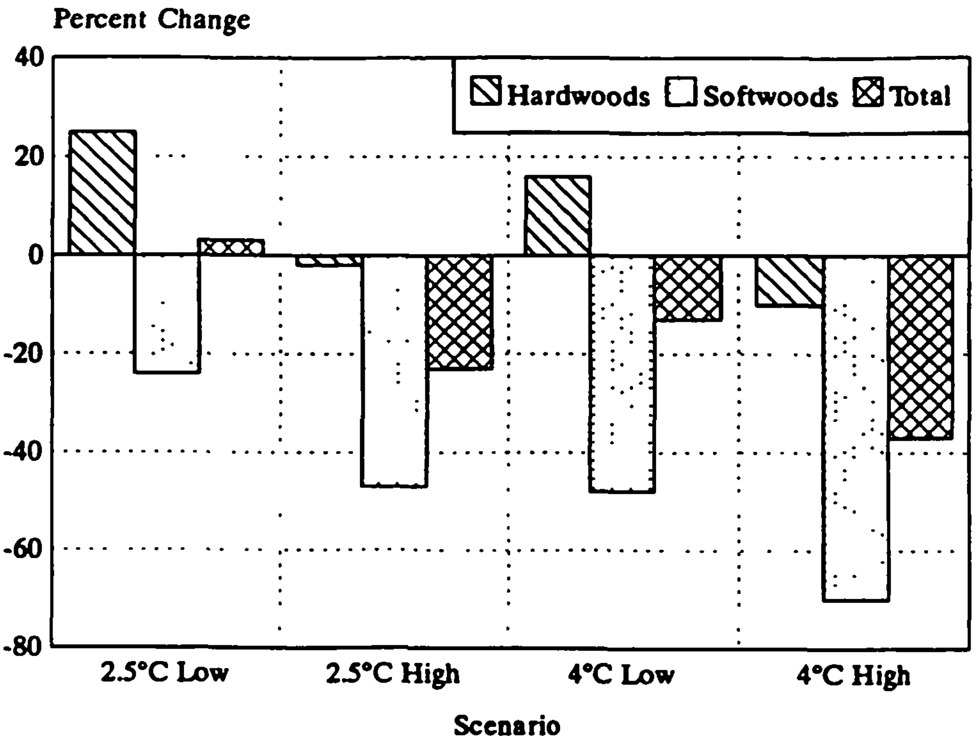
Summing across regions, the South is estimated to face decreased hardwood yields and severe decreases in softwood yields. The northeastern quadrant of the country could have significant decreases in softwood yields, but significant increases in hardwood yields. The West is estimated to have mixed results for softwood yields.

We calculated changes in national yields of hardwoods, softwoods, and all forests by weighting current growing stock in each region. The results are displayed in Table 3-8 and Figure 3-1. In spite of the effect of increased softwood yields in the western regions in some scenarios, nationwide softwood yields are estimated to decrease in all scenarios. The results for hardwood yields are very sensitive to assumptions about the CO_2 fertilization effect. When no CO_2 effect is assumed, national hardwood yields decline. When a CO_2 fertilization effect is assumed, national hardwood yields are estimated to increase. The combined national effects on forests tend to show either little change or reductions in growing stock. The most negative scenario, a 4°C warming with no CO_2 fertilization effect, has an almost 40% decline in yields Incorporating CO_2 reduces the change by about two-thirds

Table 3-8
Percent Change in National Growing Stock of Private Forests

Scenario	Hardwoods	Softwoods	Total
2.5°C without CO_2	-2	-47	-23
2 5°C with CO_2	+25	-24	+3
4°C without CO_2	-10	-70	-37
4°C with CO_2	+16	-48	-13

Figure 3-1
Percent of Change in National Growing Stock of Private Forests



The lower warming scenario, 2.5°C without CO_2, results in an almost one-quarter decline in total yields For this amount of warming, incorporating CO_2 fertilization results in a slight increase in national yields. The results reflect the importance of the degree of warming as well as the uncertainty regarding the CO_2 fertilization effect.

3.7 CONCLUSION

The estimated changes in yields vary quite considerably across the country. The variance appears to depend on such factors as magnitude of temperature change, whether the CO_2 fertilization effect is considered, latitude, elevation, and whether hardwoods or softwoods are being examined These results should be interpreted with caution because there is significant uncertainty about the sensitivity of forests to higher temperatures and elevated CO_2 levels. Other vegetation models have shown a wider range of potential climate change impacts. Biogeography and biogeochemical models have found that biomass in the United States could significantly decrease or increase. The results for this study range from virtually no change in forest yields to a significant decrease. To be consistent with the range of results from the literature, future studies should also include scenarios with significant increases in forest yields.

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CHAPTER 4
FASOM MODEL AND ECONOMIC ANALYSIS METHODS

This chapter provides a brief description of the major features and important assumptions of the FASOM model, with special attention focused on the forest sector portion of the model This chapter also describes how the forest sector portion of the model was used to simulate the economic effects of changes in forest yields and presents the yield changes used in each of the forest effects scenarios.

4.1 MODEL OVERVIEW

This economic analysis performed in this report was conducted using the timber supply portion of FASOM (Adams et al., 1994) The U.S. timber market in FASOM is modeled as a multi-regional nonlinear programming problem. FASOM maximizes the net present value of the total economic surplus associated with timber production and consumption subject to constraints that characterize flows of products between domestic supply demand regions and which account for changes in the forest inventory due to natural processes and management.

As such, FASOM simulates two inter-related sets of processes:

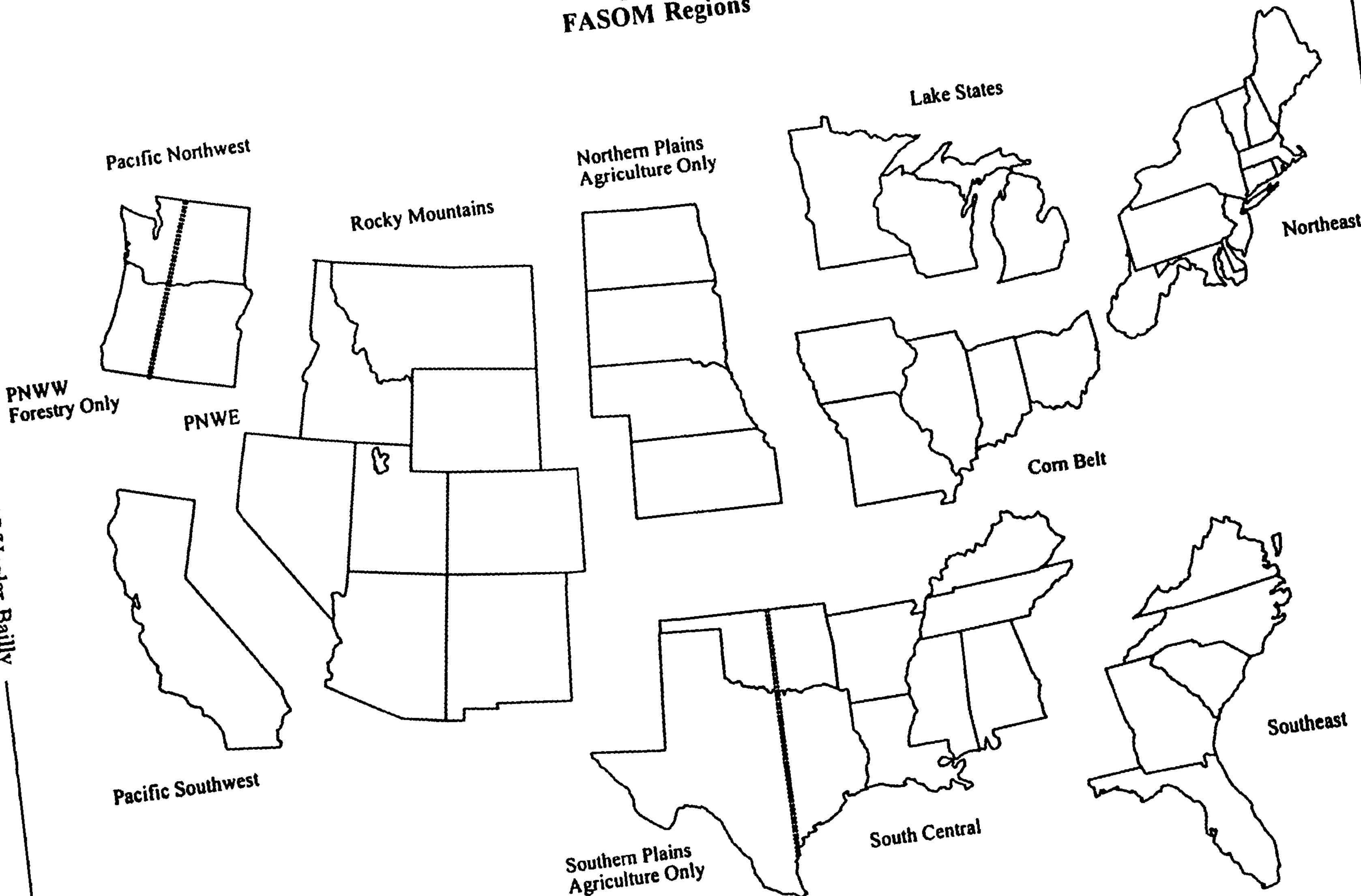
- investment in, and management of, private timberland and the production, consumption and price formation for products from that land
- the evolution of regional forest inventories on those lands, over time, as a result of regeneration, growth, and management.

These two sets of processes are linked by virtue of the fact that, because it is an economic optimization model, FASOM solves simultaneously for economically-efficient production levels and prices in the product markets in each period and for the optimal levels of investment in regeneration and management of timberland.

FASOM contains nine timber supply regions[1] and a single national demand region. These regions coincide with those used by the USDA Forest Service, with minor exceptions (see Figure 4-1). Production, consumption and price formation are simulated for two species

[1] The supply regions, in Figure 4-1, are Pacific Northwest-West and -East, Pacific Southwest, Rocky Mountains, Lake States, Corn Belt, S. Central, Northeast, and Southeast.

Figure 4-1
FASOM Regions



(softwood and hardwood) and three product types (sawtimber, pulpwood, and fuelwood), for a total of six products. The model is designed to simulate market behavior over a 100-year period, with explicit accounting on a decade by decade basis. The model incorporates linear national demand curves for forest products, by decade, for the projection period 1990-2080 Production on public timberland is treated as exogenous, which is consistent with public policy Changes in public harvest volumes influence product prices, harvest levels and timber inventories because through their effects on demand. If public harvests are increased, the total supply available for consumption also increases. As a result, stumpage prices fall, harvests on private timberland are reduced, and the inventory on private timberland increases.

The forest sector of FASOM simulates the use of existing private timberland as well as the reforestation decision on harvested land. The outflow flow of land from timberland to other land uses is exogenous in the forest sector version of the model (but endogenous in the joint sector model). Forested land is differentiated by region, the age cohort of trees,[2] ownership class, cover type, site condition, management regime, and suitability of land for agricultural uses FASOM accounts for carbon accumulation in forest ecosystems on private timberland, as well as the fate of this carbon, both at and after harvest.

A unique feature of FASOM is the way it addresses the problem of terminal conditions Trees may have rotation lengths that would carry them beyond the explicit time frame of the model. To get around this problem, terminal conditions must be specified At the time of planting, producers should anticipate a discounted flow of net returns that justify stand establishment costs This is done with "terminal conditions," which represent the projected net present value of an asset for all time periods beyond the end of the model projection Terminal conditions in FASOM are resolved using downward sloping demand curves for the terminal inventory

The model provides the following output information·

- The net present value of total surplus in U.S timber markets. This consists of
  - **Consumer surplus of product buyers.** Conceptually, this is the maximum amount of money these buyers would be willing to pay for a product, rather than do without it, less the amount they actually have to pay.
  - **Producer surplus (for both domestic and foreign producers).** Conceptually, this is the amount of money that a producer receives for a product less the minimum cost of producing that output.

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[2] Forest lands are grouped in ten 10-year age cohorts· 0 to 9 years, 10 to 19, ... , 90 + years. Harvesting is assumed to occur at the midyear of the cohort.

- **Value of the terminal inventory.** This is equal to the terminal inventory volume times its marginal value.
- **Production (harvest) levels.** Timber volumes (cu ft) by product, species, and region.
- **National product consumption and price levels.** Volumes by product, species, region, and dollars per cu ft by product and species.
- **Inventory volumes and acres.** By region, owner group, species and various indicators of productivity, land class, and management regime.

For the purposes of this study, FASOM can simulate adaptation to climate change by timber producers and consumers in a number of different ways. These include:

- **Changes in the location where trees are planted.** FASOM can shift planting away from lower growth to high growth regions.
- **Changes in management intensity.** FASOM can increase yields of a species in a given region by shifting reforested acres into a higher management intensity.
- **Changes in species.** FASOM can shift the species distribution in a region through planting.
- **Changes in rotation lengths.** FASOM can harvest existing stands earlier to avoid exposure to reduced growth at later ages and to allow replanting of stands into different species and management intensities. FASOM can also vary the rotation lengths of re-forested stands consistent with the economic optimum.
- **Changes in harvesting capacity.** FASOM can increase or reduce investment in the amount of harvesting capacity in a region.
- **Changes in timberland investment.** FASOM can simulate disinvestment in timberland, by idling the land and reducing management costs to zero.
- **Price-based resource conservation.** Physical changes in yields directly and indirectly affect current and future stumpage prices and land rents. As seen in this study, decreases in yields make it more costly for producers to supply stumpage, leading them to cut back harvesting. Consumers react to higher prices by reducing their consumption.

4.2 FOREST SECTOR DETAIL

Although FASOM can be run as a linked, two-sector model, this analysis was performed using a stand-alone version of the forest sector. The decision to use this version, as opposed to the linked model, was based on the fact that consistent climate effects scenarios for the two sectors are not readily available Generating these scenarios using climate and physical effects models in the sectors was well beyond the scope of this research. Preliminary analyses conducted using hypothetical estimates of forest and agricultural yield changes, using the linked model showed highly-dependent scenario results.

A mathematical exposition of the forest sector portion of FASOM is contained in Appendix C. The forest sector in FASOM consists of the following basic building blocks·

- demand functions for forest products
- timberland area and inventory structure and dynamics
- production technology and costs.

4.2.1 Product Demand Functions

FASOM employs a single national demand region for forest products that treats only the log market portion of the sector. The parameters for these demand functions were derived from the regional stumpage demand equations in TAMM.[3] There is, in fact, very little interregional shipment of logs in the U.S. forest sector. Competitive price relations between regions at the log and stumpage market levels are maintained through extensive trade and competition at the secondary product level (e.g., lumber, plywood, pulp) Use of a single consuming region for logs emulates the effects of competition at higher market levels without the use of an explicit representation of activity at these levels

The demand for logs derives from the manufacture of products at higher market levels In FASOM, log demands are aggregated into six categories· sawlogs, pulpwood, and fuelwood for both softwoods and hardwoods Log volumes are adjusted to exclude all but the growing stock portion [4] Thus, demand is for growing stock log volumes delivered to processing facilities Log demand curves are derived from solutions of the TAMM and NAPAP (Ince, 1994) models by summing regional derived demands for logs from manufacturing at higher market levels (sawlogs from TAMM, pulpwood from NAPAP). Fuelwood demand, which is not price sensitive in TAMM, is represented by a fixed minimum demand quantity and a fixed price National fuelwood demand volumes by decade were derived from appropriate

[3] The parameters of the demand equations in TAMM are estimated using econometric methods and are re-estimated periodically by the USDA Forest Service.

[4] Nongrowing stock volumes are included only for carbon accounting.

scenarios in the 1993 Timber Assessment Update report (Haynes et al., 1994a). Demand curves are linearized about the point of total decade quantity and average decade price. These demand functions are shifted, exogenously, for the period 1990-2040 based on macroeconomic forecasts of key driver variables that reflect the underlying secondary product demand environment (e.g., population, GNP, housing starts, expenditures on repair and maintenance costs), secondary processing technology, and secondary product capacity adjustment across regions. The forecast values for these variables are held constant after 2040. These forecasts are presented more fully in Haynes et al. (1994a).

Off-shore trade in forest products occurs at the supply region level and includes both softwood and hardwood sawlogs and pulpwood. Fuelwood is not traded. Price-sensitive, linear demand (export) or excess supply (import) relations were developed for the various regions and products as appropriate for their current trade position. For example, the Pacific Northwest-West region faces a net export demand function for softwood sawlogs but no offshore trade demand for hardwood products or other softwood log products.

4.2.2 Inventory Structure and Dynamics

Forest inventory in FASOM is divided into a number of strata, each representing a particular set of region, forest type (species), private ownership, site class, age, agricultural use suitability, and timber management intensity characteristics. Each stratum is characterized in terms of the number of timberland acres and the growing stock volume per unit area (in cubic feet per acre) it contains Inventory estimates for the existing forest inventory on private timberland are drawn from data used in the 1993 Timber Assessment Update (Haynes et al., 1994a)

The descriptors used in FASOM to characterize the structure of the inventory on private timberland in each region are as follows·

- **Owner groups.** Forest industry and other private.[5]

- **Forest type/species.** Softwood and hardwood in the current rotation and immediately preceding rotation.

- **Suitability for agricultural use.** Land is classified by type of alternative use for which it is suited (crop, pasture, or forest) and by its present use (crop, pasture, or forest). Multiple suitability classes are only used for the other private ownership, because all forest industry timberland is classified as forest only.

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[5] Unlike Powell et al. (1993), the other private inventory in FASOM does not include Native American lands. Harvests on these lands are included with the other public exogenous harvest group.

- **Site quality classes.** High, medium, and low based on the Forest Service productivity classification scheme.

- **Management intensity classes (MIC).** Three current classes for both private owner groups (high, medium, and low) are based on a qualitative characterization drawn from the management intensity classes used in the ATLAS system (Haynes et al., 1994b) A fourth class, low-low, is used to characterize any future harvested timberland that is passively managed thereafter and is not converted to agriculture.

- **Age cohorts.** Ten-year intervals, based on FIA descriptions, from the 0-9 year class (just regenerated) to the 90+ year class.

Any portion, from 0 to 100%, of a stratum can be harvested at a time. The harvested acres then flow back into a pool from which they can be allocated for several different modes of regeneration as new timber stands or shifted to agricultural use. FASOM allows for newly regenerated stands, whether on timberland or agricultural land, to be subject to several different levels of management intensity. Although management intensity shifts cannot occur after a stand has been regenerated (as can occur within ATLAS), this is not thought to be a problem, given that the model employs perfect foresight in allocating land to competing activities

FASOM simulates the growth of existing and regenerated stands by means of timber yield tables, which give the net wood volume per acre in unharvested stands for strata (e.g., owner, species) by age cohort Relative density adjustment mechanisms (Mills and Kincaid, 1992) were used to adjust tree volume stocking levels in deriving yields for existing timberland and for any timberland regenerated into the low timber management class. Timber yields for plantations on agricultural lands are based on the most recent, reconciled estimates by Moulton and Richards (1990) and Birdsey (1992) [6]

The above growth and inventory structure is used only for private timberland.[7] Two additional categories of forest land also need to be addressed. public timberlands and nontimber, forested land. Private timberland constitutes about 70% of total timberland and about 50% of the total forest land in the United States. Timberland in various public

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[6] Timber yields contained in Moulton and Richards (1990) were derived from estimates for plantations from Risbrudt and Ellefson (1983). In some cases such as for the Rocky Mountains region, these estimates have been the subject of some debate because they are fairly high relative to yields on commercial timberland. Estimates of timber yields used by Birdsey (1992), based on yield tables in ATLAS and used for the RPA, are much lower

[7] Under Forest Service definitions (adopted here), forest land is any land with at least 10% tree cover (as would be identifiable in an aerial photograph) Timberland is forest land that has the capability to grow at least 20 cubic feet per acre per year of commercial timber products.

ownerships—including federal, state, and local owners—represents about 30% of the timberland and about 20% of the forest land in the United States. Data from which to sufficiently characterize the site quality and age structure of the public inventory in the East were not available when parallel private timber data sets were assembled for the FASOM study. In the West, which contains the majority of public timberland, the USDA Forest Service is in the process of collecting the necessary data for public timberlands to augment the private inventory data. Currently, the data that do exist for public timberlands in the West are relatively sparse and difficult to organize, and the earliest date that a full reliable set may possibly be available is 1997 for use in the next RPA Assessment. Because of the current unavailability of data for key regions and the complexity and cost associated with developing an inventory of public timberlands, FASOM does not model their inventory. Harvest on these lands is taken as exogenous. This is consistent with current public policy and the expected direction of future policies that will most likely place increasing weight on the management of public lands for nonmarket benefits.

Nontimber, forested land constitutes about 30% of the forest land in the United States. This includes transition zones such as areas between forested and nonforested lands that are stocked with at least 10% of forest trees It also includes forest areas adjacent to urban and developed lands (e.g., Montgomery County, Maryland) and some piñon-juniper and chaparral areas of the West. Although this area is large, the data to characterize the site class and inventory structure of this inventory are much poorer than for public lands. Also, the fact that this land is not very productive and is widely dispersed among private owners with a variety of management objectives makes it a very difficult "target" for either regulatory or incentive-based forest management programs In light of these difficulties, harvest on this land is taken as exogenous and changes in inventory volumes or structure are not accounted for in the model.

4.2.3 Production Technology, Costs, and Capacity Adjustment

Harvest of an acre of timberland involves the simultaneous production of some mix of softwood and hardwood timber volume In FASOM, this is translated into hardwood and softwood products (sawlogs, pulpwood, and fuelwood) in proportions that are assumed to be fixed. The product mix changes over time as the stand ages and between rotations if the management regime (intensity) changes. Downward substitution (use of a log "normally" destined for a higher valued product in a "normally" lower valued application) is allowed when the price spread between pairs of products is eliminated. Sawlogs can be substituted for pulpwood and pulpwood can be substituted for fuelwood, provided that the prices of sawlogs and pulpwood, respectively, fall low enough (or the substitutes increase high enough) to become competitive substitutes for pulpwood and fuelwood, respectively. This "down grading" or interproduct substitution is technically realistic and prevents the price of the pulpwood from rising above that of sawlogs and the price of fuelwood from rising above that of pulpwood.

Strata in the inventory have specific management (planting and tending) costs that vary by inventory characteristics and type of management. These costs were derived from a variety of sources, including Moulton and Richards (1990) and those used in the 1989 RPA Timber Assessment (Alig et al., 1992).[8] Each product, in turn, has specific harvesting and hauling costs (hauling in this instance relates to the movement of logs from the woods to a regional concentration or delivery point) These costs were derived from the TAMM data base and cost projections used in the Forest Service's 1993 RPA Timber Assessment Update (Haynes et al., 1994a).

Consumption of sawlogs and pulpwood in any given time period is restricted by available processing capacity in the industries that use these inputs. FASOM solves for investment in additional capacity by allowing purchases of capacity to occur incrementally at externally specified prices. This raises the maximum capacity in both current and future periods. It also reduces producers' surplus by the cost of the new capacity acquisition. Over time, capacity declines by an externally specified depreciation rate. Capacity increments in any period are also limited by preset bounds. Since capacity may be added but not fully depreciated before the end of the projection, a standard accounting practice is employed. Specifically, the objective function is augmented by a term giving the current market value of the undepreciated stock.

4.2.4 The FASOM Tableau: Forestry Component

A tabular overview of the forestry component of FASOM *for a single region* is given in Table 4-1 The formulation in the table is consistent with the equations in Appendix C governing production of stumpage, capacity, terminal inventory, and the conservation of land It also includes the land balances shared by the forestry and agricultural sectors. The columns in this table represent variables, and the rows represent equations. The tableau has been simplified so that it can be presented on a single page and still convey the basic structure and features of the model The tableau does not portray external product trade (import/export) activities or constraints nor does it show the data computations that are made within the GAMS code The carbon sector is also omitted

4.3 APPROACH, INPUTS, AND LIMITATIONS OF ANALYSIS

This section outlines the approach used to simulate the economic effects of changes in forest productivity. It identifies the specific yield changes used in the analysis by region and species for each scenario. Finally, it addresses the impact of model limitations on the analysis

[8] See Appendix C for a more detailed description of the timber growth and yield, management costs, and assumptions about trends in nonagricultural uses of forested lands.

Table 4-1
Sample Tableau for Overall FASOM Model Emphasizing Forestry Component
(Note: The coefficients give the signs/values of the parameters in the model)

Equations		1 Harvest Existing Land				2 Reforest Now for Harvest			Reforest in +10 for Harvest in		3 Transfer Forest Land to Ag Use			3 Transfer Ag Land to Forest Use			4 Ag Land Use			5 Transport Forest Products			6 Sell Forest Products			7 Build Forest Process Capacity			9 Terminal Value		RHS
		Now	+10	+20	Never	+10	+20	Never	+20	Never	Now	+10	+20	Now	+10	+20	Now	+10	+20	Now	+10	+20	Now	+10	+20	Now	+10	+20	Timb	Cap	
Objective Fn		-	-	-	-	-	-	-	-	-	-	-	-				+/-	+/-	+/-	-	-	-	+	+	+	-	-	-	+	+	
Existing Forest		+1	+1	+1	+1																										≤ +
Forest Products Supply	Now	-																		+1											≤ +
	+10		-			-															+1										≤ +
	+20			-			-		-													+1									≤ +
Forest Products Demand	Now																			-1			+1								≤ 0
	+10																				-1			+1							≤ 0
	+20																					-1			+1						≤ 0
Forest Products Capacity	Now																						+1			-					≤ +
	+10																							+1		-	-				≤ +
	+20																								+1	-	-	-			≤ +
Reforested Lands Balance	Now	-1				+1	+1	+1			+1			-1																	≤ -
	+10		-1			-1			+1	+1		+1			-1																≤ -
	+20			-1			-1			+1			+1			-1															≤ -
Ag Lands Balance	Now										-1			+1			+1														≤ +
	+10										-1	-1		+1	+1			+1													≤ +
	+20										-1	-1	-1	+1	+1	+1			+1												≤ +
Max Land Transfer	to Ag										+1	+1	+1																		≤ +
	to For													+1	+1	+1															≤ +
Terminal Balance	Timber				-1			-1		-1																			+1		≤ 0
	Capacity																									-	-	-		+1	≤ 0

4.3.1 Approach

In Chapters 2 and 3 we developed yield changes for commercially important hardwood and softwood forest types in the FASOM regions. These scenarios were based on information from a wide number of published studies and the authors' judgment about the effects of changes in climate and CO_2 fertilization on forest ecosystems. Four scenarios were developed, based both on the extent of climate change (2.5°C and 4°C) and a sensitivity range (low and high)· 2 5 low, 2.5 high, 4.0 low and 4.5 high The sensitivity range was intended to reflect uncertainty associated with the magnitude of the warming and the fertilization effects of CO_2 from the published literature and variation in the literature.

There are at least two different approaches that one can take to simulate the impacts of changes in climate and elevated CO_2 concentrations on forests. The first is to try to simulate the effects of changes in climate and CO_2 on forests slowly, as they occur over time. For convenience, and to be consistent with the science, we can call this a "transient" approach. The second is to move forward in time and evaluate the economic impacts of changes in forest productivity once the changes in forest productivity have reached a significant level This is the so-called "equilibrium" approach, so named because it assumes that the forest ecosystem has fully adjusted to a fixed change in climate and CO_2, usually associated with a doubling

FASOM is capable of employing either approach. yields can either be adjusted slowly over time in the model or all at once However, there are a number of other complications that arise in selecting between these two approaches One that is very important is that changes in forest productivity, as simulated by all the different types of models we looked at, take a very long time. Once a CO_2 doubling is achieved, which may take 35 to 75 or more years to reach, it takes on the order of centuries for plant communities to fully adjust to these changes. This feature of CO_2 buildup, climate change, and community ecosystem response creates several interesting problems for economic modelers

First, some economic models, and FASOM is one of these, simply cannot be run over these long time spans because of computational limitations. In that case, a transient analysis that is truncated in time may give a distorted picture of the economic implications of climate change if the changes in yields that are outside of the model's time domain are large in magnitude

A second problem, which is an issue for both the transient and equilibrium approaches, is related to the need to forecast future changes in economic variables that are exogenous to the economic model In FASOM, these variables either determine the future demand for stumpage products, for example, population, housing starts, and Gross National Product, or else determine the level of technology used to harvest trees and then convert stumpage into wood products Not only are these variables very difficult to forecast 20 to 100 or more years in the future, in many cases they are not even exogenous, but can be expected to change as society adapts to climate change over time.

Any errors or biases that are in the forecasts one makes about these variables will propagate through an economic model, and unless the model is classically linear, will result in even larger errors and possibly biases in the model forecasts of endogenous variables of interests. Given the long time periods with which one must work in climate change analyses and the widely acknowledged problems associated with forecasting economic variables that far into the future, the errors and biases added by these forecasts could arguably swamp the errors and biases inherent in climate and forest ecosystem models. As an example, one can probably eliminate much of the impact of climate change on many natural resource sectors using straight line projections of technological change over the last 100 years. However, it is far from clear that historical rates of technological change in yields and processing technology can be maintained far into the future.

As noted above, the problem of forecasung exogenous economic variables is shared by both the transient and equilibrium approaches Furthermore, a true equilibrium approach would also involve having to forecast the forest inventory from the present well into the future once a doubling of CO_2 was achieved, and then simulating the adjustment of that inventory to the equilibrium adjustments of the various plant communities, a formidable undertaking.

Given all of the above problems, we decided to take an approach first suggested in the climate change context by Callaway et al. (1982) In his study of methods for estimating the economic effects of climate change on the agricultural sector, he suggested that an alternative approach would be to impose an instantaneous equilibrium change in productivity on a renewable resource sector *under current (i.e., base case) economic conditions*, and then trace the economic effects of these changes in productivity over time on the sector using the same values for exogenous economic variables as in the base case.

This approach has both limitations and strengths The major limitation is that this approach overstates the value of damages (or benefits) in a way that is indirectly related to the rate of change in physical impacts Another drawback of this approach is that it does not take into account advancements in technology that might offset the negative impacts, or enhance the positive impacts, of climate change However, economists have not been very successful in projecting technological change over long periods of time, and instead have been forced to make educated, "exogenous" guesses about what future technological change might look like The major benefit of this approach is that it holds all inputs to the analysis constant at base case values and focuses entirely on the effects of changes in physical productivity on the relevant renewable resource sector. These effects are not confounded by the errors in one's assumptions about future economic conditions.

This approach provides a relevant policy context for evaluating the economic effects of climate change on renewable natural resource sectors. Estimates of annualized changes in consumer and producer surplus can be viewed as the long run welfare impacts of an equilibrium change in climate The impacts on production levels, product prices and inventories can, in turn, be can also be interpreted as long run adjustments to an equilibrium climate change. However, because endogenous technological change is not (and perhaps can never be) factored into the analysis, adverse economic impacts will be somewhat overstated. This is because the application of specific technological advancements to mitigate climate change would not be adopted in the future unless they made society better off.

4.3.2 Inputs: Yield Changes by Region and Species

The yield changes we developed in Chapters 2 and 3 for commercially important hardwood and softwood forest types in the FASOM regions are shown in Table 4-2. They were translated into scalar factors, expressed as 1 plus the fractional change in yields for all species in all regions There are two sets of yield tables in FASOM: one for the existing inventory and one for the inventory that replaces it. These yield tables relate the amount of growing stock timber volume on an acre of timberland to the age of the cohort on those acres through yield coefficients. For each scenario, all of the yield coefficients for a given region and species, except those in the base year (1990), were multiplied by the scalar yield change coefficient associated with that region and species.

In summary, this approach is consistent with the assumption that the productivity of timberland in the United States moves from its state in 1990 to a state dominated by climate change by 2000 and remains constant thereafter. This sudden change in yields, while it is not realistic, not only allows one to define a worst case transition, but also provides a long period of adjustment to the lower yields. An alternative is to gradually alter the yields in the model over time, and look at the economic adjustment to these more gradual shifts In this case, economic adjustments will also take place more gradually and welfare losses will be smaller. The problems with this transient approach are that, in most cases, we do not have good information about transient yield changes, and it is difficult to run FASOM for more than 100-120 years, making it difficult to look at the transition in a realistic time frame

There are at least three points that need to be made about these yield changes that have important ramifications for the economic analysis that follows in the next chapter. Specifically, these points are

- The decreases in softwood yields in the South (Southeast and South Central regions) should be regarded as especially severe in all cases This is not only because the South produces more softwood products than any other region, but also because rotation lengths are relatively short compared to other regions, so that under normal conditions "gaps" in the inventory can be filled more quickly by reforestation in the South than elsewhere.

- The 2.5 scenario without CO_2 has softwood yield decreases that are more severe in the South than in the 4.0 sensitivity scenario, with CO_2.

Table 4-2
Percent Changes in Yields by Region and Species for Four Climate Scenarios

Region	Scenarios			
	2.5 with CO_2 Change	2.5 without CO_2 Change	4.0 with CO_2 Change	4.0 without CO_2 Change
Softwood				
Pacific Northwest-West	20	-10	-32	-53
Pacific Northwest-East	20	-10	-32	-53
Northeast	-40	-55	-68	-78
Lakes States	-51	-64	-66	-76
Corn Belt	-51	-64	-66	-76
Southeast	-56	-83	-76	-100
South Central	-75	-87	-76	-100
Rocky Mountains	70	30	79	33
Pacific Southwest	20	-10	-32	-53
Hardwood				
Pacific Northwest-West	0	0	0	0
Pacific Northwest-East	0	0	0	0
Northeast	46	14	71	36
Lakes States	39	11	53	21
Corn Belt	38	11	53	21
Southeast	20	-10	-8	-30
South Central	0	-20	-44	-60
Rocky Mountains	0	0	0	0
Pacific Southwest	0	0	0	0

- In all scenarios, hardwood yields do not decrease, or else they increase, in at least seven of the nine regions. This can potentially create opportunities for substituting hardwoods for softwoods. As it turns out, this is a complicated issue that is explored at the end of Chapter 6.

4.3.3 Limitations of the Economic Analysis

No economic model or analytical approach is perfect. Both will suffer from limitations, and it is always important to identify these limitations and point out how they might affect the economic analysis. We have identified three important limitations of the economic analysis in this report. Although they have already been discussed in connection with the analysis, it is helpful to present them together.

- **Agricultural and forest sectors are not linked.** The linked, two-sector model was not used in this analysis because of the lack of consistent physical effects scenarios across the two sectors in existing studies. Linkages between the two sectors are important when climate change differentially affects the opportunity cost of land across sectors, causing land to move to better opportunities. There is no current scientific basis for determining whether this will be the case. We simulated hypothetical yield changes in both sectors using the linked model However, the results did not show large land shifts between the two sectors relative to the base case.

- **Climate impacts on forests in other regions were not included in the analysis.** This type of analysis was not done because of the lack of information about effects of climate change on the export demand and import supply curves in the FASOM model Climate change will influence forest productivity in other regions of the world These changes have the potential to indirectly shift the comparative that various regions have in the production of stumpage and wood products made from stumpage relative to other goods In that case, changes in trade patterns in wood products would be accompanied by changes in stumpage and product prices, harvest levels, and inventory stocks, and the welfare of U.S consumers and producers. If forest productivity increases in other countries relative to the United States, then America could potentially import more logs and primary products and, thus, offset some of the economic losses that would occur otherwise. This possibility is particularly relevant when it comes to Canada.

- **The model does not include specific MICs or technological advances to adapt to the effects of climate change.** While the model has a wide range of management intensity classes to deal with current conditions, none were specifically tailored to the direct effects of climate change. This limitation was not thought to be serious in light of the management opportunities already in the model

4.4 REFERENCES

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CHAPTER 5
RESULTS OF THE ECONOMIC ANALYSIS

In this chapter we present the major results for the base case and the climate change scenarios. We focus on the time paths of effects of the simulated yield changes on

- the magnitude and composition of consumer and producer surpluses
- the magnitude and regional distribution of producer surpluses
- aggregate product prices
- aggregate production (i.e., harvest) levels
- inventory levels

5.1 THE BASE CASE SUMMARIZED

The results for the base case are presented and explained in detail in Appendix F of Adams et al. (1994) Here we provide a summary of the trends in the base case that we believe are directly relevant to the climate change scenarios. These trends are the following:

- **Demand shifts.** Product demands in FASOM increase (i.e., the demand functions shift out) from 1990 to 2030 in response to exogenous forecasts for key driver variables such as GNP and housing starts. Demand function parameters are held fixed after 2030. No explicit assumptions about technological change are assumed in these forecasts.

- **Supply shifts.** As indicated previously, no specific technological advancements are included other than those that are reflected in current management practices and genetic stock.

- **Product prices.** For the most part, aggregate product prices did not change much over time, rising from about $1 35/cu ft in 1990 to $1.43/cu ft in 2060.

- **Production levels.** Aggregate production (i.e., harvest) levels for hardwoods and softwoods (combined) increased over the period 1990-2030 from about 170 billion cu ft to 230 billion cu ft and then leveled off as demands stabilized in 2030.

- **Inventory volumes.** Projected inventory volumes for hardwoods and softwoods (combined) rose from about 440 billion cu ft in 1990 to 490 billion cu ft in 2030 and then dropped back to 475 billion cu ft by 2060

- **Inventory structure.** The major structural change in the inventory during this period was an increase in softwood inventory volumes and a decrease in hardwood inventory volumes, due to conversion of hardwood to softwood acres and downgrading

- **Management intensity.** The combined features of increased production and relatively stable product prices can be explained in part by the conversion of acreage from hardwoods to softwoods and the redistribution of the inventory from medium and low management intensities into the high and passive management (low-low) management intensity categories, respectively.

5.2 CLIMATE CHANGE SCENARIOS

In this chapter, we present the results of the climate change scenarios grouped by topic (i.e., welfare, prices, production, and inventory levels) rather than by scenario to make it easier for the reader to compare the results across scenarios.

5.2.1 Welfare

Table 5-1 summarizes the effects of the yield changes on the magnitude and composition of welfare components in the forest sector. Consumer surplus includes the surplus of domestic buyers of hardwood and softwood stumpage, primarily firms. Producer surplus is the surplus of private timberland owners in the United States. Foreign trade surplus is the surplus of offshore buyers of U.S. stumpage. The terminal inventory surplus is measured by the market sale value of the inventory at the end of the period (2080). The public cut surplus is the producer surplus associated with the exogenous harvest of public lands. In theory, these rents could be captured by the federal government; however, in practice, a substantial portion of these rents accrue to private owners who contract with the government to harvest the timber on public lands.

Decreases in the annualized value of total surplus range from about 4% in the 2.5 with CO_2 scenario to about 19% in the 4 0 without CO_2 scenario. This translates into fairly substantial annualized[1] losses: $2.5 billion/yr and $12 billion/yr, respectively. These losses are near the lower end of the range of losses estimated by Callaway et al. (1986)—$3.4 to $5.0 billion/yr —and more recently by Cline (1992)—$3.3 billion/yr. In general, the surplus losses, as well as the changes in the individual surplus components, increase with both the magnitude of the temperature change and the CO_2 fertilization effect The one possible exception to this is the 2.5 without CO_2 scenario in which the decrease in total welfare and the changes in the individual welfare components are higher in magnitude (in both directions) than in the 4.0

[1] The annualization factor is $(r) \times [1 - (1 + r)^{-n}]^{-1} = 0.0412$ for $n = 90$ and $r = 0\ 04$.

Table 5-1
Annualized Values[1] of Welfare Components for the Base Case and Percent Changes from the Base Case for Four Climate Change Scenarios

Welfare Component	Base ($ Millions)	2.5 with CO_2	2.5 without CO_2	4.0 with CO_2	4.0 without CO_2
Consumer Surplus	56,748	-17.42%	-33.47%	-28.34%	-42 09%
Producer Surplus	3,871	145.67%	237.40%	194.50%	207.69%
Foreign Trade Surplus	324	-21.79%	-39.34%	-35.62%	-50.10%
Terminal Inventory	1,805	-6.13%	-13.89%	-11.33%	-33.13%
Public Cut	2,023	79.56%	159.84%	137.05%	222.87%
Total Surplus	**64,771**	**-4.35%**	**-10.73%**	**-9.42%**	**-18.68%**

[1] Annualized values calculated for 1990-2080 using a discount rate of 4%

with CO_2 scenario As suggested previously, this is because the softwood yield decreases in the South are higher in the 2 5 without CO_2 scenario than in the 4.0 with CO_2 scenario.

The magnitude of the gains and losses in the individual welfare components also varies considerably over the four scenarios. For example, consumer surplus is reduced by 17 42% ($9 9 billion/yr) in the 2.5 with CO_2 scenario and by 42.09% ($24 billion/yr) in the 4 0 without CO_2 scenario. Producer surplus, on the other hand, increases in all scenarios. The welfare gains for this group range from 145.67% ($5.6 billion/yr) in the 2.5 with CO_2 scenario to 207 69% ($8 billion/yr) in the 4 0 without CO_2 scenario. The difference in the direction of the changes in consumer and producer surpluses is explained by the extremely inelastic nature of the product demands in U.S stumpage markets. Reductions in forest yields shift the supply curves for stumpage to the left in each period, causing prices to increase along these inelastic demand curves Consumer surplus decreases (and producer surplus increases) because landowners can pass most of the price increases directly on to buyers of stumpage. This is a classic result, observed in previous studies of the forest sector's response to reduced yields by Callaway et al (1986) and Callaway (1991).

Foreign buyers of stumpage experience larger welfare losses as yields decrease for the same reasons as domestic stumpage buyers: higher prices along inelastic demand functions The value of the terminal inventory falls as the severity of the yield reductions increase. This is because, even though the "prices" associated with units of the terminal inventory increase as the inventory shrinks, the quantity demanded along the terminal inventory function declines as prices increase. Thus, the product of the two must decrease. In FASOM, the public cut is exogenous since this, historically, has been a public policy decision. The same exogenous forecast for the public cut was used in all cases. This forecast sees the public cut dropping to 2.06 billion cu ft in 2000, rising slowly to 2.2 billion cu ft by 2030, and constant thereafter. (This is consistent with current USDA Forest Service policies to eliminate clear cutting and protect endangered species.)

Estimates of the *future (i.e., undiscounted) value* of the regional producer surpluses are displayed in Figures 5-1 to 5-3 for 2000, 2030, and 2060[2] for the base case and the four climate change scenarios. The North (Figure 5-1) consists of the Northeast, Great Lakes States, and Corn Belt. The South (Figure 5-2) includes the Southeast and the South Central, and the West (Figure 5-3) includes all of the Pacific Northwest, the Rocky Mountains, and the Pacific Southwest Several important results emerge from these figures Generally speaking, the aggregate results seen in Table 5-1 are mirrored in the regional figures: reduced yields tend to increase producer surplus. This is particularly true in the North where the future values of producer surplus increase consistently, over time, with the severity of the yield reductions. This also true, but to a lesser extent, in the West, where the increases in producer surplus tend to stabilize after 2030. The pattern is most uneven in the South, where the producer surpluses initially fall relative to the base case in the two with CO_2 scenarios and increase in the two without CO_2 scenarios. Also, the yield losses in the 4.0 without CO_2 scenario are so extreme that, unlike other regions, the producer surplus gains are smaller than in all the other climate change scenarios for 2030 and 2060.

Finally, the severity of the yield losses also affects the ordering of the producer surpluses across regions. In the base case, the South has the highest producer surplus, followed in order by the West and the North. However, this order is reversed somewhat in 2000, with the West taking over as the leader. The sudden decline of the South in this regard is explained not only by the very large yield decreases in the region, but also by the fact that the rotations are shorter and that it is the major producing region of stumpage in 1990. Thus, it is initially affected more adversely than all the other regions. In later years, the South also falls behind the West in terms of the magnitude of producer surplus in the 2 5 without CO_2 (in 2030) and 4 0 (in 2030 and 2040) without CO_2 sensitivity cases. When yield losses are very high, the direct effect of reduced output on revenues outweighs the indirect effects of inelastic demands on prices. Therefore, profits fall

[2] Although the projection period is 1990-2080, information for FASOM is truncated at 2060 in all figures in case terminal conditions influence the 2070 and 2080 projections.

Figure 5-1
Projected Producer Surplus for the North
Base Case and 4 Climate Change Scenarios
2000, 2030, and 2060

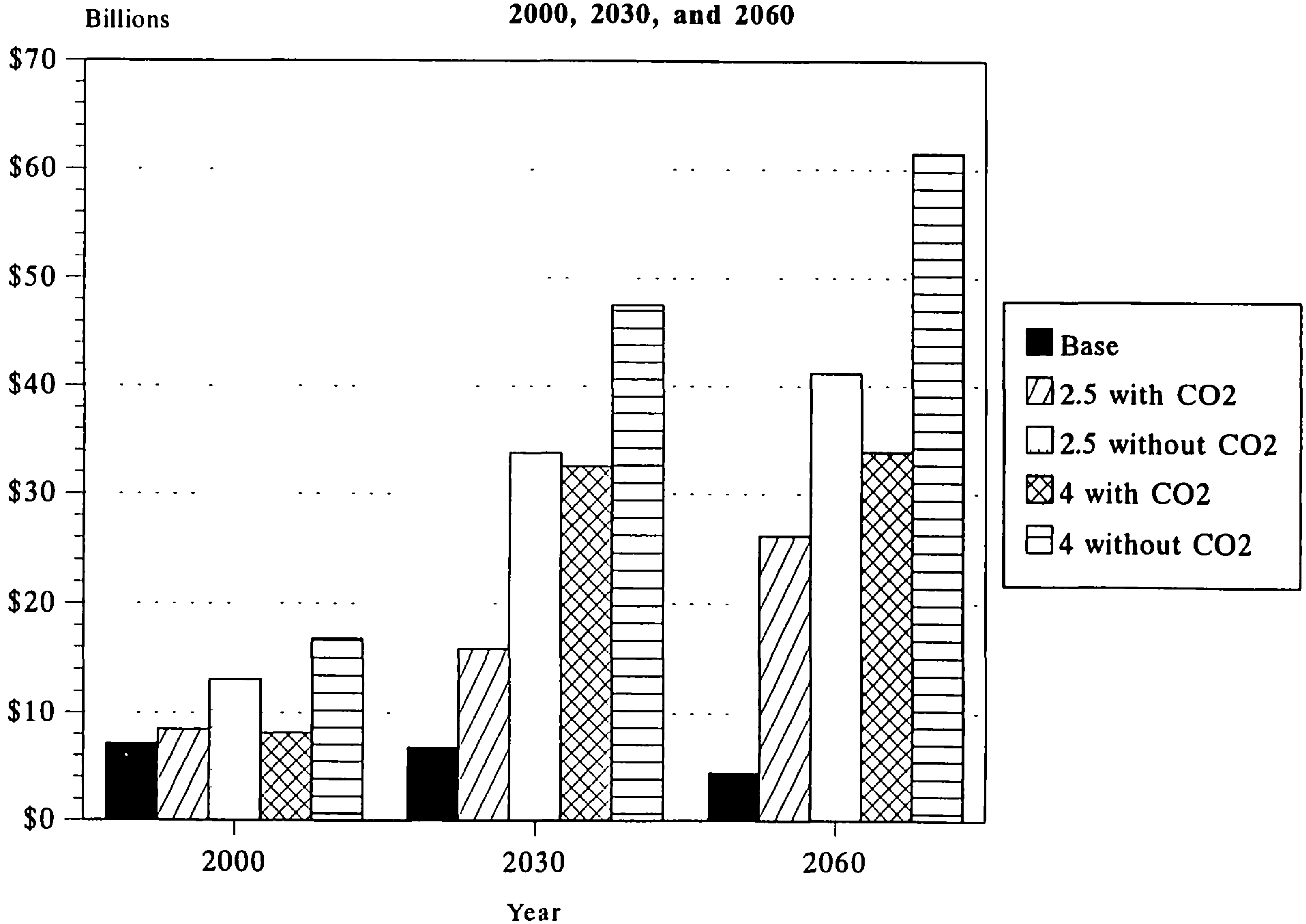


Figure 5-2
Projected Producer Surplus for the South
Base Case and 4 Climate Change Scenarios
2000, 2030, and 2060

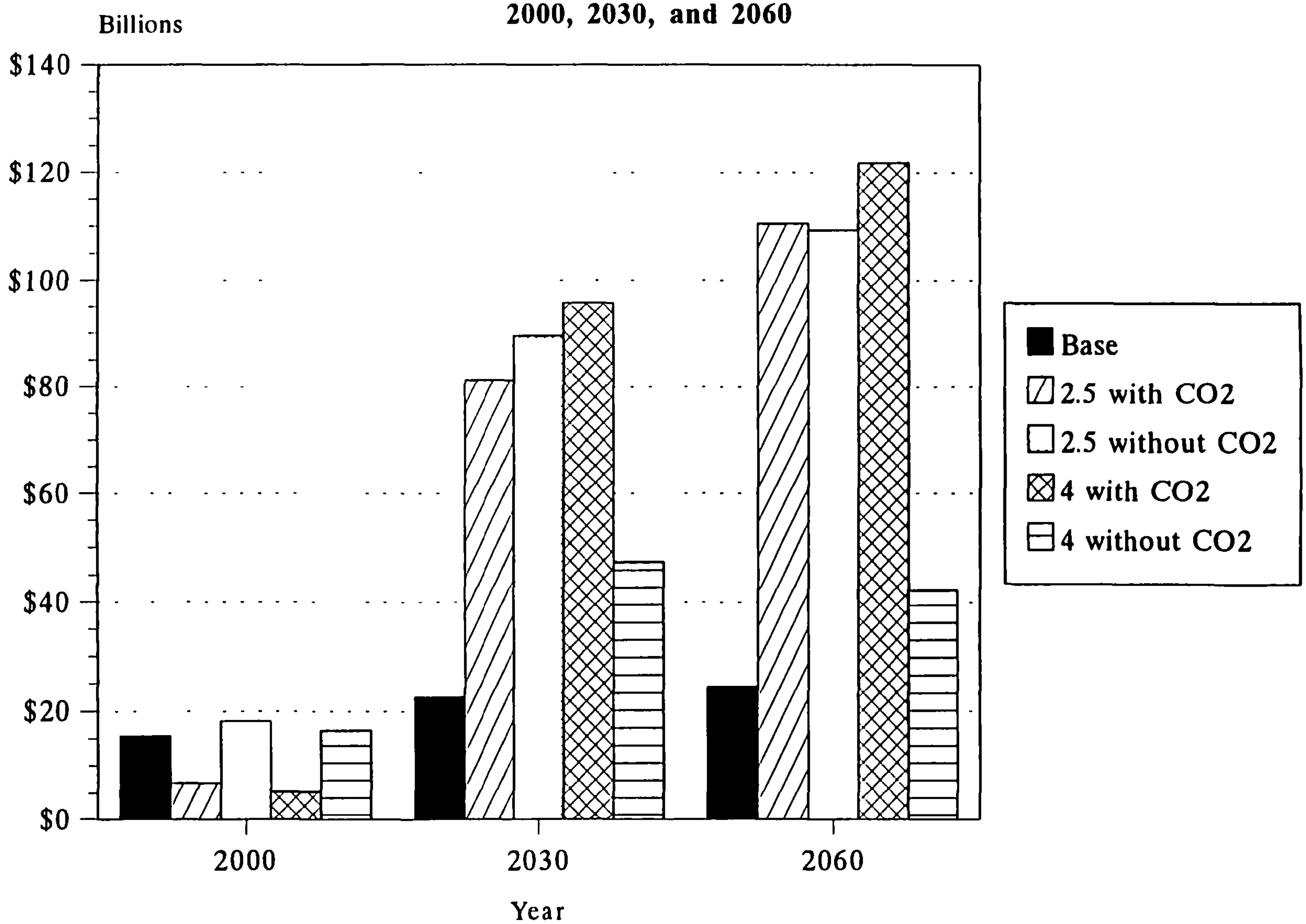
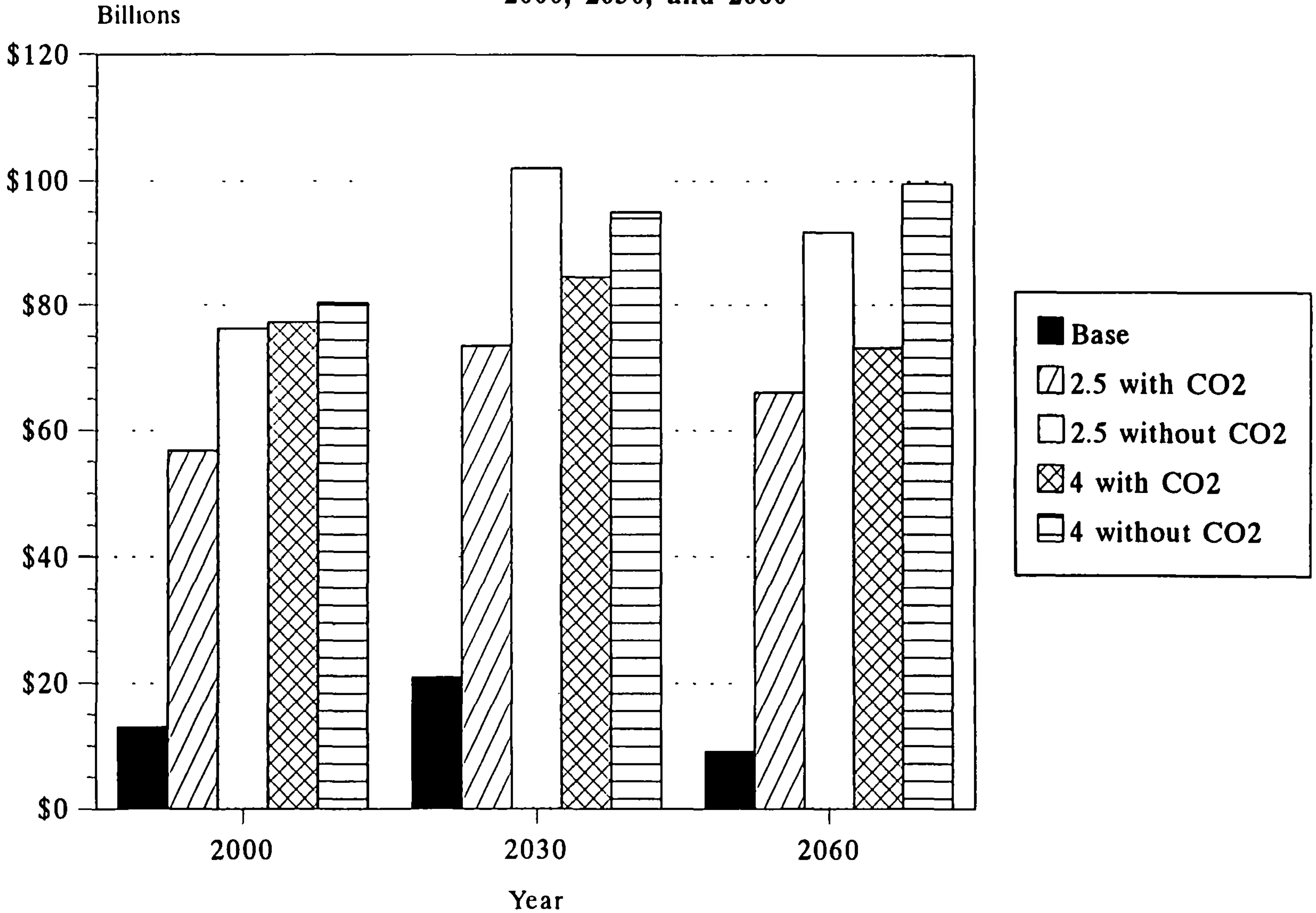


Figure 5-3
Projected Producer Surplus for the West
Base Case and 4 Climate Change Scenarios
2000, 2030, and 2060



5.2.2 Product Prices

FASOM projections of aggregate product price indices, as measured by the Tornquist-Theil price index, are shown for softwood in Figure 5-4, for hardwood in Figure 5-5, and for the two species combined in Figure 5-6. The index in all scenarios is based (i.e., it is equal to unity) at 1990 price levels for softwood and hardwood products (pulp, sawtimber, and fuelwood) in the base case.[3] As can be seen in Figure 5-4, softwood prices increase dramatically relative to the base case in all of the scenarios. These dramatic price increases are due to reductions in timber supplies in each period as a result of the yield reductions in the in the base case. climate change scenarios. The average annual price increases for 1990 to 2060 range from about 1%/yr for the 2.5 with CO_2 scenario to about 1.8%/yr for the 4.0 without CO_2 scenario. This is approximately consistent with a doubling and quadrupling of softwood product prices, relative to base case prices in 1990. And it is these high prices that explain the substantial losses in consumer surplus and increases in producer surplus, shown earlier in Table 5-1

Predictably, the direction of the changes in hardwood prices in Figure 5-5 is largely (but not entirely) negative, both in absolute terms and relative to the base case. The pattern of price changes in all scenarios is the same: falling from 1990 to 2030 and then rising from 2030 to 2060 Hardwood prices in the two with CO_2 scenarios are consistently lower than in the base case. Hardwood prices in the two without CO_2 scenarios are lower than in the base case until 2040 to 2060, when they rise The fact that hardwood prices stay fairly low is because hardwood yields in all scenarios increase in the North, are constant in the West, and fall only in the South. The upward trend in hardwood prices from 2030 onward reflects a projected increase in the management intensity of hardwoods, as producers try to make up for reduced softwood productivity. The large disparity between the growth in softwood and hardwood price indices indicates that FASOM finds it unprofitable to convert hardwood growing stock acreage to softwoods, thereby easing the price pressure on softwood products. We will further explore this issue at the end of this chapter

Finally, the combined price indices in Figure 5-6 reflect the importance of softwood production. The price indices for all the climate change scenarios are slightly lower in each year than the corresponding softwood price indices

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[3] The Tornquist-Theil price index (P_t) is calculated from i = 1, . . ., n goods for period t = 0, . . ., T from the following: $\ln(P_t) = \sum_i 0.5(s_{it} + s_{i0}) \ln(P_{it}/P_{i0})$, where $s_{i,t}$ = the expenditure share of product i in period t and P_{it} = the price of product i in period t. In our calculations, all indices are evaluated using 1990 base case prices and shares for P_{i0} and s_{i0} Thus the base period index = 1.00 in 1990.

Figure 5-4
Projected Tornquist-Theil Softwood Price Index
for Softwood Forest Products Prices
Base Case and 4 Climate Change Scenarios, 1990 to 2060

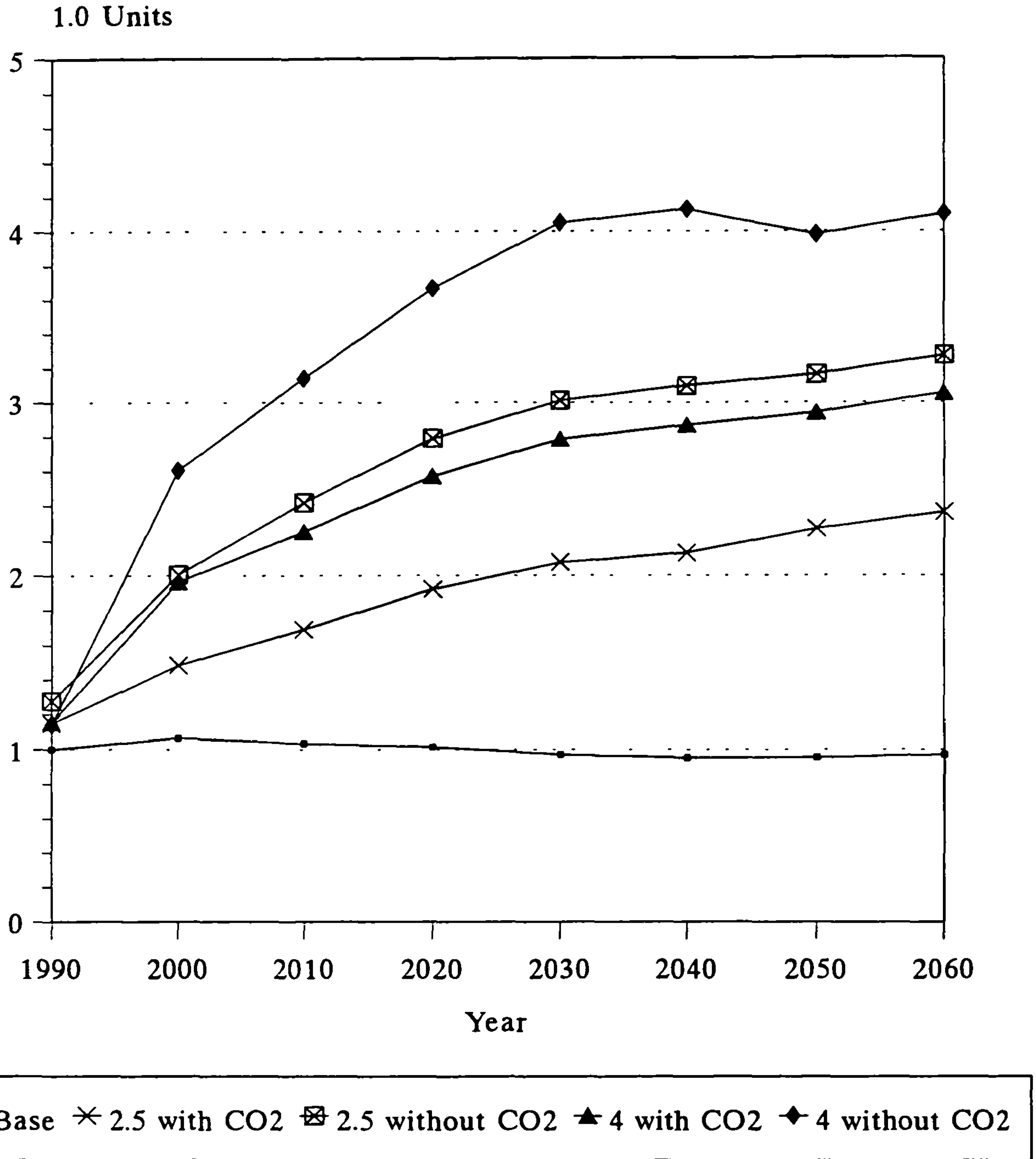


Figure 5-5
Projected Tornquist-Theil Hardwood Price Index
for Hardwood Forest Products Prices
Base Case and 4 Climate Change Scenarios, 1990 to 2060

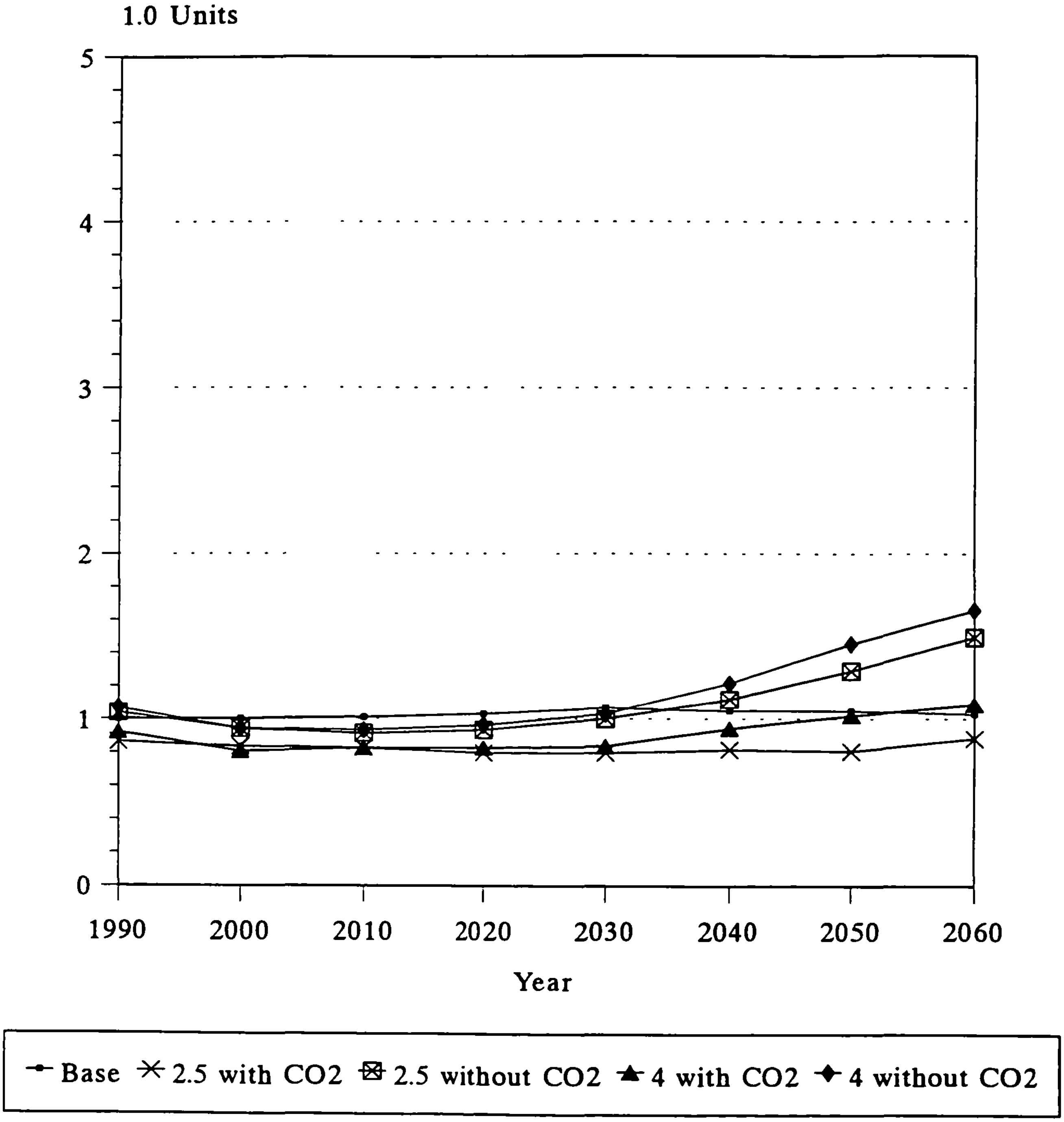
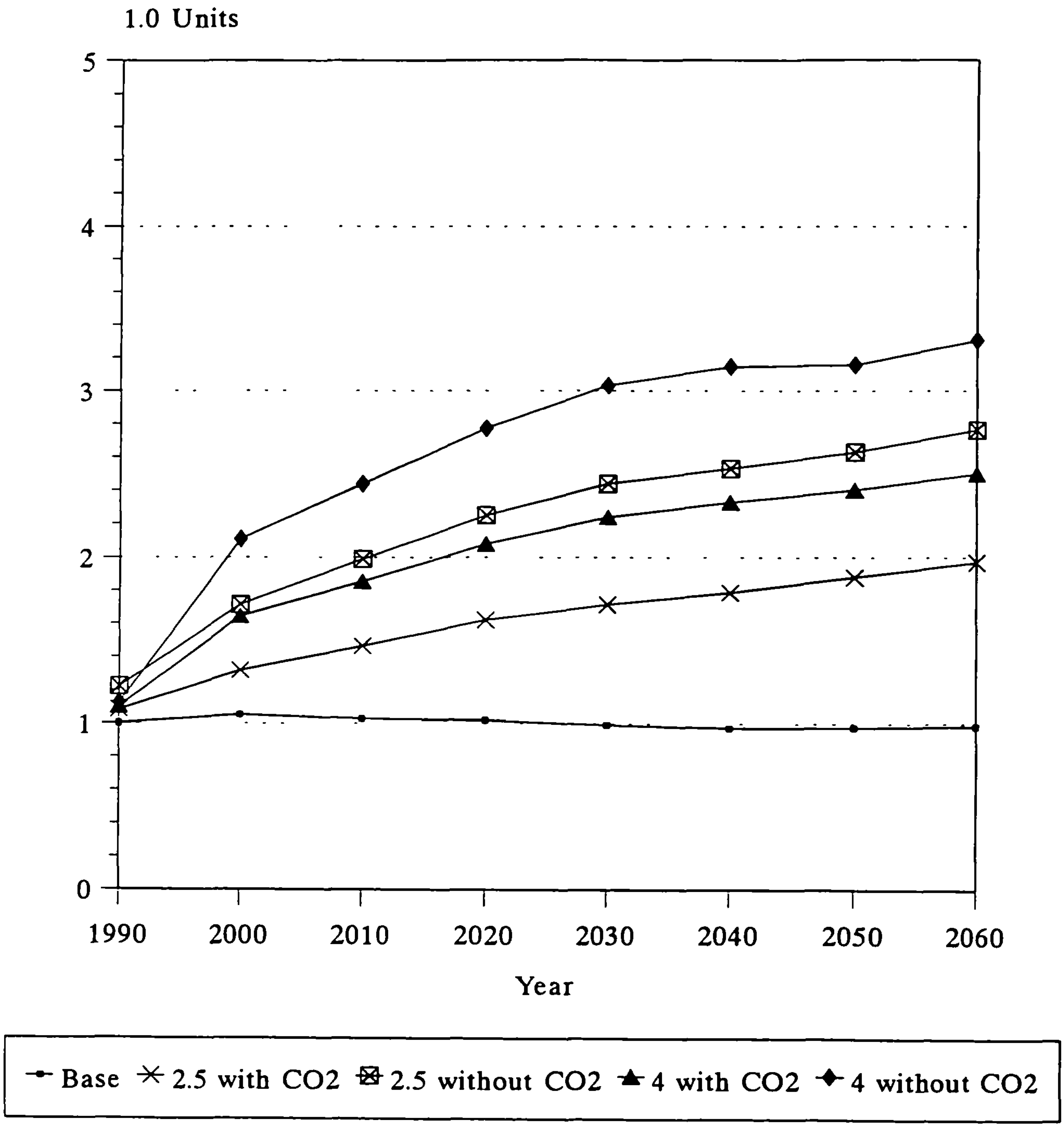


Figure 5-6
Projected Tornquist-Theil Price Index
for Forest Products Prices
Base Case and 4 Climate Change Scenarios, 1990 to 2060



5.2.3 Production (Harvests)

FASOM projections of the production of pulpwood, sawtimber, and fuelwood (combined) are shown for softwoods in Figure 5-7, for hardwoods in Figure 5-8, and for the two species combined in Figure 5-9. In the base case, softwood production is initially flat at about 110 billion cu ft/yr because of limited supplies in the South and Pacific Northwest in the merchantable age classes. Thereafter, production increases, as demands shift out, until 2030, when product demands stabilize and a more or less "steady state" level of softwood production is achieved at about 150 billion cu ft/yr. The impact of the yield reductions on production follows a common pattern in almost all of the scenarios. Production in all scenarios drops sharply from 1990 to 2000 because of the shortage of timber in the merchantable age classes. After that, production increases slightly up until 2030 in all of the scenarios, except for the 4.0 without CO_2 scenario in which it is more or less constant from 2000-2010 to 2060. For the remaining scenarios, production decreases slightly after 2030. Overall, production levels in 2030 are about 25% (2.5 with CO_2) to 65% (4 0 without CO_2) below those in the base case, depending on the severity of the yield reduction. This spread is only slightly larger by 2060.

Hardwood production (Figure 5-8) in the base case follows the same general pattern as softwoods, although the increase in production through 1990 to 2030 is more or less constant in response to increasing demands for hardwood products. After 2030, hardwood product demand curves, like their softwood counterparts, cease to shift out in FASOM, and production stabilizes at about 80 billion cu ft/year. Hardwood production in the four climate change scenarios follows this same pattern However, hardwood production in all of the climate change scenarios increases more rapidly than in the base case, such that in 2030 hardwood production levels in all these scenarios are slightly higher than in the base case This is possible due to substantial increases in hardwood inventory acreage in regions where yields are increased, i.e , in the North (and in the Southeast in the 2.5 with CO_2 scenario) After 2030, production dips back down in three of the four climate change scenarios However, in the 2 5 with CO_2 scenario, increased hardwood supplies in the North and Southeast make it possible to sustain production levels somewhat above those in the base case (and at lower prices), even after 2030.

Combined hardwood and softwood production levels (Figure 5-9), like the aggregate price indices, reflect the importance of softwood in total production. Combined production levels in the climate change scenarios in 2030 range from about 15% (2.5 with CO_2) to 40% (4.0 without CO_2) below base case values, depending on the severity of the yield losses. Decreases in production by 2060 are somewhat larger.

Figure 5-7
Projected Softwood Production
Base Case and 4 Climate Change Scenarios
1990 to 2060

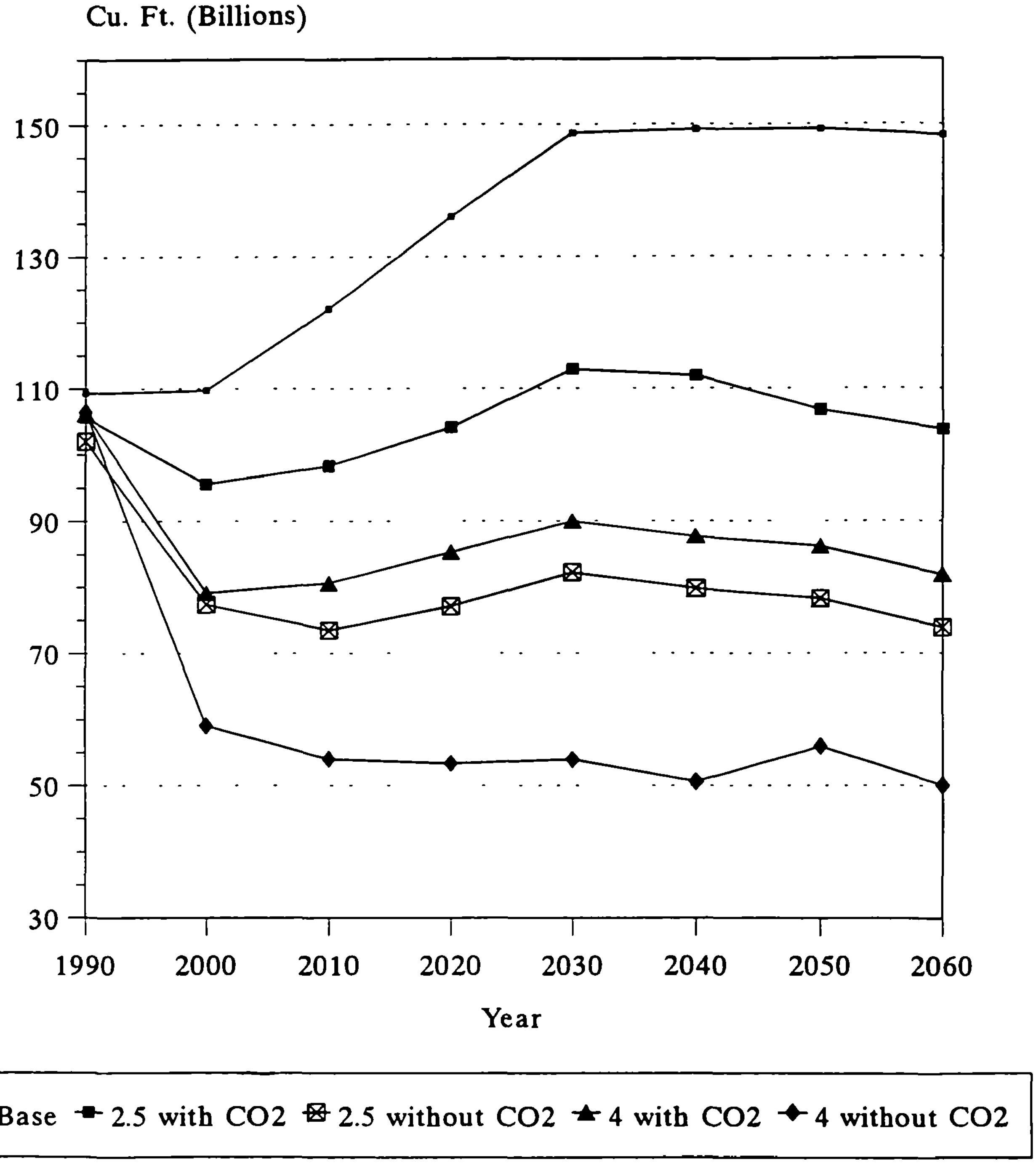


Figure 5-8
Projected Hardwood Production
Base Case and 4 Climate Change Scenarios
1990 to 2060

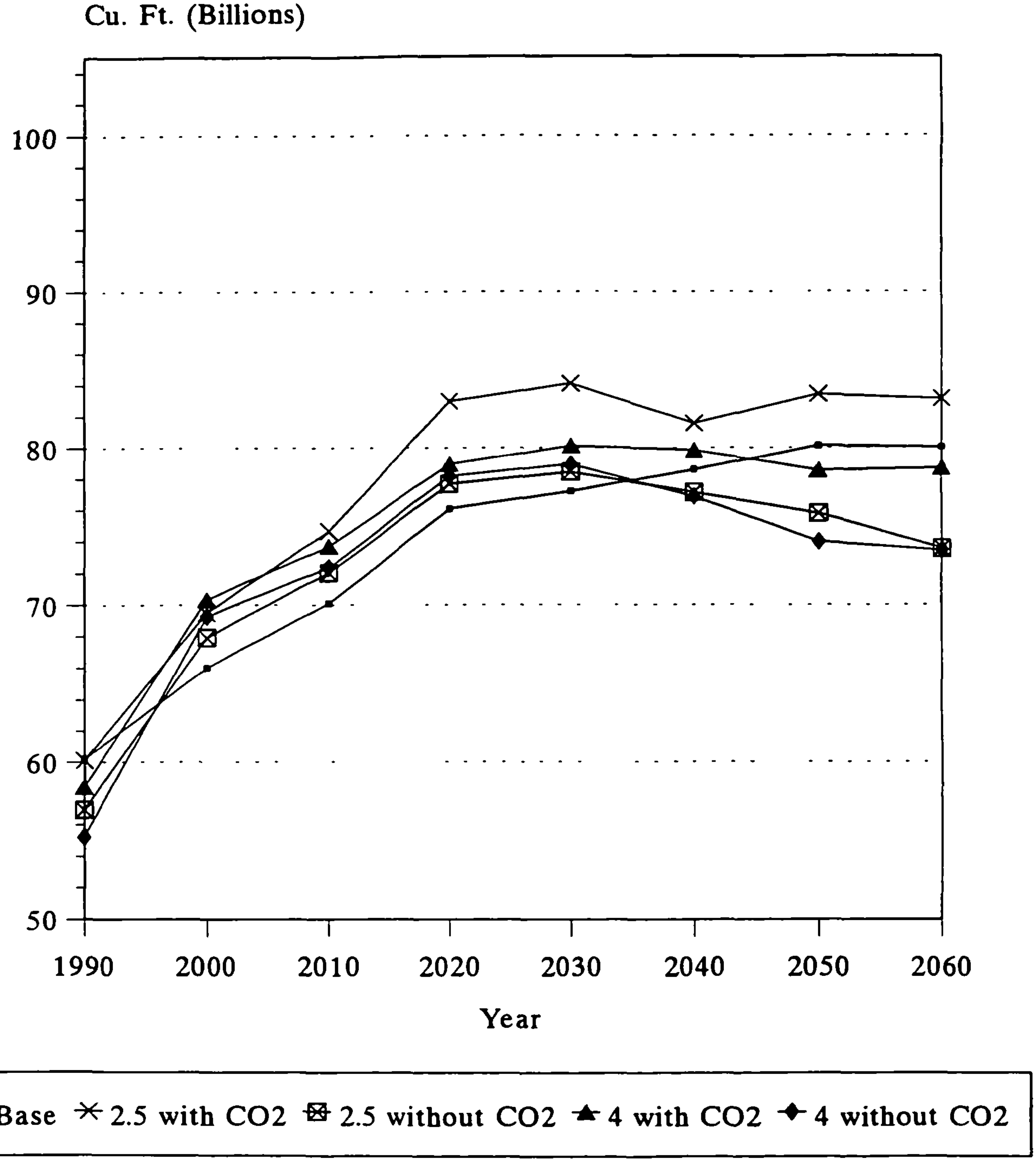
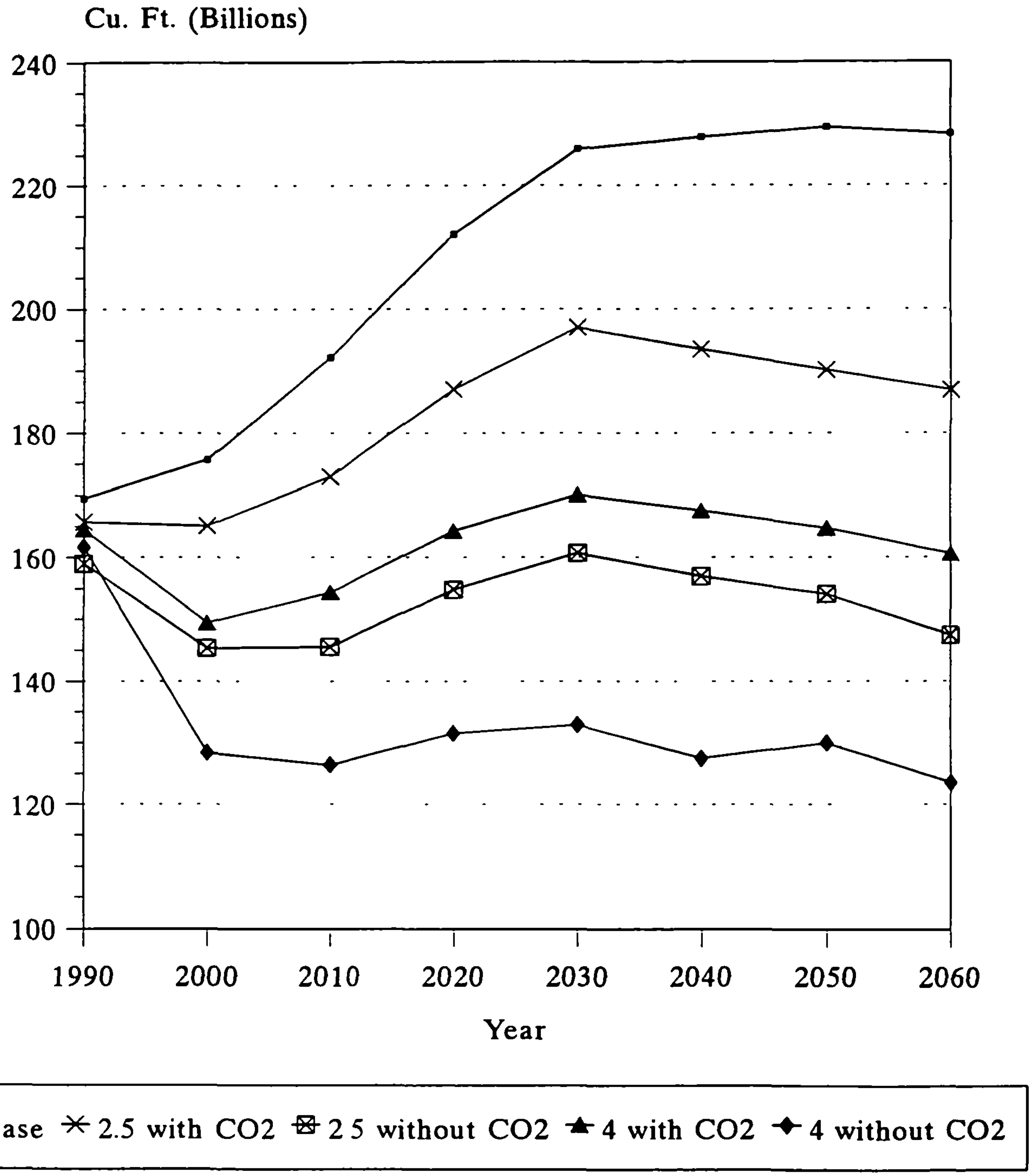


Figure 5-9
Projected Total Production
Base Case and 4 Climate Change Scenarios
1990 to 2060



5.2.4 Inventory Levels

FASOM projections of inventory volumes over time are shown for softwoods in Figure 5-10, for hardwoods in Figure 5-11, and for the two forest types combined in Figure 5-12. The base case softwood inventory level (Figure 5-10) drops from 1990 to 2000 because of the lack of timber in the merchantable age classes in the South and Pacific Northwest. However, from 2000 onward, until 2060, the softwood inventory in FASOM increases, from 178 billion cu ft in 2000 to 240 billion cu ft in 2060. The climate change scenarios share with the base case an initial drop in softwood inventory stocks, although the magnitude of these decreases increases with the severity of the yield decrease. The inventory drop in the 2.5 with CO_2 scenario is just about equal to that in the base case. However, the softwood inventory in the 4.0 without CO_2 scenario is about 40% below the base case inventory in 2000. After 2000, the inventory levels in all of the climate change scenarios decrease very slightly. By 2030, the softwood inventory in the 2.5 with CO_2 scenario is about 22% below the base case inventory, whereas the inventory level in the 4.0 without CO_2 scenario is fully 70% below the base inventory in that same year

As expected, the hardwood inventory levels shown in Figure 5-11 mirror the changes in hardwood prices and production levels. Inventory levels in the 2.5 with CO_2 and 4.0 with CO_2 scenarios increase initially, faster than in the base case, and remain higher than the base inventory level until 2030 After 2030, inventory levels in both these scenarios decline. By 2060, the hardwood inventory in the 2.5 with CO_2 scenario is about the same as in the base case, while the inventory in the 4.0 with CO_2 scenario is only about 5% lower than in the base case Hardwood inventory levels in the two without CO_2 cases are consistently lower than those in the base case. By 2060, the inventory levels in these two scenarios converge together at a point about 25% lower than the hardwood inventory in the base case.

The hardwood inventory is consistently larger than the softwood inventory in all the scenarios (except the base case). However, the species composition of the combined inventory varies considerably from scenario to scenario and from year to year. This is reflected in the pattern of inventory changes shown in Figure 5-12. For example, in the 2.5 with CO_2 scenario the inventory expansion from 1990 to 2020-2030 and the decline thereafter largely reflect the movement of the hardwood inventory. For the other climate change scenarios, the expansion of the hardwood inventory from 1990 to 2030 helps to moderate the decrease in total inventory levels; thereafter the steady decline in the combined inventory levels also tends to reflect the decrease in hardwood inventories. By 2060, the difference between the combined inventory volume in the base case and the four climate change scenario ranges from about 15% (2.5 with CO_2) to about 45% (4.0 without CO_2)

It should be noted that inventory volumes cannot decline permanently and still sustain production. The figures in this section do not show the inventory volumes in 2070 and 2080, which are still lower than those observed in 2060. This raises the very serious issues of the sustainability of the U S forest sector in the face of the types of yield declines used in this

Figure 5-10
Projected Softwood Inventory Volume
Base Case and 4 Climate Change Scenarios
1990 to 2060

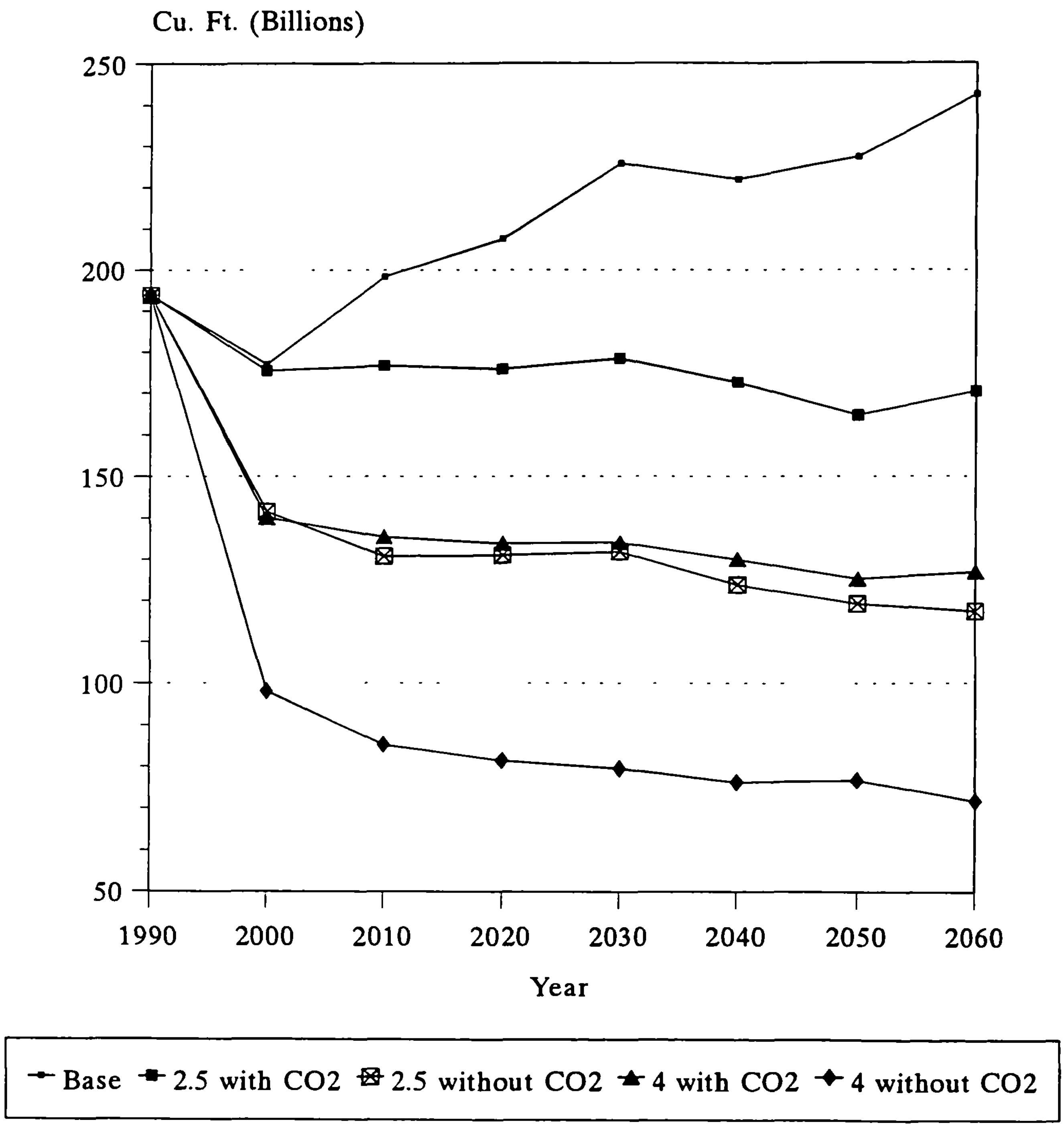


Figure 5-11
Projected Hardwood Inventory Volume
Base Case and 4 Climate Change Scenarios
1990 to 2060

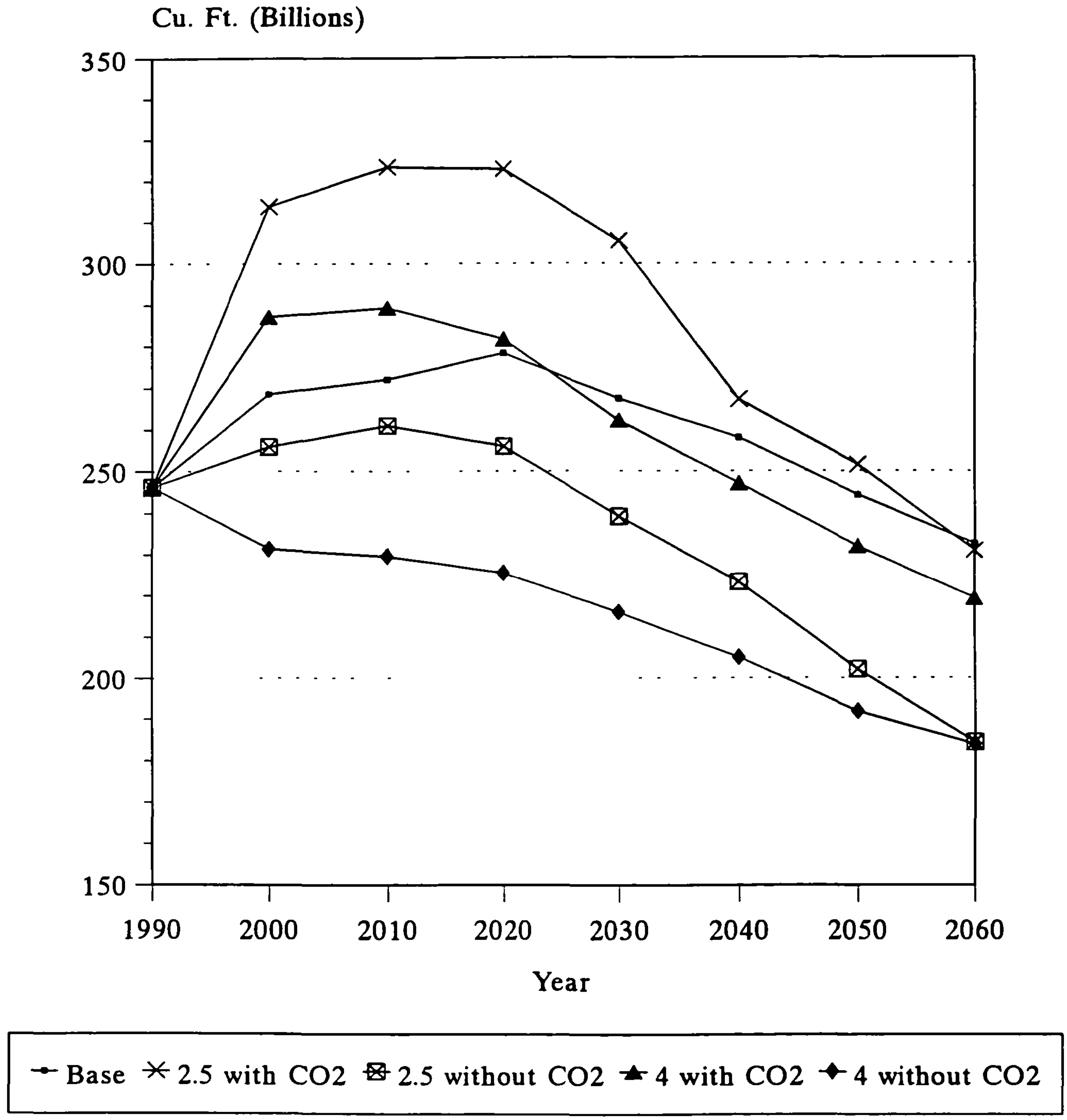
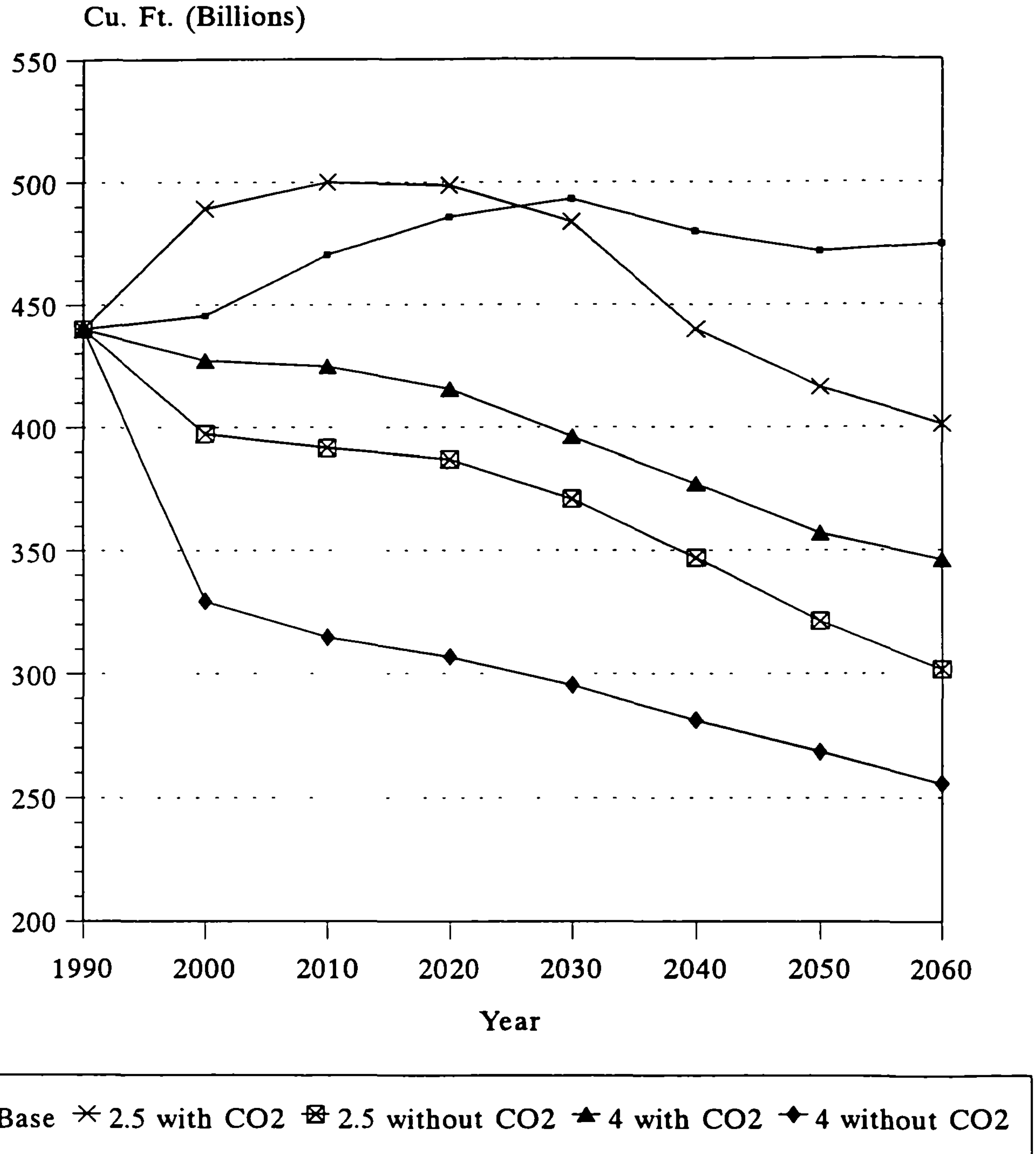


Figure 5-12
Projected Total Inventory Volume
Base Case and 4 Climate Change Scenarios
1990 to 2060



study. Unfortunately, we did not run the model for a period longer than 90 years to further examine this problem. Having said that, we note that FASOM does not include the Canadian stumpage market. Softwood inventory volumes in Canada are substantial and, because of Canada's location, global warming could actually enhance timber yields in most of that country In that case, the Canadian timber supplies would act as a "safety valve" and relieve some of the pressure on the U S. domestic inventory. Depending on the magnitude of the yield increases in Canada, adequate timber supplies could well be maintained to keep product prices from rising above the $3-$4/cu ft level. This would lower consumer surplus losses, but it would also greatly reduce, and perhaps reverse, the producer surplus gains observed in this study. Thus, the domestic winners and losers from global climate change could be reversed if forest yields in Canada increase substantially.

5.3 SUBSTITUTION ISSUES

One of the important features of the climate change scenarios was the difference in the yield changes across the two species. As shown in Table 2-2, hardwood yield reductions were never as severe as softwood reductions in the South, and hardwood yields increased in all of the scenarios in the North and remained constant in the West. As a result, we saw that while softwood prices increased dramatically in all the scenarios, hardwood prices were fairly flat; that hardwood production did not deviate greatly from the base case; and that hardwood inventory volumes in some cases were higher than base case levels. This portrays a picture of a "two-tier" timber economy with either limited room for substitution among species or one in which whatever substitution opportunities exist have already been exploited.

From a conceptual standpoint, there are three different points at which substitution between species can occur in the timber economy First, landowners can harvest their timber of one species and reforest that land in another species Second, the stumpage of one species can be processed at the mill as a product from another species. An example of this would be the ability to substitute hardwood pulpwood for softwood pulpwood. Finally, end use demands can shift such that the product demand for one species increases while the demand for another species falls. As the relative price of softwood increased, one might become willing to substitute hardwood lumber for softwood lumber [4] However, this assumes that such substitution possibilities exist. At the current time, this is not the case and there are only limited opportunities for this to occur because of the price-induced evolution of the end-use species match.

FASOM is currently designed, conceptually, to "handle" all types of substitution between products. However, extreme substitutions between hardwood and softwood at higher market

[4] Substitution away from wood to other materials is governed by exogenous shifts in the demand functions as market conditions change over time.

levels are not reflected in the observed data for stumpage supplies and demand Thus, these substitutions cannot be reflected very well in the estimated parameters of the stumpage demand equations. In FASOM, land can be converted from hardwoods (or softwoods) to softwoods (or hardwoods) after harvest. This conversion must involve planting the new species, so a positive cost is associated with this type of land substitution. These costs are in the range of $25 to $85 per acre. Currently, FASOM allows downward, interproduct substitution from sawtimber to pulp for the same species, and from hardwood and softwood pulp to softwood fuelwood. The model does not allow interspecies substitution for either pulpwood or sawtimber. Interspecies substitution for sawtimber is technically costly and, for some products, simply infeasible. However, interspecies substitution for pulpwood is currently being practiced and is feasible at very low costs in some regions.

We decided to explore the impact of increasing both land substitutability and interspecies product substitution on the climate change scenarios. Because this was an exploratory investigation, we limited the scope of the analysis to a single scenario, the 4.0 without CO_2 case This scenario was selected because the very large reductions in softwoods yields in this scenario, especially in the South, should make hardwood substitution more valuable to the model.

We performed two sets of experiments on this scenario. First, we reduced the cost of converting land from hardwood to softwood growing stock systematically by 25% and 50% We selected these percentages because they were indicative in past practice of the proportion of establishment cost that the federal government has historically been willing to subsidize in its reforestation programs Second, we reset the conversion costs to their original (base case) levels and then added the possibility of substituting hardwood pulp for softwood pulp at the mill We added this possibility because it is currently feasible in some regions For both of these experimental cases, we ran FASOM with and without the yield changes in the 4 0 without CO_2 scenario.

The results of the land substitution experiment were clear cut. There was virtually no effect on the species composition of the inventory, on price and production levels over time, or on welfare This is because the large softwood yield reductions in the 4.0 without CO_2 scenario make it economically infeasible to convert hardwood acreage to softwood acreage at even 50% of the current conversion cost. This type of substitution might become profitable at lower conversion costs, but we did not explore this possibility, since there is no reason to believe that such cost reductions would be achieved or that the government would be willing to cost share a larger amount.

The second experiment was more successful at producing substitution However, before looking at the results of this experiment, it is helpful to look at the projected price paths for softwood and hardwood pulpwood shown in Figures 5-13 and 5-14. As can be seen, the prices diverge sharply in all the scenarios. For the 4.0 without CO_2 scenario, softwood prices in 2030 and 2060 are about $6.00/cu ft and $6.10/cu ft, respectively, and the corresponding

Figure 5-13
Projected Price Path
Softwood Pulpwood
1990 to 2060

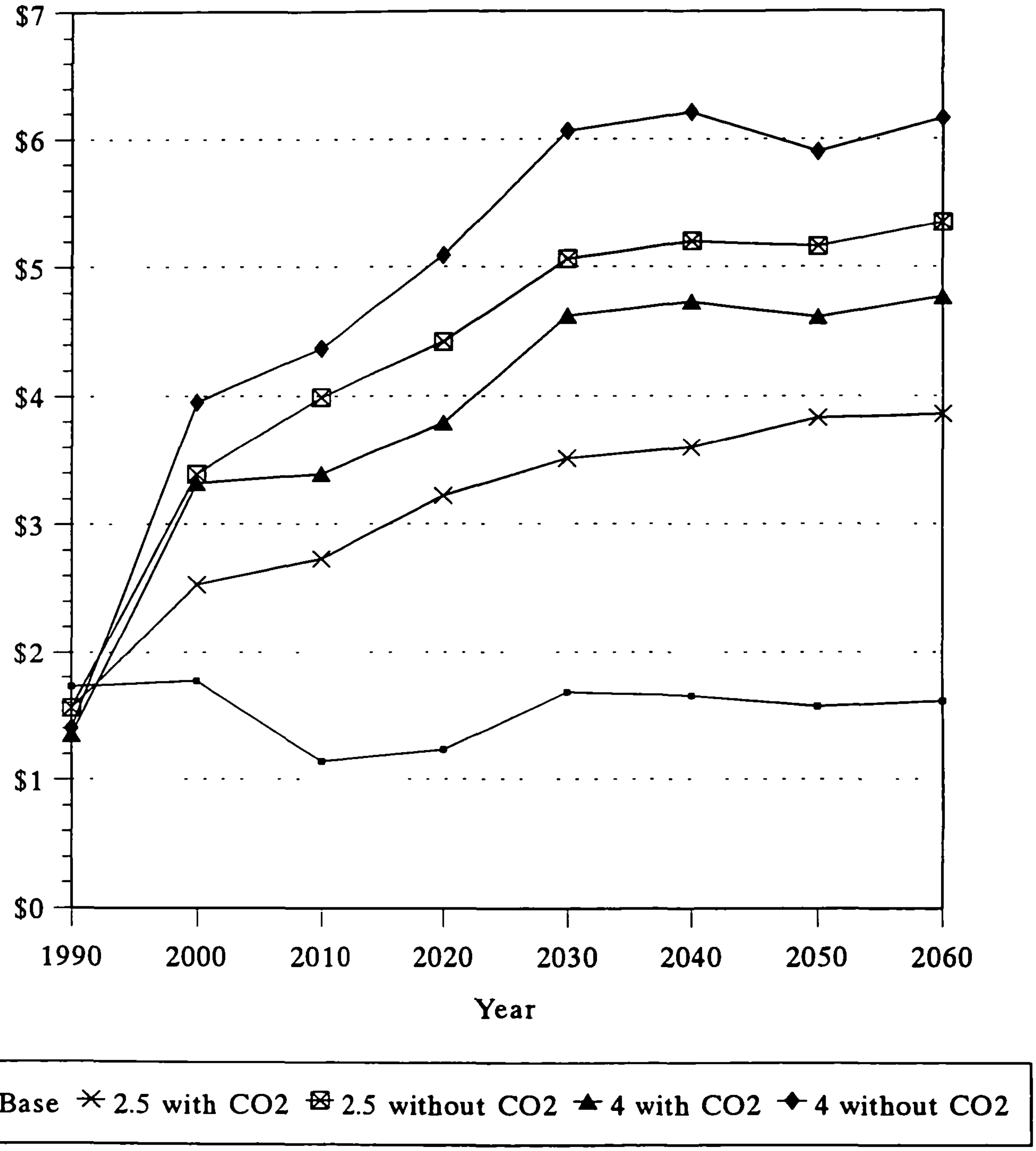
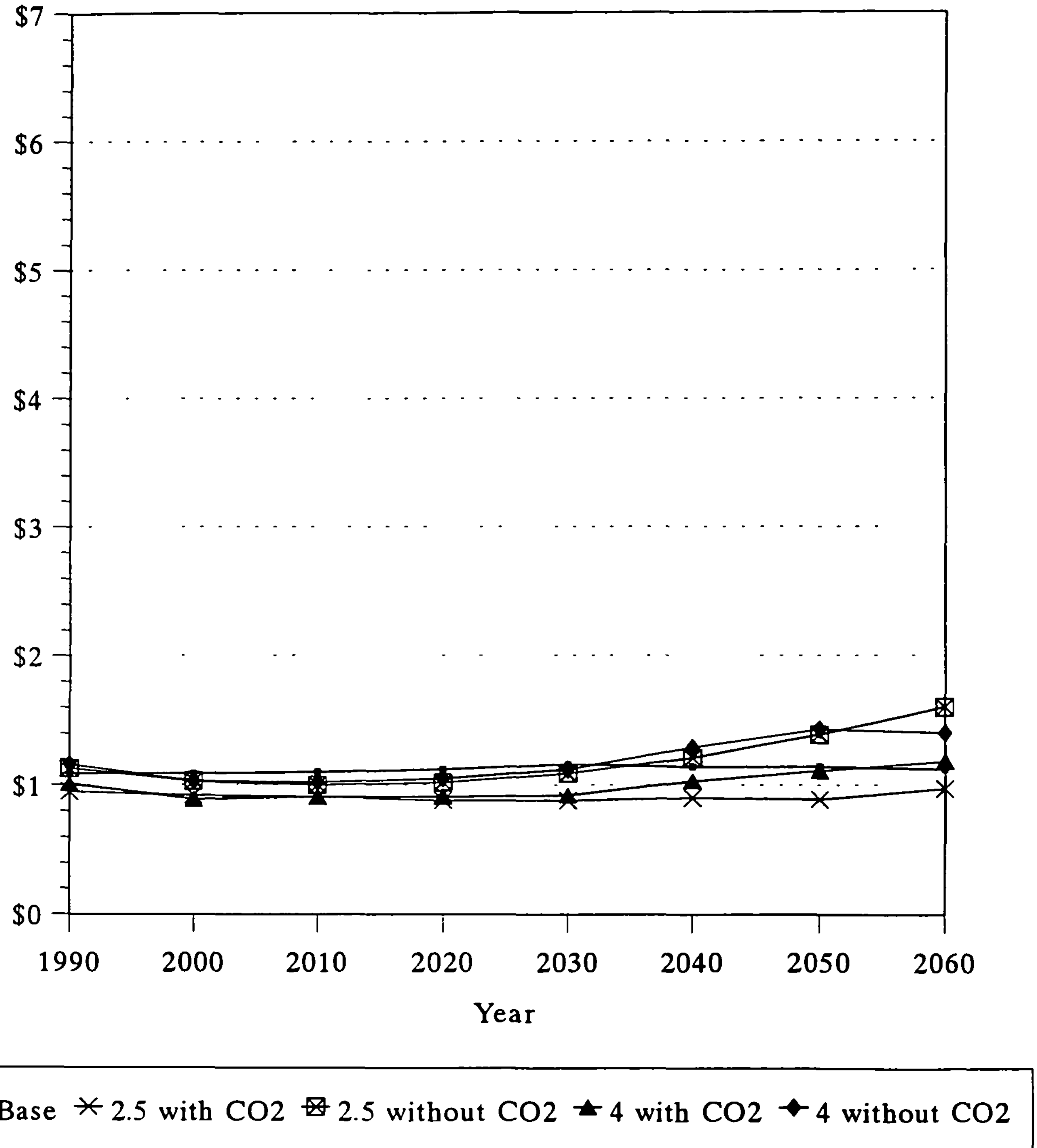


Figure 5-14
Projected Price Path
Hardwood Pulpwood
1990 to 2060



hardwood pulpwood prices are in the neighborhood of $1.10 to $1.20. The $5.00 or so price difference between these products suggests that there are ample opportunities for substitution

The results of the second substitution experiment (hardwood pulp for softwood pulp) can be seen partially in Figures 5-15 through 5-17. Figure 5-15 shows the price paths of softwood pulpwood for the original base case, for the revised base case (with interspecies substitution), for the 4.0 without CO_2 scenario, and for the revised 4.0 without CO_2 scenario The important feature about this figure is that the price path for pulpwood in the revised case increases at a much more gradual rate than in the original case. In 2030, the price of pulpwood in the revised 4.0 without CO_2 scenario is about $2.50/cu ft, as opposed to about $6.00/cu ft in the original 4.0 without CO_2 scenario. By 2060, the difference has narrowed somewhat, but it is still substantial; pulpwood sells for about $3.55/cu ft in the revised 4.0 without CO_2 scenario and about $6.10/cu ft in the original 4.0 without CO_2 experiment.

Figure 5-16 shows the price paths of hardwood pulpwood for the original base case, for the revised base case (with interspecies substitution), for the 4.0 without CO_2 scenario, and for the revised 4.0 without CO_2 scenario Since softwood and hardwood pulpwood are perfectly substitutable, the price paths for softwood pulpwood and hardwood in the revised base case and revised 4 0 without CO_2 scenario track each other perfectly, separated only by a $.10 processing cost differential. Thus, in the case of hardwood pulpwood, the introduction of substitution at the mill leads to much sharper increases in the price of hardwood pulpwood than in the original scenarios.

Finally, Figure 5-17 presents the Tornquist-Theil price indices for the two base cases and two 4 0 without CO_2 scenarios. With substitution, the price index in the revised 4.0 without CO_2 falls below that in the 4.0 without CO_2 scenario until 2040, when the two indices cross, and then the aggregate price in the revised case is somewhat higher. Recall that the index is based on production in 1990 for the original base case. If the index were re-based in 1990 for the revised base case, then the aggregate prices for the revised 4 0 without CO_2 scenario would be consistently lower.

Table 5-2 compares the welfare estimates for the original and revised base case and 4 0 without CO_2 scenarios. Enhancing the substitution possibilities in this experiment substantially reduces welfare losses. Overall, the percentage reduction in the annualized value of total welfare in the 4.0 without CO_2 case was 18.7% or a loss of about $52.7 billion, whereas in the revised 4.0 without CO_2 scenario this was reduced to a welfare loss of 14.4%, or about $55.6 billion, which translates into about $9.3 billion/yr when annualized Thus, the introduction of technological change in this experiment reduced net welfare losses by approximately $3 billion/yr

Enhancing the substitution possibilities in the model also affected the distribution of welfare gains and losses. In the revised 4.0 scenario, both producer and consumer surpluses are increased relative to the original 4 0 without CO_2 scenario Relative to the revised base, the

Figure 5-15
Projected Softwood Pulpwood Price Path
for Base Case, 4 Hi Scenario, Rev. Base Case, Rev. 4 Hi Scenario
1990 to 2060

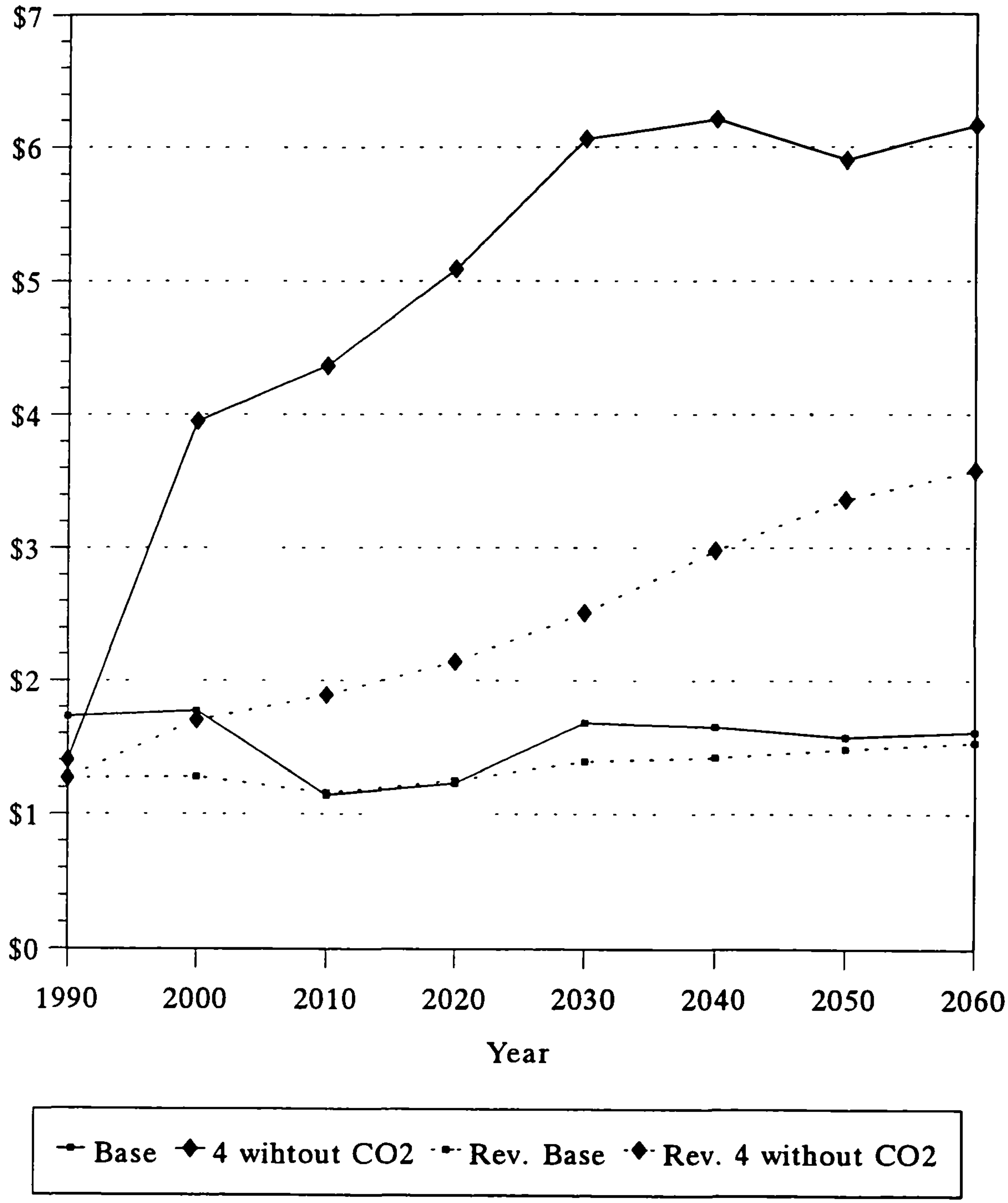


Figure 5-16
Projected Hardwood Pulpwood Price Path
for Base Case, 4 Hi Scenario, Rev. Base Case, Rev. 4 Hi Scenario
1990 to 2060

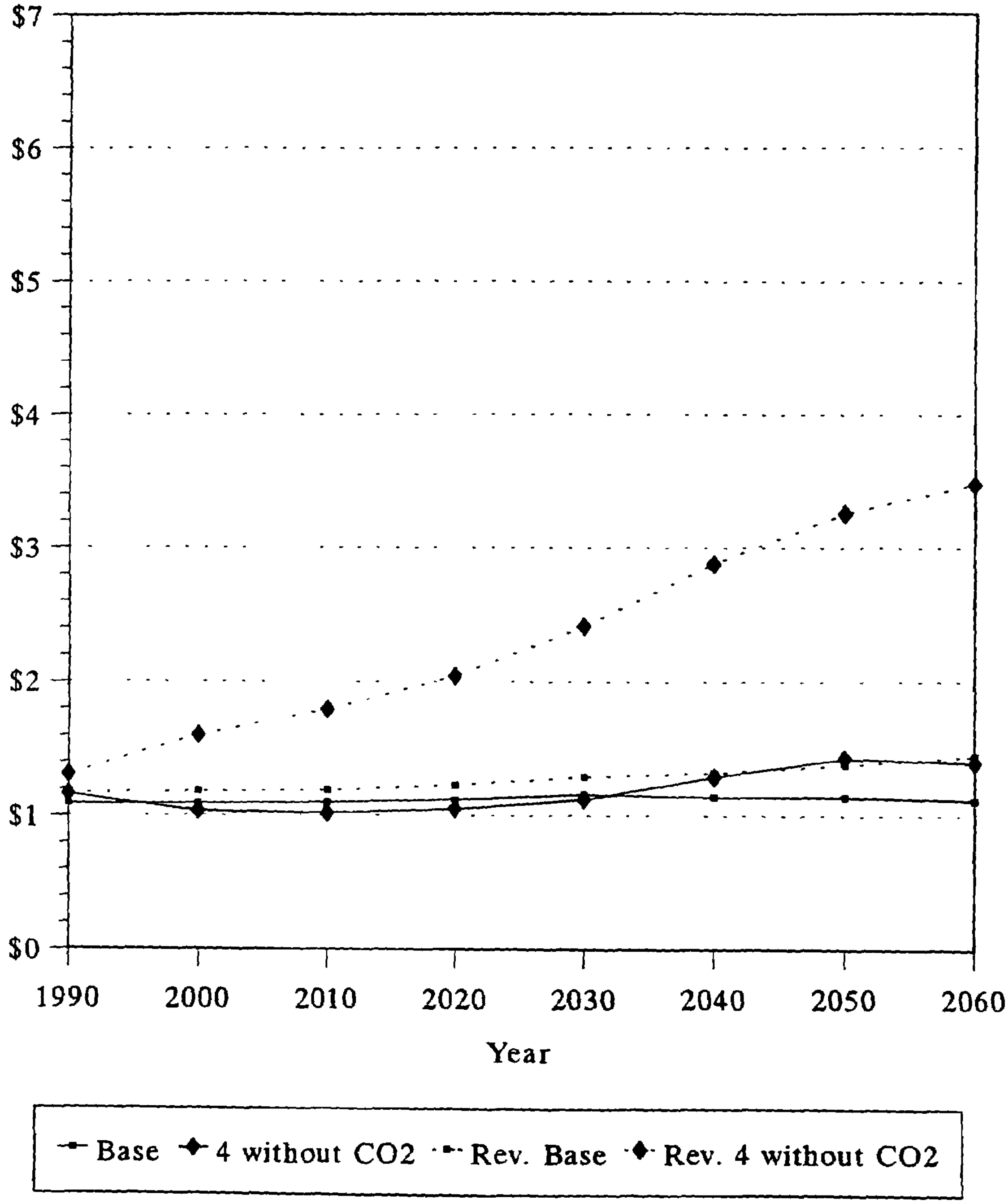


Figure 5-17
Projected Tornquist-Theil Price Index
for Forest Products Prices
Base Case, 4 Hi Scenario, Rev. Base Case, Rev. 4 Hi Scenario, 1990 to 2060

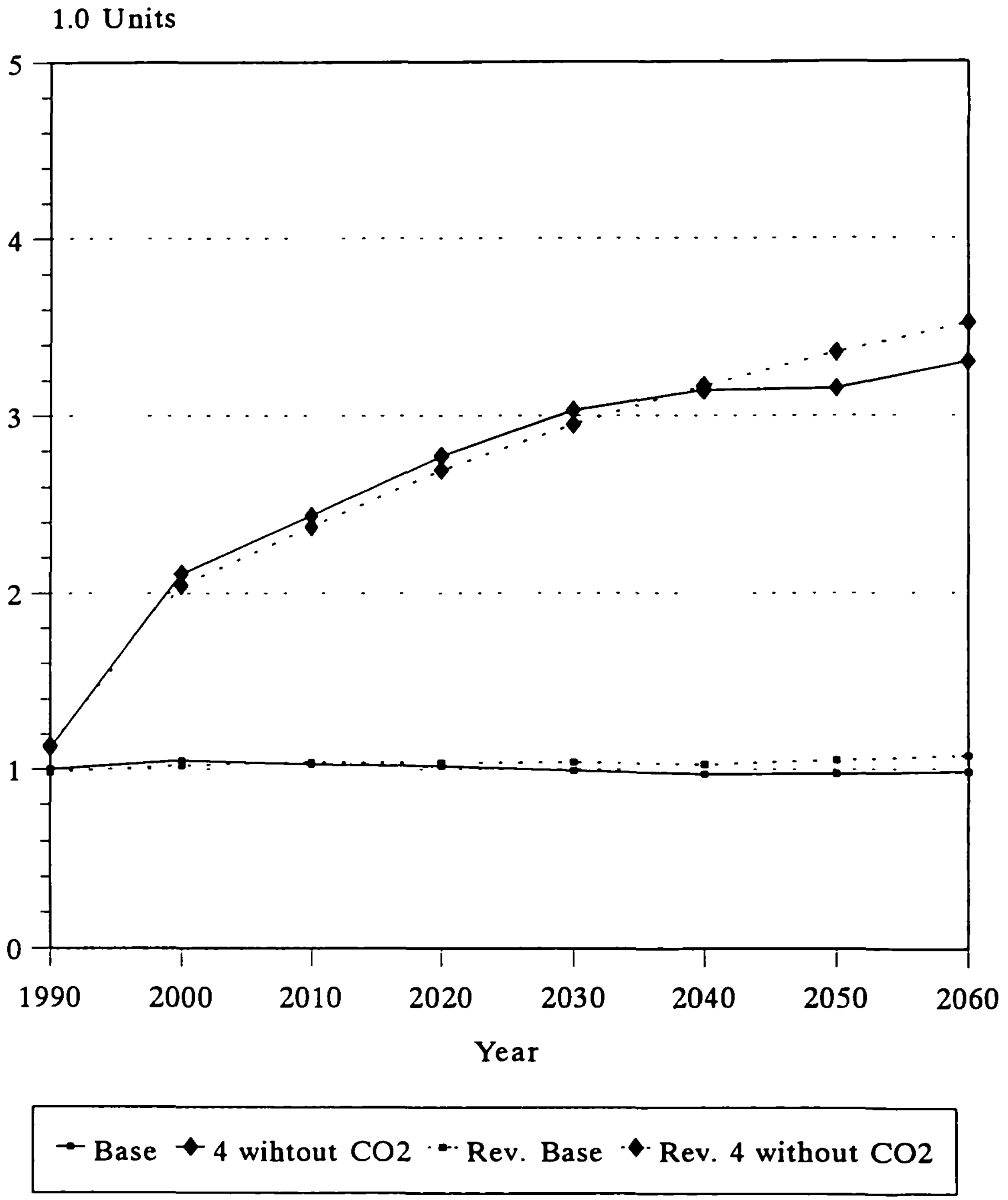


Table 5-2
Annualized Values[1] of Welfare Components
for the Base Case and Revised Base Case
Compared with the Original and Revised 4.0 without CO_2 Scenarios
($ Millions)

Welfare Components	Base	4.0 without CO_2	Revised Base	Revised 4.0 without CO_2
Consumer Surplus	56,748	32,862 (-42.1%)	56,675	33,297 (-41.2%)
Producer Surplus	3,871	11,910 (207.7%)	4,180	15,039 (259 8%)
Foreign Trade Surplus	324	162 (-50.1%)	320	161 (-49.7%)
Terminal Inventory	1,805	1,207 (-33.1%)	1,795	1,179 (-34.3%)
Public Cut	2,023	6,532 (222.9%)	1,997	5,961 (198.5%)
Total Surplus	64,771	52,673 (-18.7%)	64,967	55,637 (-14 4%)

[1] Annualized values calculated for 1990-2080 using a discount rate of 4%.

decrease in consumer surplus in the revised 4 0 without CO_2 scenario was slightly less severe than in the original 4.0 without CO_2 scenario (-41.5% vs -42.09%). At the same time, the relative increase in producer surplus in the revised 4 0 without CO_2 scenario was quite a bit larger than in the original 4.0 without CO_2 scenario (259 79% vs. 207 69%)

The two substitution experiments showed that while climate change may make it economically infeasible to replant softwoods on hardwood acreage, welfare losses would be reduced in all the climate scenarios by substitution of hardwood for softwood pulpwood, where feasible It is also quite possible that large future differences between softwood and hardwood products would not persist, because these would create long-run substitution opportunities to replace softwood sawtimber products with hardwood sawtimber through technological change. At the same time, these price differences might be expected to induce further substitutions in consumption of hardwood for softwood products further up the product chain All of these substitutions have the long-run potential to further reduce the welfare losses simulated with FASOM in this study.

5.4 REFERENCES

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CHAPTER 6
CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

In this report, we reviewed published literature in which the authors estimated the effects of climate change on forest productivity in the United States. We used the results from these studies and other published literature about CO_2 fertilization to develop our own estimates of regional and national changes in hardwood and softwood yields. The yield changes were estimated based on results from the literature using the so-called "gap models." These models provide regional estimates of how yields of specific species may change over time in response to climate change. Four climate change scenarios were developed, which use different levels of temperature change and the effects of elevated CO_2 on yields. In general, the results from the literature are that climate change would lead to a decline in softwood yields across most of the East, Central, and South, with mixed results in the Northwest and Mountain states. The decline in softwoods is estimated to be particularly severe in the South. On the other hand, hardwood yields are generally estimated to increase in northern states and have mixed results in southern states. These differences in response between hardwood and softwood species and between regions had important consequences for the economic results.

A multi-regional timber supply model of the United States was used to simulate the economic effects of these forest yield changes on welfare, stumpage harvests and prices, and forest inventory stocks over time. The results from this analysis indicated economic losses to consumers and producers ranging from \$2.8 billion/yr to \$12 billion/yr, depending on the severity of the changes in climate. Average product prices increased steadily in all scenarios By 2060, these prices had risen about 100 to 200% in response to climate-induced supply shortages Total production of stumpage products decreased in response to these higher prices. Projected total production in 2060 was about 25 to 65% below base case levels As might be expected, forest inventory stocks declined steadily over the period. By 2060, forest inventory volumes were from 15 to 45% below stocks in the base case. After 2060, projected inventory stocks continued to decline in the model, raising questions about the sustainability of the forest inventory.

The FASOM results largely reflect the importance of the softwood resource in the South in the overall forest economy. All of the changes in softwood prices, softwood production, and softwood inventories were larger in absolute magnitude (i.e., worse) than for hardwoods. Simulated increases in hardwood yields, introduced into FASOM, helped moderate welfare losses. In general, hardwood price increases were very modest in comparison to softwood price changes, and the effects of the scenarios on hardwood production and inventory volumes were also quite small by comparison.

Because of the large quantitative differences in the impacts on hardwoods and softwoods, this study also explored the effects of lowering the costs of converting land from hardwoods to softwoods and increasing the substitutability of hardwood pulpwood for softwood pulpwood We found that reducing land conversion costs did not lead to hardwood-softwood land conversion because the return on softwood acreage was still too low to justify the cost. However, increasing the substitution possibilities in the model did help to mitigate welfare losses to some extent. Large expected differences in softwood and hardwood prices due to climate change would create additional incentives to expand substitution possibilities through technological change, further mitigating the effects of climate change on welfare in the forest sector.

6.1 CONCLUSIONS

The major conclusions of this study are as follows·

- Studies using gap models indicate there could be significant changes in yield of U.S. forests. Softwood yields are estimated to decline outside of the northwestern quadrant of the country. In the deep South, softwoods are estimated to be virtually eliminated Yields could fall significantly in the Northeast quadrant of the country. In parts of the Northwest quadrant, softwood yields could increase.

- In contrast, the literature shows that hardwood yields could increase In the North, hardwood yields could more than double. In the South, whether yields increase or decrease depends on the magnitude of temperature change and the CO_2 fertilization effect.

- Studies of climate change impacts on vegetation using biogeography and biogeochemical models tend to show a wider range of variation in the potential changes in vegetation than studies using the gap models. Some of these studies conclude that there could be significant increases in biomass in the United States, while others conclude there could be significant decreases. Based on a review of all of the literature, it is uncertain whether biomass in the United States will increase or decrease in response to climate change.

- The FASOM analysis revealed important differences in the magnitude of the welfare losses due both to the magnitude of the simulated climate changes and the sensitivity of yields. The total welfare losses in the two 4.0° scenarios (-9.42% and -18.68%) were almost twice as high as the losses in the 2.5° scenarios (-4.35% and -10.73%). The differences in the welfare losses across the sensitivity levels (high versus low) were almost as great (-4.35% and -9.42% versus -10.73% and -18.68%).

- The distribution of total welfare losses due to climate change could be very uneven In all cases, buyers of stumpage were much worse off because of the yield reductions, while timberland owners were made much better off by the same yield reductions. This phenomenon is due largely to the highly price-inelastic nature of stumpage demands in the United States.

- All of the scenarios produced long-term large declines in the softwood inventory. These decreases called into question the sustainability of the softwood resource in the United States in the face of yield changes predicted in the literature.

- The study showed that expanded opportunities for substituting hardwoods for softwoods at the mill and in consumption would, in the long run, help offset the welfare losses reported in this study.

- The study did not include Canada because of model limitations. Increases in softwood yields in Canada could offset much of the "damage" to U.S. stumpage markets in that increases in Canadian supplies would help to offset domestic supply losses. This would improve the welfare condition of U.S. buyers of stumpage, but it would also result in lower profits for U.S. timberland owners, relative to the results reported in this study.

6.2 SUGGESTIONS FOR FURTHER RESEARCH

Additional research should be conducted to improve our understanding of the biophysical impacts of climate change on forests We need to improve our knowledge of the transient response of forests to climate change In particular, we need a better understanding of how forests would respond to a warmer and wetter climate and the extent to which CO_2 fertilization would mitigate negative climate change effects and enhance any positive climate change effects

We believe that there are at least four areas in which additional research would further enhance our ability to understand how the U S. forest sector might respond to changes in climate.

The first involves developing scenarios with significant increases in timber yields in the United States The VEMAP study (see Chapter 2) found that a number of vegetation models, run under similar climate change scenarios as those used in studies on which we relied for this report, estimated increases in vegetation cover and productivity over the United States. To reflect the potential for increased yields, the results from these models should be transformed into regional changes in hardwood and softwood yields and run through FASOM.

The second area involves running FASOM with climate change scenarios included in both the agricultural sector and the forest sector. This study was performed using the stand-alone forest sector version of FASOM. As a result, the land base available to the forest sector was exogenous. However, since the simulated impacts of the yield changes on the forest inventories were fairly substantial, it would make sense to allow land to move back and forth between the two sectors in response to endogenously determined changes in land rents in the two sectors. This would require developing consistent yield change scenarios and assumptions across the two sectors.

The third area of research that would improve this study involves expanding the FASOM forest (and possibly agricultural) sectors to include Canada. The softwood resource base in Canada is currently quite large. Canadian stumpage does not compete with U.S. supplies in our domestic market because of trade barriers, other opportunities in overseas markets, and higher marketing costs. However, since the relative impacts of climate change on forest yields will probably favor Canada, the economic situation could change and with it would come incentives to reduce trade barriers Thus, as we have suggested above, the omission of Canada from the analysis could seriously bias the impacts, causing welfare losses to be higher than they would be if Canada were included in the analysis. One potentially troublesome aspect of including Canada in FASOM is that it would involve the development of data in FASOM for the Canadian softwood inventory, which is poorly documented. However, it would be possible to develop the Canadian inventory in much less detail than applies to the U.S. inventory. One could then conduct some preliminary analyses with the modified version of the model to determine if the inclusion of Canada produces enough uncertainty in the results to warrant further data development.

Alternatively, and perhaps more generally, it may be possible to incorporate the impacts of climate change effects in other regions on exports and imports in FASOM. This could possibly be done using the global forest model currently maintained by the Center for International Trade in Forest Resources (CINTRAFOR). By running climate change scenarios and physical effects scenarios through this model, it would be possible to develop information that could be used to parameterize the import supply and export demand functions in FASOM to reflect climate change impacts

Fourth, we believe it is important to extend the analysis of interproduct and interspecies substitution to determine the extent to which further substitution possibilities can reduce welfare losses The most obvious initial effort would involve extending the pulp substitution analysis to all the scenarios, including also any costs that might be required to make these substitutions technically feasible Further efforts could be focused on delimiting and including feasible substitutions of hardwood sawtimber for softwood sawtimber and on exploring interproduct substitution in demand

Finally, it should be recalled that the yield shifts used in the analysis were introduced in an equilibrium adjustment framework. For any given set of yields, this type of analysis produces fairly severe negative economic impacts. However, one can be reasonably certain that, given time to adjust to these impacts, the actual impacts of yield changes similar to the ones used in this study would be smaller. How much smaller is difficult to determine because of the problems associated with forecasting adaptive technological change. However, given the magnitude of the impacts seen here, it may be worthwhile to look at how the impacts of yield changes will affect stumpage markets, if these changes are introduced slowly, for example, over the period from 1990 to 2050 or so.

Including all of these refinements into the analysis would greatly improve our understanding of the long-run responsiveness of the forest sector in the United States to climate change.

APPENDIX A

Appendix A
Details on Estimating Changes in Growing Stock of Softwoods in Pacific Northwest, Pacific Southwest, and Rocky Mountain Regions

A.1 Pacific Northwest and Pacific Southwest

As mentioned in Chapter 3, to estimate changes in yields of softwood forests in the West, we first had to estimate changes in habitable area as elevation shifts. Fred Swanson (Forestry Science Laboratory, Corvallis, Oregon) provided a profile of a typical, 7000 feet high mountain in the western Cascades We assumed this profile was representative of mountains in the Pacific Northwest and Pacific Southwest. We further assumed that softwood forests, and Douglas fir in particular, are currently found at 500 to 1000 meter elevations (Urban et al., 1993). Using shifts in elevation zones reported by Urban et al. and King and Tingey, we assume that a 2.5°C warming would shift elevation zones up 500 meters and a 4°C warming would shift elevation zones 1000 meters upslope. Using the mountain profile provided by Swanson, we calculated the change in area at these elevations. The area between 1000 and 1500 meters is 60% smaller than the area between 500 and 1000 meters, while the area between 1500 and 2000 meters is 83% smaller than the area between 500 and 1000 meters

We then developed estimates of how yields at different elevations would change As stated above, we used Urban et al.'s results for current elevations For the 2.5°C scenarios We assumed that yields in the 1000 to 1500 meter zone are the same as in the 500 to 1000 meter zone under current climate For the 4°C scenario, we assumed that yields in the 1500 to 2000 meter zone are the same as in the 500 to 1000 meter zone under current climate and yields in the 1000 to 1500 meter zone are equal to yields in the 500 to 1000 meter zone under the 2 5°C scenarios. Adjustments for CO_2 fertilization were made in the manner described in Chapter 2

For the 2 5°C high scenario, we assumed:

- At 500-1000 m, 50% yield decline according to OSU
- At 1000-1500 m, yields same as currently at 500-1000 m.

For the 2 5°C low scenario, we adjusted yield estimates to account for CO_2:

- At 500-1000 m, 30% decline in yields
- At 1000-1500 m, 25% increase in yields.

For the 4°C high scenario, we assumed:

- At 500-1000 m, 90% yield decline according to GISS
- At 1000-1500 m, yields decline according to 2.5°C high scenario (50%)
- At 1500-2000 m, yields same as currently at 500-1000 m.

For the 4°C low scenario, we adjusted yield estimates to account for CO_2:

- At 500-1000 m, 80% decrease in yields
- At 1000-1500 m, 33% decrease in yields
- At 1500-2000 m, 25% increase in yields.

A.2 ROCKY MOUNTAINS

For this region, we assumed the same shifts in elevation as were assumed for Pacific Northwest. The procedure for estimating changes in yields is similar to that used in the Pacific Northwest/Southwest:

For the 2.5°C high scenario, we assumed:

- At 500-1000 m, 10% yield decline according to OSU
- At 1000-1500 m, yields same as currently at 500-1000 m.

For the 2 5°C low scenario, we adjusted yield estimates to account for CO_2:

- At 500-1000 m, 20% yield increase
- At 1000-1500 m, 25% yield increase.

For the 4°C high scenario, we assumed:

- At 500-1000 m, 20% yield decline according to GISS
- At 1000-1500 m, 10% yield decline similar to 500-1000 m under 2.5°C high scenario
- At 1500-2000 m, yields same as currently at 500-1000 m.

For the 4°C low scenario, we adjusted yield estimates to account for CO_2:

- At 500-1000 m, 10% increase
- At 1000-1500 m, 20% increase (similar to 500-1000 m under 2.5°C low scenario)
- At 1500-2000 m, 25% increase.

APPENDIX B

APPENDIX B
TABLES

This appendix contains the tabular information from the Figures in Chapter 6. For consistency, the titles of the tables in this appendix refer to their corresponding figure in Chapter 6.

Table B–1 (Figures 6–1 thru 6–3)
Future Value of Producer Surplus by Region
($ Millions)

REGION	BASE	2.5 LOW	2.5 HIGH	4.0 LOW	4.0 HIGH
			2000		
North	7,125	8,462	13,071	8,129	16,762
South	15,481	6,804	18,233	5,271	16,488
West	13,058	56,757	76,276	77,265	80,387
			2030		
North	6,758	15,867	33,776	32,522	47,528
South	22,639	81,172	89,517	95,902	47,295
West	21,013	73,465	102,004	84,541	95,012
			2060		
North	4,382	26,135	41,178	33,853	61,522
South	24,412	110,476	109,292	121,881	42,179
West	9,212	66,020	91,715	73,149	99,614

Table B−2 (Figures 6−4 thru 6−6)
Tornquist−Theil Division Price Indices for Product Prices, by Species

	BASE	2.5 LOW	2.5 HIGH	4.0 LOW	4.0 HIGH
Combined Hardwood & Softwood					
1990	1	1.08	1.22	1.1	1.12
2000	1.05	1.32	1.71	1.64	2.11
2010	1.03	1.46	1.99	1.85	2.44
2020	1.02	1.62	2.25	2.08	2.77
2030	0.99	1.71	2.44	2.24	3.03
2040	0.97	1.79	2.53	2.33	3.14
2050	0.98	1.88	2.63	2.40	3.16
2060	0.98	1.97	2.76	2.50	3.31
Softwood					
1990	1.00	1.15	1.28	1.15	1.14
2000	1.06	1.48	2.01	1.96	2.60
2010	1.03	1.69	2.42	2.25	3.14
2020	1.01	1.92	2.79	2.57	3.67
2030	0.97	2.07	3.01	2.79	4.05
2040	0.95	2.13	3.10	2.87	4.13
2050	0.95	2.27	3.16	2.94	3.98
2060	0.97	2.36	3.28	3.06	4.10
Hardwood					
1990	1.00	0.86	1.04	0.92	1.07
2000	1.00	0.84	0.94	0.81	0.94
2010	1.01	0.83	0.91	0.83	0.93
2020	1.03	0.80	0.93	0.82	0.96
2030	1.07	0.80	1.00	0.83	1.03
2040	1.05	0.81	1.12	0.94	1.21
2050	1.05	0.81	1.29	1.02	1.45
2060	1.03	0.88	1.49	1.09	1.66

Table B-3 (Figures 6-7 thru 6-9)
Forest Products Production (MMCF) by Species

YEAR	BASE	2.5 LOW	2.5 HIGH	4.0 LOW	4.0 HIGH
			Softwood		
1990	109260	105619	102017	106095	106458
2000	109688	95574	77413	79129	59073
2010	122080	98290	73476	80623	53987
2020	136014	104086	77100	85317	53332
2030	148727	112901	82232	89951	53976
2040	149260	111931	79829	87695	50616
2050	149301	106725	78280	86171	55938
2060	148346	103744	73880	81901	50036
			Hardwood		
1990	60181	60104	56967	58393	55229
2000	66012	69490	67938	70328	69282
2010	70093	74664	72050	73703	72376
2020	76096	82961	77693	78946	78186
2030	77211	84103	78445	80113	78941
2040	78587	81565	77140	79832	76857
2050	80127	83412	75791	78550	74002
2060	80029	83111	73552	78686	73443
			Total		
1990	169441	165723	158984	164488	161687
2000	175700	165064	145351	149457	128355
2010	192173	172954	145526	154326	126363
2020	212110	187047	154793	164263	131518
2030	225938	197004	160677	170064	132917
2040	227847	193496	156969	167527	127473
2050	229428	190137	154071	164721	129940
2060	228375	186855	147432	160587	123479

Table B-4 (Figures 6-10 thru 6-12)
Inventory Volume (MMCF) by Species

YEAR	BASE	2.5 LOW	2.5 HIGH	4.0 LOW	4.0 HIGH
			Softwood		
1990	193802	193802	193802	193802	193802
2000	176961	175359	141457	139992	98079
2010	198259	176676	130740	135381	85229
2020	207459	175798	130986	133813	81406
2030	225762	178395	131789	134009	79492
2040	221907	172595	123785	129951	76235
2050	227360	164664	119234	125225	76695
2060	242332	170463	117410	126926	71673
			Hardwood		
1990	246249	246249	246249	246249	246249
2000	268496	313822	255871	287064	231308
2010	272085	323559	260951	289291	229485
2020	278372	322932	255994	281690	225456
2030	267467	305407	239168	262180	215893
2040	258065	267257	223272	247109	204939
2050	244313	251500	202080	231876	191786
2060	232465	230867	184340	219330	183871
			Total		
1990	440051	440051	440051	440051	440051
2000	445457	489181	397328	427056	329387
2010	470344	500235	391691	424672	314714
2020	485831	498730	386980	415503	306862
2030	493229	483802	370957	396189	295385
2040	479972	439852	347057	377060	281174
2050	471673	416164	321314	357101	268481
2060	474797	401330	301750	346256	255544

Table B–5 (Figures 6–13 thru 6–16)
Forest Product Prices for Hardwood–Softwood Pulpwood Experiment

PRODUCT	YEAR	BASE	2.5 LOW	2.5 HIGH	4.0 LOW	4.0 HIGH	REV. BASE	REV. 4.0 HIGH
				Softwood				
Fuelwood	1990	0.01	0.01	0.01	0.01	0.01	0.01	0 44
Fuelwood	2000	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fuelwood	2010	0.01	0.01	0.01	0.01	0.3	0.01	0.01
Fuelwood	2020	0.01	0.01	0.08	0.09	0.61	0.01	0.01
Fuelwood	2030	0.01	0.01	0.01	0.06	0.82	0.01	0.01
Fuelwood	2040	0.01	0.01	0.01	0.01	0.51	0.01	0.01
Fuelwood	2050	0.01	0.01	0.01	0.01	0.51	0.01	0.01
Fuelwood	2060	0.01	0.03	0.01	0.01	0.01	0.01	0.01
Pulpwood	1990	1.73	1.56	1.56	1.35	1.4	1.27	1.27
Pulpwood	2000	1.77	2.53	3.39	3.32	3.95	1.28	1.7
Pulpwood	2010	1.14	2.73	3.99	3.39	4.37	1.16	1.89
Pulpwood	2020	1.23	3.22	4.42	3.79	5.09	1.25	2.14
Pulpwood	2030	1.68	3.51	5.06	4.62	6.06	1.39	2.51
Pulpwood	2040	1.65	3.6	5.2	4.73	6.21	1.42	2.98
Pulpwood	2050	1.57	3.83	5.16	4.61	5.9	1.48	3.36
Pulpwood	2060	1.61	3.86	5.35	4.77	6.16	1.53	3.58
Sawtimber	1990	1.63	2.02	2.32	2.12	2.07	1.68	2.03
Sawtimber	2000	1.76	2.43	3.29	3.22	4.4	1.78	4.48
Sawtimber	2010	1.93	2.82	4	3.83	5.38	1.9	5.39
Sawtimber	2020	1.87	3.17	4.67	4.42	6.28	1.84	6.31
Sawtimber	2030	1.58	3.41	4.96	4.61	6.72	1.73	6.64
Sawtimber	2040	1.55	3.5	5.1	4.76	6.92	1.68	6.63
Sawtimber	2050	1.59	3.73	5.27	4.98	6.71	1.69	6.68
Sawtimber	2060	1.61	3.94	5.45	5.18	7	1.71	6.81
				Hardwood				
Fuelwood	1990	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fuelwood	2000	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fuelwood	2010	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fuelwood	2020	0.01	0.01	0 01	0.01	0.01	0.01	0.01
Fuelwood	2030	0.01	0 01	0.01	0.01	0.01	0.01	0.01
Fuelwood	2040	0.01	0.01	0 01	0.01	0.01	0.01	0.01
Fuelwood	2050	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fuelwood	2060	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Pulpwood	1990	1.09	0.95	1.13	1.01	1.16	1.17	1.31
Pulpwood	2000	1.09	0.92	1.03	0.89	1.03	1.18	1.6
Pulpwood	2010	1.1	0.91	1	0.91	1.02	1.19	1.79
Pulpwood	2020	1.12	0 88	1.02	0.91	1.05	1.23	2.04
Pulpwood	2030	1.16	0.88	1.09	0.92	1.12	1.29	2.41
Pulpwood	2040	1.14	0.9	1.21	1.03	1.29	1.32	2.88
Pulpwood	2050	1.14	0.89	1.39	1.11	1.43	1.38	3.26
Pulpwood	2060	1.12	0.97	1.6	1.18	1.4	1.45	3.48
Sawtimber	1990	0.99	0.85	1.03	0.91	1.06	1.07	1.21
Sawtimber	2000	0.99	0.82	0.93	0.79	0.93	1.08	1.5
Sawtimber	2010	1	0.81	0.9	0.81	0.92	1.09	1.69
Sawtimber	2020	1.02	0.78	0.92	0.81	0.95	1.13	1.94
Sawtimber	2030	1.06	0.78	0.99	0.82	1.02	1.19	2.31
Sawtimber	2040	1.04	0.8	1.11	0.93	1.23	1.22	2.78
Sawtimber	2050	1.04	0.79	1.29	1.01	1.57	1.28	3.2
Sawtimber	2060	1.02	0.87	1.5	1.08	1.99	1.35	3.59

Table B–6 (Figure 6–17)
Tornquist–Theil Division Price Indices
For Hardwood–Softwood Pulpwood Experiment

YEAR	BASE	4.0 HIGH	REV. BASE	REV. 4.0 HIGH
1990	1.00	1.12	0.98	1.14
2000	1.05	2.11	1.02	2.04
2010	1.03	2.44	1.04	2.38
2020	1.02	2.77	1.04	2.69
2030	0.99	3.03	1.04	2.95
2040	0.97	3.14	1.03	3.17
2050	0.98	3.16	1.05	3.36
2060	0.98	3.31	1.08	3.53

APPENDIX C

Appendix C
Harvest and Management Decision Model

The purpose of this appendix is to present the equations that constitute the forest sector portion of FASOM. When this sector is run in a stand-alone capacity, the total amount of land in the forest inventory in a given year is fixed and net-migration of land is treated as exogenous. Otherwise, the sector is modeled in a manner exactly identical to that in the dual sector version of FASOM.

Subscripts (owner, land suitability class, and site class are omitted to reduce the complexity of notation)·

r	region
t	projection period (1, 2, ..., T-1, T) measured in decades
c	age (cohort) of an aggregate in existence at start of problem (1, 2, . ., N-1 where N-1 is the oldest recognized age class measured in decades)
h	age of aggregate at harvest (1, 2, ..., N-1, N where N indicates "never harvested" or not harvested during projection period)
d	date of aggregate harvest (decade midpoints 1, 2, . ., T and N as defined above)
m	management intensity class (MIC = high, medium, low, and no or "passive" management)
s	species (order) class (softwood followed by softwood, softwood followed by hardwood, hardwood followed by hardwood, hardwood followed by softwood)
g	product (softwood and hardwood sawtimber, pulpwood, and fuelwood)

Variables (activities).

$X_{r,c,d,m,s}$	acres harvested of an existing aggregate in region r, from cohort c, d periods after start of problem, in MIC m, and species s
$N_{r,t,h,m,s}$	acres regenerated in region r, period t, and harvested at age h, from MIC m and species s

$H_{g,r,t}$ total volume harvested of product g in region r, period t

$DD_{g,t}$ volume of product g consumed domestically in period t

$DE_{g,r,t}$ volume of product g exported from region r in period t

$DM_{g,r,t}$ volume of product g imported to region r, period t

$U_{g1,r,t}$ volume of product g1 "downgraded" to the next product class in region r, period t (sawtimber can substitute for pulpwood and pulpwood can substitute for fuelwood within a species and softwood fuelwood can substitute for hardwood fuelwood)

$\Delta K_{g,r,t}$ volume of log processing (consumption) capacity added for product g, region r, period t

$TH_{g,r}$ terminal (perpetual) harvest volume of product g in region r (beginning at the end of period T)

Exogenous variables and functions:

$DT_{g,r,t}$ per unit volume domestic transport costs for product g from region r, period t

$PC_{r,m,s,t}$ planting cost per acre in region r for MIC m and species class s, period t

$TT_{g,r,t}$ trade transport costs for product g in region r, period t

$XY_{g,r,c+t-1,m,s}$ per acre yields of existing aggregates of product g, in region r, at age c+t-1, MIC class m, and species class s

$NY_{g,r,h,m,s}$ per acre yields of aggregates originating during the projection period of product g, in region r, at age h, MIC m, and species class s

$GC_{r,m,s,t}$ per acre aggregate growing (or tending) costs between origination and harvest in region r, MIC m, species s, in period t

$KC_{g,r,t}$ unit capacity costs for product g, region r, period t

$PD_{g,t}$, $PE_{g,r,t}$, $PM_{g,r,t}$ national domestic demand (PD), regional export demand (PE), and regional import supply (PM) functions solved to give own price as a function of quantity for product g, region r, and period t

$PN_{g,t}$ — sum of domestic and all regional export demand functions solved to give own price as a function of quantity for product g and period t

$UC_{g,r}$ — unit cost of substituting (downgrading) product g to the next "lower" product class in region r

$R_{r,m,s}$ — approximate optimal rotation for aggregates in region r, MIC m, and species s (derived from harvest ages observed in model projections)

$NLC_{r,m,s,t}$ — net timberland area change due to shift to or from other uses in region r, MIC m, species s, in period t

$HC_{g,r,t}$ — harvesting cost per unit volume removed of product g, in region r, period t

$A_{r,c,m,s}$ — starting inventory of area in existing aggregates in region r, cohort c, MIC m, and species s

δ_g — rate of capacity depreciation for product g

i — discount rate

$K_{g,r,1}$ — volume of log processing capacity for product g, region r, at start of projection period

$HG_{g,r,t}$ — harvest from public lands of product g, region r, period t

Equations

Objective function maximize (for the set of activities shown above)

$$\sum_{t=1}^{T} (\sum_{g} \int_{0}^{DD_{g,t}} PD_{g,t}(x)dx - \sum_{r} DT_{g,r,t}(H_{g,r,t} - DE_{g,r,t} + DM_{g,r,t})$$

$$- \sum_{m}\sum_{s}\sum_{h} N_{r,t,h,m,s} PC_{r,m,s,t} - \sum_{g}\sum_{r}(DE_{g,r,t} + DM_{g,r,t})TT_{g,r,t}$$

$$- \sum_{g}\sum_{r}(H_{g,r,t} - HG_{g,r,t})HC_{g,r,t}$$

$$- \sum_r \sum_m \sum_s (\sum_c \sum_{d>t} X_{r,c,d,m,s} + \sum_{p<t} \sum_h N_{r,p,h,m,s}) GC_{r,m,s,t} - \sum_r \sum_g \Delta K_{g,r,t} KC_{g,r,t}$$

$$+ \sum_r \sum_g \int_0^{DE_{g,r,t}} PE_{g,r,t}(x)dx - \sum_r \sum_g \int_0^{DM_{g,r,t}} PM_{g,r,t}(x)dx \qquad \text{(C-1)}$$

$$-\sum_r \sum_{gl} U_{gl,r,t} UC_{g,r,t} \} (1 + i)^{-10t} + \{ \sum_g [\int_0^{\sum_r TH_{gr}} PN_{g,T}(x)dx - \sum_r \int_0^{DE_{g,r,T}} PE_{g,r,T}(x)dx]$$

$$-\sum_r [\sum_m \sum_s \frac{(\sum_c X_{r,c,n,m,s} + \sum_{p<T} N_{r,p,T-p,m,s}) (PC_{r,m,s,T} + (R_{r,m,s} - 1) GC_{r,m,s,T})}{R_{r,m,s}}$$

$$+\sum_g [(TH_{g,r} - HG_{g,r,T} - DM_{g,r,T}) (HC_{g,r,T} + DT_{g,r,T})$$

$$+(DM_{,r,T} + DE_{,r,T}) TT_{,r,T}]] \} / \{ [(1 + i)^{10} - 1] (1-i)^{-10(T+1)} \}$$

Existing acres constraints

$$\sum_d X_{r,c,d,m,s} = A_{r,c,m,s} \qquad \text{(C-2)}$$

for all r, c, m, and s.

New acres constraints:

$$\sum_c \sum_m \sum_s X_{r,c,t,m,s} + \sum_{p<t} \sum_m \sum_s N_{r,p,t-p,m,s}$$

$$- \sum_m \sum_s NLC_{r,m,s,t} = \sum_m \sum_s \sum_h N_{r,t,h,m,s} \qquad \text{(C-3)}$$

for all t and r.

Demand-supply balance constraints:

$$DD_{g,t} = \sum_{r} (H_{g,r,t} - DE_{g,r,t} + DM_{g,r,t}) + \sum_{r} U_{g1(g),r,t} - \sum_{r} U_{g2(g),r,t} \qquad \text{(C-4)}$$

for all g and where g1(g) is the index for the product that can be substituted for g and g2(g) is the index of the product for which g can be substituted.

Regional timber harvest:

$$H_{g,r,t} = \sum_{m} \sum_{s} (\sum_{c} X_{r,c,t,m,s} \, XY_{g,r,c+t-1,m,s} + \sum_{p<t} N_{r,p,t-p,m,s} \, NY_{g,r,t-p,m,s}) + HG_{g,r,t} \qquad \text{(C-5)}$$

for all g, r, and t.

Capacity constraints:

$$DD_{g,r,t} \leq K_{g,r,1}(1 - \delta_g)^t + \sum_{k=1}^{t} (1 - \delta_g)^{t-k} \Delta K_{g,r,k} \qquad \text{(C-6)}$$

for all g, r, and t

Terminal (perpetual) log supply volume:

$$TH_{g,r} = 2 \sum_{m} \sum_{s} \frac{(\sum_{c} X_{r,c,N,m,s} \, XY_{g,r,c+T-1,m,s} + \sum_{p \leq T} N_{r,p,T-p,m,s} \, NY_{g,r,T-p,m,s})}{R_{r,m,s}}$$

$$+ HG_{g,r,T} + DM_{g,r,T} \qquad \text{(C-7)}$$

for all g and r.