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Adaptation of Forests to Climate Change

Some Estimates

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RESOURCES
FOR THE FUTURE

Adaptation of Forests to Climate Change: Some Estimates

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Abstract

This paper is based on a World Bank–sponsored effort to develop a global estimate of adaptation costs, considering the implications of global climate change for industrial forestry. It focuses on the anticipated impacts of climate change on forests broadly, on industrial wood production in particular, and on Brazil, South Africa, and China. The aim is to identify likely damages and possible mitigating investments or activities. The study draws from the existing literature and the results of earlier investigations reporting the latest comprehensive projections in the literature. The results provide perspective as well as estimates and projections of the impacts of climate change on forests and forestry in various regions and countries. Because climate change will increase forest productivity in some areas while decreasing it elsewhere the impacts vary for positive to negative by region. In general, production increases will shift from low-latitude regions in the short term to high latitude regions in the long term. Planted forests will offer a major vehicle for adaptation.

Key Words: forests, climate change, adaptation, productivity, plantations, industrial wood, climate models

JEL Classification Numbers: Q20, Q23, Q55

Contents

Adaptation of Forests to Climate Change: Some Estimates

Roger Sedjo*

1. Introduction

This paper, based on a World Bank–sponsored effort to develop a global estimate of adaptation costs, considers the implications of global climate change for industrial forestry. Part of that effort was a study focused on the anticipated impacts of climate change on forests broadly and on industrial wood production in particular,[1] with a view to the likely damages and possible mitigating investments or activities.

The approach of this study does not involve any new model runs. Rather, the study draws from the existing literature and the results of earlier investigations reporting the latest comprehensive projections in the literature. The results provide perspective as well as estimates and projections of the impacts of climate change on forests and forestry in various regions and countries.

The results of this study are consistent with the general findings of the IPCC Fourth Assessment of Climate Change (2007, 275), which states, "The changes on global forest products range from a modest increase to a slight decrease, although regional and local changes will be large. Production increase will shift from low-latitude regions in the short term to high latitude regions in the long term." This correspondence is not surprising, in that this study draws in part on the IPCC findings and on the literature that went into developing those findings.

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[1] Traditional fuelwood is not covered in this study because it is generally not traded in markets, and therefore the data are limited. Global fuelwood use appears to have peaked at 1.9 billion m3 and is stable or declining (Goldammer and Mutch 2001). In general, we would expect that conditions favorable to an expanding forest would also be favorable to the creation of fuelwood, and vice versa.

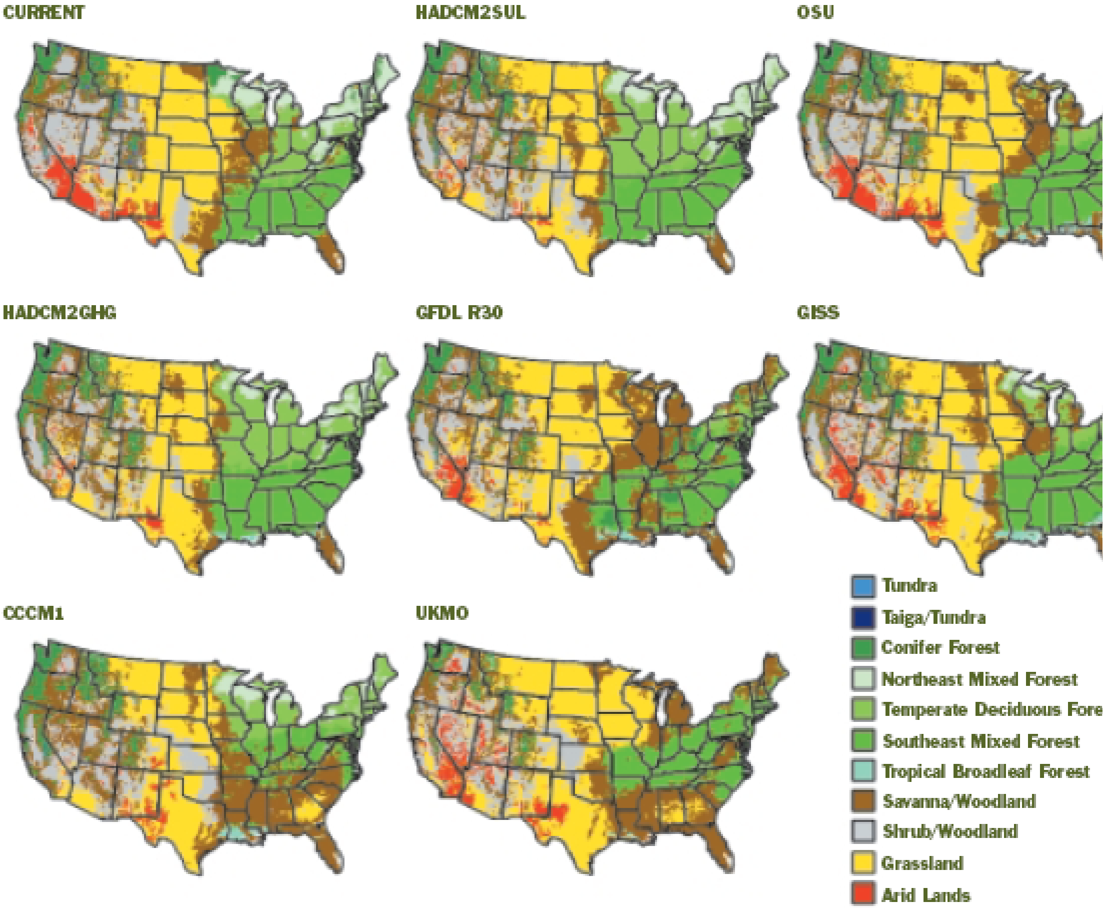
Climate-related damage to forests could include fire, infestation, disease, and wind-throw, particularly if the trees are already under stress and thus susceptible to dieback. Extreme events associated with climate change, such as windstorms and wildfire, could put even healthy forests at risk. Some forest-replacing events, however, could facilitate the transition to a newer, better-adapted forest (Sedjo 1991). Adaptation to climate change could occur naturally, through natural regeneration and tree migration, and could also be facilitated by human action if managers replant disturbed forests in species or varieties more suitable to the changed climate and establish new, replacement plantations in more suitable locations.

This paper is organized as follows. First we review the research on how climate change is expected to affect forest ecology (Section 2) and forest economics (Section 3). In Section 4, we turn to the climate change models, their assumptions and inputs, and their use in this study. Section 5 presents the results of the models as they relate to industrial forestry, and Section 6 discusses the implications of the findings, including the need for adaptation and the estimates of its costs, and notes certain limitations. Section 7 applies the model predictions to three countries: Brazil, South Africa, and China. Section 8 concludes.

2. Ecological Studies

Researchers have used ecological models to project the extent to which a specific climate change is expected to shift the geographic distribution of plants, particularly tree species (e.g., Emanuel et al. 1985; Shugart et al. 1986; Solomon et al. 1996; Neilson and Marks 1994). Forests have responded to past climate change with alterations in the ranges of important tree species (Shugart et al. 2003), but a critical issue is the rate at which tree species migrate. After the last glacial period, tree species migrated at rates of a few kilometers per decade or less, but the projected climate zones shift rate of 50 kilometers per decade could lead to massive loss of natural forests, with increased deforestation at the southern boundary of the boreal forests and a corresponding large carbon pulse (Malcolm et al. 2002). However, such a result could also lead to an increased rate of harvest to capture the value of the trees before it is lost to mortality. For typical timber production, with its managed forests and migration facilitated by human action, this negative effect of lagged migration might be of lesser importance than for natural forests.

Figure 1. Modeled Vegetation for the United States



The above maps were generated by the MAPSS vegetation distribution model (10-km resolution), and depict patterns of major vegetation types in the conterminous United States under current conditions and in response to a doubling of pre-industrial atmospheric CO_2 concentrations. The map in the top left corner represents the current distribution of major vegetation types. The remaining seven maps represent the change in distribution of those vegetation types as predicted by different climate models.

Source: Reproduced from Shugart et al. (2003)

The ecological literature suggests that warming is likely to result in an expansion of forest in high-latitude areas previously devoid of forest. In the mid-latitudes some forest species and types are likely to experience dieback while others migrate to areas with more suitable climates (Smith and Shugart 1993; IPCC 2007). Tree species at the edge of their ecological range may persist even if they are not able to regenerate in the new conditions (Clark 1998).

Figure 1 provides projections of forest configuration under several alternative general circulation models, or climate models. Note the large differences in the location of forest and other vegetative types across models. For example, while some models (e.g., CCCM and UKMO) predict the forests of the U.S. Southeast will be replaced by grasslands, others (e.g., HADCM2SUL and HADCM2GHG) expect these forests to flourish, perhaps largely because of predicted differences in moisture as well as temperature. Although models now project on subcontinental scales, they do less well in predicting regional climate effects (e.g., Climatewire 2009).

Effects of Temperature and Precipitation

Both temperature and the amount and pattern of precipitation are critical to forests. In general, warmer and wetter will enhance forest growth, while warmer and drier will likely be detrimental to growth. If drying is significant, grasses will often replace forests in natural systems (Bowes and Sedjo 1993). For the 2xCO2 climate, some biogeographical models demonstrate a poleward shift of vegetation by 500 km or more in the boreal zone (e.g., Solomon and Kirilenko 1997). The equilibrium models and some dynamic vegetation models project that this vegetation shift toward newly available areas with favorable climate conditions will eventually expand forest area and replace up to 50 percent of current tundra area.

In general, climate change is likely to shift natural forests toward the poles. Most climate models indicate that temperature changes will be least at the equator and increase as the poles are approached. Thus, for forests, the changes should be greatest in the boreal and temperate countries as boreal forests migrate into areas formerly devoid of trees, such as parts of the tundra, and temperate forests move into former boreal forest areas where soils, photoperiod, and other growing conditions are appropriate. Although not often discussed, tropical forests may be affected differently, since the anticipated amount of temperature warming is lower at those latitudes. However, tropical forests may have less tolerance for adaptation.

Perhaps more important than temperature are the changes in precipitation and moisture. Limits on moisture could result in forestlands' being converted to grasses. Although climate models are not generally regarded as good predictors of regional precipitation changes, the interiors of continents tend to be dry, and this tendency should be exacerbated under climate change and warming.

Carbon Dioxide Fertilization

Climate change is also projected to alter tree productivity—in the aggregate, in a positive direction (Melillo et al. 1993). Although the science is still inconclusive and the effect appears to vary considerably (see Shugart et al. 2003, 19–20, for a detailed discussion of the literature), increasing concentrations of atmospheric CO_2 may increase production through carbon dioxide fertilization. Early experiments in closed or open-top chambers demonstrated very high potential for CO_2-induced growth enhancement, such as an 80 percent increase in wood production for orange trees (Ipso et al. 2001). The Free-Air CO_2 Enrichment (FACE) experiments demonstrated a smaller effect of increased CO_2 concentration on tree growth. Long-term FACE studies suggest an average increase in net primary productivity (NPP) of 23 percent (range, 0 to 35 percent) in response to doubling CO_2 concentration in young tree stands (Norby et al. 2005). However, another FACE study of mature, 100-year-old tree stands found little long-term increase in stem growth (Korner et al. 2005), which might be partially explained by the difficulties in controlling for constant CO_2 concentration in a large-scale experiment. However, economic models often presume high fertilization effects, as did Sohngen et al. (2001), who used projections of 35 percent more NPP under a 2x CO_2 scenario. Regardless of the contradictory effects of variations in CO_2 concentration, however, empirical evidence indicates that forest growth rates have been increasing since the middle of the 20th century, as noted by Boisvenue and Running (2006).

Disturbances and Extreme Events

Natural disturbances—including wildfires, outbreaks of insects and pathogens, and extreme events such as high winds—are an integral part of the forest environment. These disturbances are often stand-replacing events. As a changing climate creates new conditions and increases stress on the ecological systems, the forest adapts and evolves. Climate change will almost surely change the timing of the disturbances and will probably increase their severity. Indeed, climate-induced changes in disturbance regimes already appear to be occurring (e.g., van Mantgem et al. 2009; Westerling et al. 2006). Modifications of temperature and precipitation can weaken the forest and increase the frequency and intensity of infestation and fire; these indirect effects may be as important as the direct effects of higher temperatures and drier conditions. An example of such a situation may be the devastating beetle outbreak in Canada’s western forests (Kurz et al. 2008). Many observers believe the beetle population has flourished because the warmer winters have dramatically reduced insect mortality. Note that extreme events generally are not independent but rather act in concert with forest system biological weakness. This weakness can reflect the age and/or health of the forest and may also be associated with the unsuitability of the forest types established under the earlier climate regime. New types may need to accompany climate change. Indeed, some have argued that extreme events in forestry often facilitate the replacement of an established forest with a new, perhaps more resilient forest (Sedjo 1991).

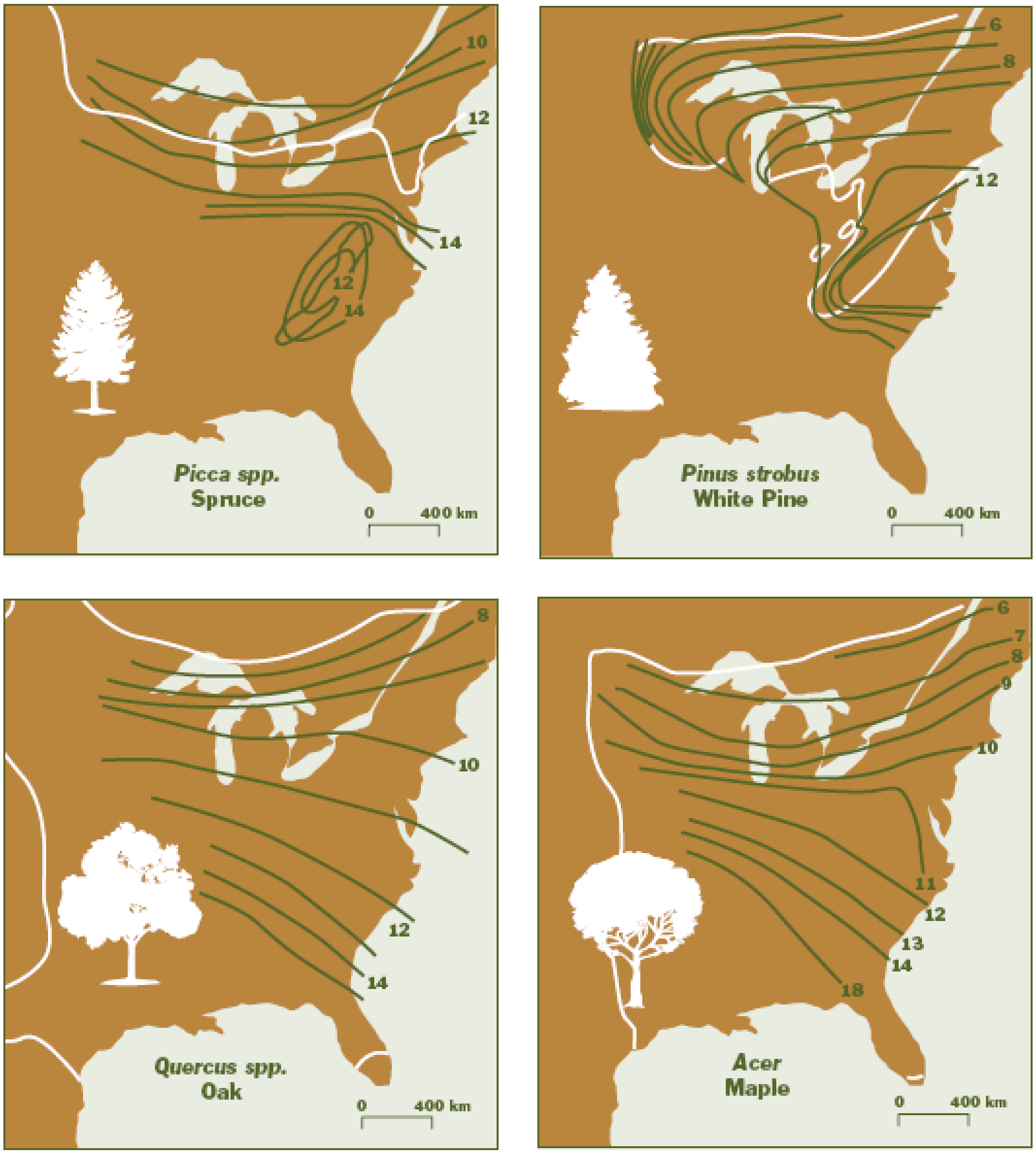
Ecological Response and Adaptation

Evidence indicates that natural forests have been migrating at least since the last glacial period as the earth warmed and moisture patterns changed. Tree species have migrated and adapted to changing environments, in some cases creating forests with a new combination of tree species (Shugart et al. 2003). Figure 2 shows the migration of some forest species in North America in the postglacial period. However, climate changes have accelerated in recent decades, and if migration and adaptation cannot keep pace, some observers anticipate an increase in dieback toward the end of this century (IPCC 2007, Chapter 4).

3. Economic Studies

Some researchers have examined the implications of climate change for industrial wood production (Figure 3). One early economic assessment of regional climate impacts on forests and agriculture was the MINK study (Rosenberg et al. 1991, 1993), which examined the ability of the agricultural and forest sectors of a region of the United States to adapt to the new and changing climate, with mobility of crops and forests playing a major role. A country-focused effort, by Joyce et al. (1995), looked at the U.S. forest sector using the Terrestrial Ecosystems Model (TEM) to predict changes in timber growth rates, timber inventories, and timber supply. An early global effort by Binkley (1988) focused on forestry’s response to climate and used a simple regression approach. Darwin et al. (1995) examined the adjustment of agriculture and forest markets to climate change in the United States. However, the computable general equilibrium (CGE) approach used did not capture the intertemporal adjustment process so critical in forests. More recent efforts include those by Perez-Garcia et al. (1997, 2002) and Irland et al. (2007), who used global forest economic models to examine the effect of climate change on forest growth and its effects on timber markets. Even though the analyses used TEM, the approaches ignored the dynamic migration aspects of tree species. Moreover, extreme events could well increase because of climate change, yet few forest production models include these effects.

Figure 2. Tree Species Migration since Most Recent Glacial Period



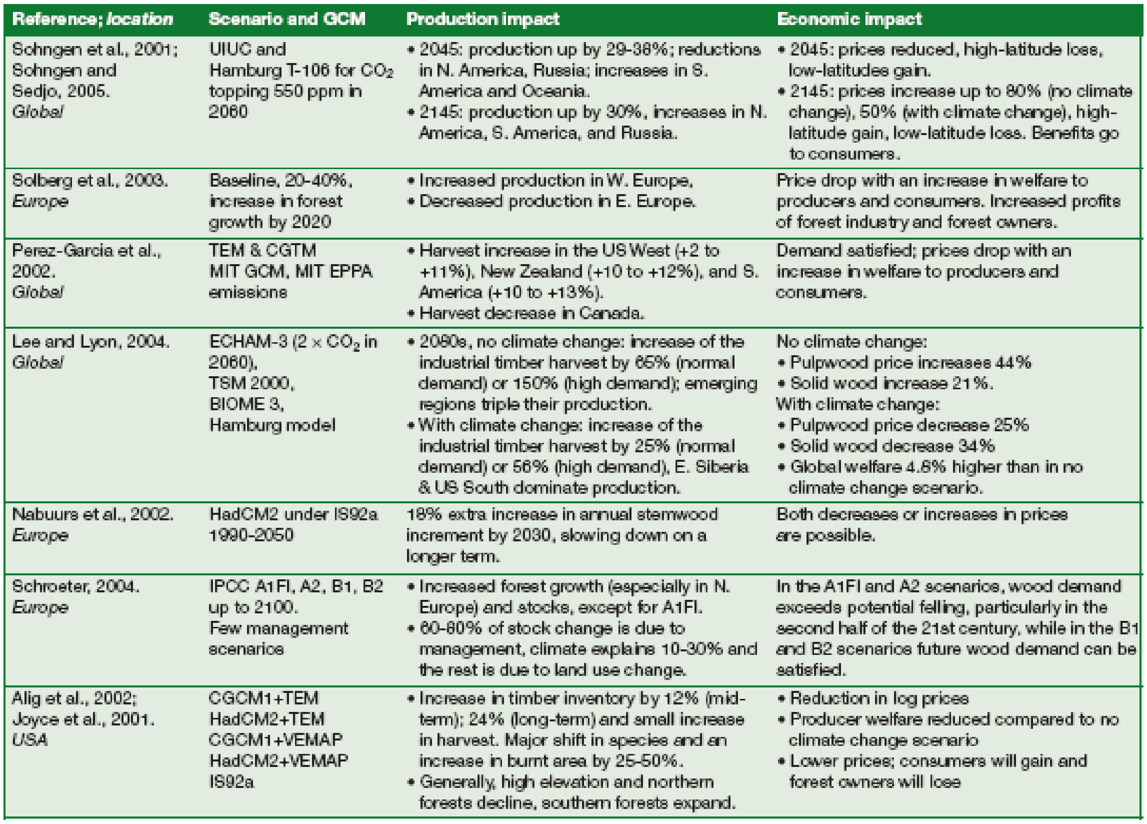
The lines in the maps above mark the boundaries of the species ranges in units of millennia (e.g., 12 indicates the range boundary of the species 12,000 years ago). The changes in the species ranges are in response to climate changes of roughly the same magnitude as that projected over the 21st Century due to climate change. The species clearly displayed marked differences with respect to their migration patterns and rates.

Source: Reprinted from Shugart et al. 2003.

The economic study that most directly and comprehensively examined the effects of climate change on forests is Sohngen et al. (2001), whose approach uses the modified Timber Supply Model (Sedjo and Lyon 1990). This report uses those results and the results of its successor models, particularly Sohngen et al. (2001) and Daigneault et al. (2007), to estimate the baseline and the climate change deviations from that baseline. Subsequent efforts using a variant of the same model provide additional inputs. These models generate projections of the global forest and associated timber harvests with and without climate change into the middle of the 22nd century. The basic models are not calibrated to either GDP or population. Rather, they make some simplifying assumptions on the demand side, and the focus of the analyses is on the supply side. Earlier sensitivity analysis shows that the projections are, to a large extent, only minimally affected by modest demand-side changes (see Sedjo and Lyon 1990). Based on the assessment of these projections, adaptation measures are suggested to mitigate likely damages, and preliminary costs are estimated.

Other studies that are particularly relevant to this current study include Shugart et al. (2003) and Kirilenko and Sedjo (2007).

Figure 3. Expected Effects of Climate Change on Industrial Forestry



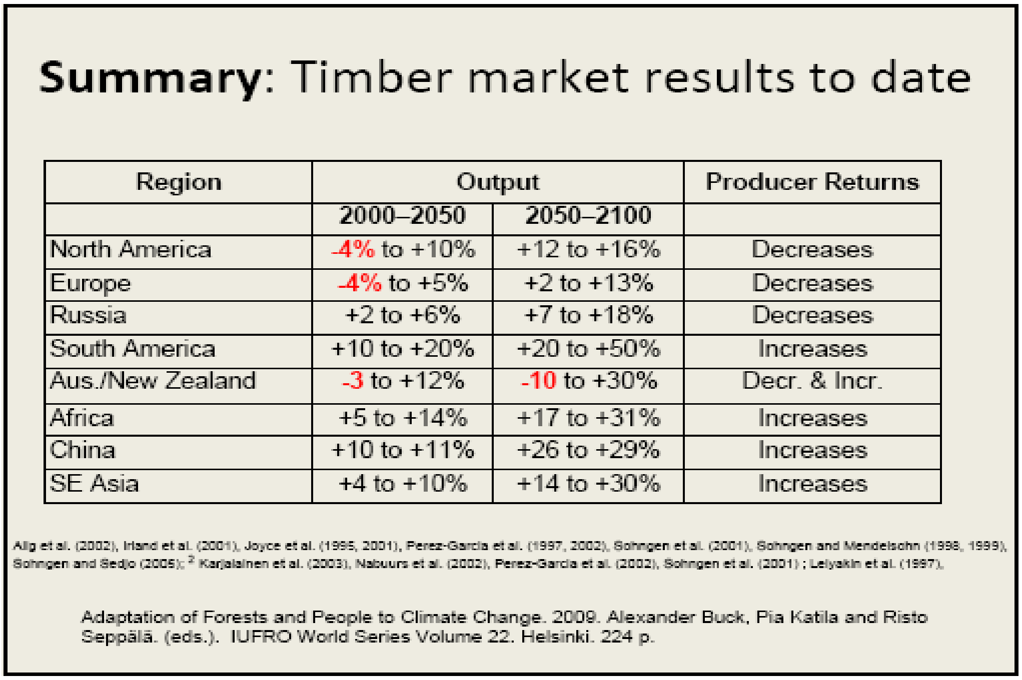
Reference; ***location***	**Scenario and GCM**	**Production impact**	**Economic impact**
Sohngen et al., 2001; Sohngen and Sedjo, 2005. *Global*	UIUC and Hamburg T-106 for CO_2 topping 550 ppm in 2060	• 2045: production up by 29-38%; reductions in N. America, Russia; increases in S. America and Oceania. • 2145: production up by 30%, increases in N. America, S. America, and Russia.	• 2045: prices reduced, high-latitude loss, low-latitudes gain. • 2145: prices increase up to 80% (no climate change), 50% (with climate change), high-latitude gain, low-latitude loss. Benefits go to consumers.
Solberg et al., 2003. *Europe*	Baseline, 20-40%, increase in forest growth by 2020	• Increased production in W. Europe, • Decreased production in E. Europe.	Price drop with an increase in welfare to producers and consumers. Increased profits of forest industry and forest owners.
Perez-Garcia et al., 2002. *Global*	TEM & CGTM MIT GCM, MIT EPPA emissions	• Harvest increase in the US West (+2 to +11%), New Zealand (+10 to +12%), and S. America (+10 to +13%). • Harvest decrease in Canada.	Demand satisfied; prices drop with an increase in welfare to producers and consumers.
Lee and Lyon, 2004. *Global*	ECHAM-3 (2 × CO_2 in 2060), TSM 2000, BIOME 3, Hamburg model	• 2080s, no climate change: increase of the industrial timber harvest by 65% (normal demand) or 150% (high demand); emerging regions triple their production. • With climate change: increase of the industrial timber harvest by 25% (normal demand) or 56% (high demand), E. Siberia & US South dominate production.	No climate change: • Pulpwood price increases 44% • Solid wood increase 21%. With climate change: • Pulpwood price decrease 25% • Solid wood decrease 34% • Global welfare 4.8% higher than in no climate change scenario.
Nabuurs et al., 2002. *Europe*	HadCM2 under IS92a 1990-2050	18% extra increase in annual stemwood increment by 2030, slowing down on a longer term.	Both decreases or increases in prices are possible.
Schroeter, 2004. *Europe*	IPCC A1FI, A2, B1, B2 up to 2100. Few management scenarios	• Increased forest growth (especially in N. Europe) and stocks, except for A1FI. • 60-80% of stock change is due to management, climate explains 10-30% and the rest is due to land use change.	In the A1FI and A2 scenarios, wood demand exceeds potential felling, particularly in the second half of the 21st century, while in the B1 and B2 scenarios future wood demand can be satisfied.
Alig et al., 2002; Joyce et al., 2001. *USA*	CGCM1+TEM HadCM2+TEM CGCM1+VEMAP HadCM2+VEMAP IS92a	• Increase in timber inventory by 12% (mid-term); 24% (long-term) and small increase in harvest. Major shift in species and an increase in burnt area by 25-50%. • Generally, high elevation and northern forests decline, southern forests expand.	• Reduction in log prices • Producer welfare reduced compared to no climate change scenario • Lower prices; consumers will gain and forest owners will lose

Source: Reprinted from IPCC (2007)

The IPCC Fourth Assessment of Climate Change (Easterling and Aggarwal 2007, 275) finds that globally, forest production will see "a modest increase to a slight decrease, although regional and local changes will be large." It also notes that the "production increase will shift from low-latitude regions in the short term to high-latitude regions in the long term."

Although most of studies find that forest productivity and area increase modestly as the climate changes, uncertainties increase over the longer term. IPCC (2007, 227) anticipates "significant forest dieback towards the end of the century." This dieback, exacerbated by climate change, is likely to become more severe as today's forests are replaced by forests more appropriate to the changing climate.

Figure 4. Timber Market Results to Date



Summary: Timber market results to date

Region	Output		Producer Returns
	2000–2050	2050–2100	
North America	-4% to +10%	+12 to +16%	Decreases
Europe	-4% to +5%	+2 to +13%	Decreases
Russia	+2 to +6%	+7 to +18%	Decreases
South America	+10 to +20%	+20 to +50%	Increases
Aus./New Zealand	-3 to +12%	-10 to +30%	Decr. & Incr.
Africa	+5 to +14%	+17 to +31%	Increases
China	+10 to +11%	+26 to +29%	Increases
SE Asia	+4 to +10%	+14 to +30%	Increases

Alig et al. (2002), Irland et al. (2001), Joyce et al. (1995, 2001), Perez-Garcia et al. (1997, 2002), Sohngen et al. (2001), Sohngen and Mendelsohn (1998, 1999), Sohngen and Sedjo (2005); [2] Karjalainen et al. (2003), Nabuurs et al. (2002), Perez-Garcia et al. (2002), Sohngen et al. (2001) ; Lelyakin et al. (1997).

Adaptation of Forests and People to Climate Change. 2009. Alexander Buck, Pia Katila and Risto Seppälä. (eds.). IUFRO World Series Volume 22. Helsinki. 224 p.

Source: Reprinted from IUFRO World Series Volume 22.

4. Methodology and Models

The basic approach to analyzing the economic impact of climate change on forests requires integrating three types of models: climate, ecological, and economic. The general circulation (climate) models and ecological models, combined, represent the climate-modified environment. Economists then treat this as the underlying production function, upon which economic models are imposed. However, since different climate and ecological models are used, the underlying production functions are often different, even for the same region. Some have not allowed for natural and/or human-induced mobility of forests and other vegetation. Many of the ecological models have focused only on individual countries or regions. In most cases the models examine the effects of warming on aspects of terrestrial vegetation.

Of the economic models developed to examine long-term timber supply, some have been modified to examine the effects of climate change on forestry. Certain models have also been modified to estimate the effects of forestry on climate change, since forest activities can both sequester and release carbon, thereby either offsetting or enhancing some global warming.

This report uses a consistent methodological approach that now has a well-established literature. The study draws heavily from the results of Sohngen et al. (2001) utilizing a modified version of the Timber Supply Model (Sedjo and Lyon 1990). This economic model is used with an ecological model and two climate models.

Climate Models: Hamburg and UIUC

The analysis assumes that the climate changes linearly until 2060, at which time it stabilizes at an atmospheric CO_2 level of approximately 550 (parts per million) ppm—that is, a doubling of the 1998 atmospheric CO_2 level of 340 ppm. Steady-state forecasts from the Hamburg T-106 model (henceforth, “Hamburg”; Claussen 1996; Bengtsson et al. 1996) and the UIUC model (Schlesinger et al. 1997) are used to predict changes in climate for 0.5 x 0.5 degree grid cells across the globe.

Globally, Hamburg predicts a 1°C increase in temperature over land and water, while UIUC predicts a 3.4°C change. The Hamburg scenario predicts relatively larger temperature changes in the high latitudes than does the UIUC scenario, and the UIUC scenario predicts larger temperature changes in the low latitudes. These regional differences suggest that the two climate models will forecast different regional effects on timber supply.

In general, a warmer and wetter climate is likely to promote forest growth (Bowes and Sedjo 1993). Both models show an increase in average NPP over the base and forest growth in the aggregate benefits. The Hamburg results might be viewed as the “wet” results, giving generally higher productivity, while the UIUC “dry” results are modestly less productive. The Hamburg scenario generates an average increase in forest NPP above the base of 38 percent, while the UIUC generates an NPP increase of 29 percent above the baseline. The carbon dioxide fertilization effect is a major contributor to the positive results. It enables plants to use water more efficiently, potentially offsetting some declines in moisture.

Tables 1–4 provide the projected estimates of Sohngen et al. (2001), which form the basis of this paper. As with almost all studies of the effects of climate change on forests, the results show increased biological forest productivity, with forest area roughly unchanged, and a modest increase in timber harvests, which results in an overall decline of wood prices. All the large developing regions show net benefits over the period to 2050 and generally beyond. Forest stock cannot increase indefinitely, and at some future time stocks must stabilize or, as suggested by Fishlin et al. (2007), decline. However, this need not imply a decrease in industrial wood supplies.

Ecological Model: BIOME3

An ecological model, the global terrestrial biosphere model BIOME3[2] (Haxeltine and Prentice 1996; Haxeltine 1996), is used to predict the vegetative changes expected given the climate changes predicted by the two climate models. BIOME3 includes carbon fertilization through the physiological effects of increased carbon dioxide on plants' water use efficiency. The model estimates the equilibrium changes in the distribution of timber species and the productivity of those species across the globe. Although some models predict net primary productivity (see Melillo et al. 1993) and some models predict global changes in the distribution of forest types (see Neilson and Marks 1994), most models do not capture the two effects simultaneously.

The approach of Sohngen et al. (1999) considers two types of transition and optimizes over both effects. In one, the forest adapts to new conditions through the movement of species across the landscape. This transition occurs without dieback as forest regeneration quickly fills in the gaps left by dying trees.

The other involves forest dieback, the loss of a large fraction of the existing stock (see King and Neilson (1992), and Smith and Shugart (1993). By directly affecting stock, dieback can cause net growth in our timber types to decline even if NPP is positive. Dieback also alters timber harvests because some of the stock that dies back will be harvested and gradually replaced by regeneration. Under dieback, timber prices are slightly higher because the value of the salvage is lower than that of timber from live trees. The proportion of salvage in each timber type varies by region.

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[2] Biomes are ecological types that represent accumulations of different species, referred to as forest types.

Assessing the two effects is important because changes in NPP can affect species dominance within a forest type, and the species present can affect NPP. In the long run, the yield of forests is likely to rise because of both factors. First, BIOME3 predicts that climate change increases the annual growth of merchantable timber by raising NPP (the “BIOME3” columns in Table 2). This is the only effect captured by most other climate change studies of forests (Joyce et al. 1995; Perez-Garcia et al. 1997; McCarl et al. 1999). Second, BIOME3 predicts that more productive species move poleward. This tends to increase the average timber yield for most regions by increasing the area of more productive species, although the effects depend on the climatic conditions.

For example, the prediction for North America is that long-run timber yield should increase 17 percent from the NPP increase alone, but with the expansion of southern species into territory previously occupied by northern species, the economic model predicts an average (continental) increase in merchantable yields of 34 to 41 percent. Alternatively, long-run merchantable timber yield in Europe is not predicted to increase as much under Hamburg as would be predicted by the change in NPP from BIOME3 alone (i.e., 23 percent change in NPP and 4 percent change in merchantable timber yield; Table 2) because Hamburg suggests that species movement in Europe is mostly an expansion of forests into marginal shrublands in Mediterranean areas. Though more productive than shrublands, these new forests are less productive than current forests in Europe, and they lower the long-run average yield of all forests. The change is similar for the UIUC scenario (23 percent change in NPP and 24 percent change in merchantable timber yield) because UIUC predicts mostly conversion of northern species to southern species and less forest expansion (see Table 1).

Note, however, that productivity increases over time are different from a future loss of biomass. Forests cannot expand forever. Thus, even with higher growth, forest stock will inevitability decline after a period of initial increase. Thus the two statements in the IPCC (2007, 227, 275) report cited above, projecting increased growth and a decline in biomass at some future time, need not be in fundamental conflict.

Although initial stocks are not heavily influenced by climate change in the regeneration scenario, harvesting behavior is affected. For instance, in northern regions where it becomes possible to introduce fast-growing southern timber types, landowners may have an incentive to harvest even young trees to make way for the new species.

The results are reported in Sohngen et al. (1999) for the two climate models. In the Hamburg scenario, BIOME3 predicts fairly large losses of existing timber stands in high-latitude regions but a global forest expansion of 27 percent and a 38 percent increase in productivity.

With the UIUC scenario, predicted losses of existing stands are even more widespread, overall forests expand less (19 percent), and productivity increases less (29 percent). The projected changes in the distribution of timber species and the productivity of those species by location are based on net primary productivity changes and carbon dioxide fertilization effects.

With climate change, the ecological model BIOME3 predicts large conversions from one forest type to another, large conversions of nonforest land to forestland, and higher NPP. Using the Hamburg climate scenario, BIOME3 predicts fairly large losses of existing timber stands in high-latitude regions but an overall global forest area expansion of 27 percent and a 38 percent increase in productivity. With the UIUC scenario, predicted losses of existing stands are even more widespread, overall forests expand less (19 percent), and productivity increases less (29 percent). Although the results are limited by reliance on only one ecological model, the results are broadly consistent with the literature (see Watson et al. 1998; Gitay et al. 2001).

BIOME3 provides more disaggregated results than the economic model can use. The data are aggregated and provide predicted effects for each contiguous forest type in BIOME3 for each region in our economic model. These aggregated effects are used to predict changes in average productivity, changes in forest types, and the area of land that can be regenerated in each timber type, in the economic model.

Table 1 provides the Sohngen et al. (2001) estimates of the percentage change in forest area in the long term (to 2145), based on the Hamburg and UIUC climate scenarios of the late 1990s used for the BIOME3 ecological projections. Note that under both models, eight of the nine regions experience a net area change over this period. Additionally, all the regions experiencing decline are developed regions.

Table 1. Percentage Change in Forest Area to 2145, Based on Hamburg and UIUC Climate Scenarios

	Hamburg			UIUC		
	Net Area Change	Accessible Net Change	Inaccessible Net Change	Net Area Change	Accessible Net Change	Inaccessible Net Change
High-Latitude Forests						
North America	3	(7)	35	4	(2)	24
Europe	16	14	23	7	4	36
Former Soviet Union	12	14	13	14	15	15
China	41	5	188	20	0	109
Oceania	(3)	(12)	20	0	6	38
Low- to Mid-Latitude Forests						
South America	42	6	44	27	(2)	33
India	10	9	--	(1)	(1)	--
Asia-Pacific	23	0	28	33	(3)	39
Africa	71	5	74	38	(4)	41
Total	27	5	41	19	5	31

Notes: Accessible forest areas are forests used for industrial purposes. For the low- to mid-latitude forests, accessible areas include only industrial plantations and highly managed forests. For the Asia-Pacific region, inaccessible forests are the valuable dipterocarp (tropical hardwood) forests. Inaccessible forests also expand in both ecological scenarios for that region, but those changes are suppressed here to show changes for the most important market species.

Source: From Sohngen et al. (2001).

Table 2 provides estimates of the percentage change in NPP and timber growth rates by 2145 for the two climate models. For all regions except Oceania, both NPP and timber yield rates are positive. Oceania experiences a decline in NPP for only the Hamburg model.

Table 2. Percentage Change in Timber Growth Rates to 2145

	Hamburg		UIUC	
	BIOME 3 Predicted Percentage Change in NPP	Percentage Change in Merchantable Timber Yield	BIOME 3 Predicted Percentage Change in NPP	Percentage Change in Merchantable Timber Yield
High-Latitude Forests				
North America	17	34	17	41
Europe	23	4	23	24
Former Soviet Union	53	44	52	66
China	36	27	38	32
Oceania	(16)	10	13	29
Low- to Mid-Latitude Forests				
South America	46	42	23	23
India	45	47	28	29
Asia-Pacific	29	28	12	11
Africa	37	37	21	21

Note: NPP = net primary productivity.
Source: Sohngen et al. (2001).

Table 3 presents the percentage change in regional timber production estimated by the Hamburg and UIUC models for three 50-year periods to 2145. For all periods and regions the change is positive except for the three Hamburg projections for Oceania and two projections for North America.

Table 3. Percentage Change in Regional Timber Production for 50-Year Periods

	Hamburg			UIUC		
Region	1995–2045	2045–2095	2095–2145	1995–2045	2045–2095	2095–2145
High-Latitude Forests						
North America	(1)	12	19	(2)	16	27
Europe	5	2	14	10	13	26
Former Soviet Union	6	18	71	3	7	95
China	11	29	71	10	26	31
Oceania	(3)	(5)	(10)	12	32	31
Low- to Mid-Latitude Forests						
South America	19	47	50	10	22	23
India	22	55	59	14	30	29
Asia-Pacific	10	30	37	4	14	17
Africa	14	31	39	5	17	7
All Forests	6	21	30	5	18	29

Source: Sohngen et al. (2001).

Table 4 draws the summary results from Table 3, adjusted to the year 2050. Note that projected timber production in North America and Oceania has declined modestly under the Hamburg scenario, but only North American production has declined under the UIUC scenario.

Table 4. Percentage Change in Regional Timber Production to 2050

	Hamburg	UIUC
Region	1995–2050	1995–2050
High-Latitude Forests		
North America	(1)	(2)
Europe	6	11
Former Soviet Union	7	3
China	12	11
Oceania	(3)	13
Low- to Mid-Latitude Forests		
South America	19	10
India	22	14
Asia-Pacific	10	4
Africa	14	5
All Forests	6	5

Source: Adapted from Sohngen et al. (2001).
Note: The results for 1995–2045 were straight-line extended to 2050.

To summarize, all the developing regions show positive growth in timber production to the year 2050. Additionally, all the regions with nonnegative growth to 2050 under the Hamburg scenario also show continued expansion to 2145. Also, all regions show timber production expansion after 2050 under the UIUC scenario. Note that all the developing country regions see timber harvest increases both to 2050 and continuing to 2145.

For the period to the middle of the 21st century, total global forest timber harvests increase about 6 percent. The largest percentage increases occur in the developing world, specifically China, South America, India, the Asia-Pacific, and Africa. Europe and the former Soviet Union also experience modest gains, with declines only in North America. Oceania has a decline under one climate model and an increase with the other.

Economic Model: TSM

The timber supply model of Sohngen et al. (1999) is applied to the vegetative changes to project industrial wood availability and costs, which are reported in Sohngen et al. (2001). The results of Sohngen et al. (1999) are for the period to 2060 but are adjusted in this report to 2050. The model focuses on net primary productivity and assumes a carbon fertilization enhancement of 35 percent (Haxeltine 1996). Although some believe this figure high (Norby et al. 2005), the consensus is that fertilization and forest growth are increasing (Boisvenue and Running 2006).

TSM was developed as an optimizing control theory model to focus on industrial timber supply by region and land class. The supply regions have varying locations, species, site conditions, and harvesting and transport costs. Initially, the supply regions consisted of 22 homogeneous land classes. A large, nebulous area of unmanaged land was assumed to autonomously provide a certain portion of the world's industrial wood. Subsequently, additional regions have been added to the model as greater detail became available; substantial detail on the supply factors can be found in Sedjo and Lyon (1990). About 50 regions were used in the 2001 version that generated the results for this study. The model is designed to capture the intertemporal transition nature of the forest inventory, with young trees becoming older and experiencing growth. Both natural and plantation forests are included, although as different land classes. Growth is unmanaged in natural stands but subject to modification through forest management. Plantations are managed intensively. Also, additional areas of plantation can be added gradually, subject to the availability of suitable land and economic returns.

Four transient ecological change scenarios are developed to provide decadal predictions of the ecological variables described above. These include dieback and regeneration scenarios for both the Hamburg and UIUC climate scenarios. The dynamic economic model takes these decadal predictions as exogenous and predicts how timber markets may react. The economic model uses dynamic optimization techniques to predict how a risk-neutral supplier would change planting, management, and harvesting decisions. Aggregating these changes across the global market, the model predicts how harvest quantities and therefore prices will change. The model does not capture feedback effects from the market back onto climate itself because these feedbacks are expected to be small. However, the market does affect ecosystem dynamics, since market forces can facilitate change if slower-growing trees or trees destined for dieback are harvested and if trees designed for the new climate are planted.

The model incorporates forest management and silvicultural practices, alternative species, and various growth rates, harvest costs, and delivered costs to mills. It adjusts the level of management to economically optimal levels and allows for new plantation forests to be established where economically justified. It includes many land classes and site and climatic conditions, which give rise to a host of individual regional supply curves. Locational considerations and transport costs are built in, given the relationship between the regional mills and the major market locations.

The model follows each land class through time, noting the age and size of the various trees. An optimal economic rotation is determined endogenously within the model. However, that rotation may vary with the market price. Each period the separate supplies are aggregated, and together with demand, a price that clears the market is determined. The model is forward looking (rational expectations) and thus considers current demand and supply conditions in the context of future conditions. The model maximizes the sum of producer's and consumer's surplus for each period and for the system.

Given global demand and the supply from different producers and regions, the model determines optimal harvest levels and forest management investments through time. The model has been used to address not only timber supply issues (Sohngen et al. 1999) but also questions of forest carbon sequestration (Sedjo et al. 2000; Sohngen and Sedjo 2006) and long-term international trade adjustments (Daigneault et al. 2007). The version of the model used in this study examines forest modifications in response to climate change (Sohngen et al. 2001): the climate change estimates are applied to ecological systems to project the forest ecosystem around 2050. The underlying economic projections are then applied to this 2050 forest. The approach reports and compares the situation under two climate change scenarios with the projections for the baseline case—that is, a scenario without changes due to climate change.

A slightly updated version of the model was used by Daigneault et al. (2007) to examine the effects of changes in exchange rates on production and trade flows. The basic run of that model, which did not assume climate change or exchange rate changes, was used as the updated base; its results are presented in Figure 5. The global model covers all major timber-producing regions of the world.

Contrary to earlier FAO predictions that demand for industrial timber would grow quickly, to 2.1 billion m^3 per year by 2015 and 2.7 billion m^3 by 2030 (Sedjo and Lyon 1983), actual demand growth has been much slower. For example, the current demand, 1.6 billion m^3 per year, is just slightly above the 1.5 billion m^3 demand in the early 1980s (FAO 2005a). Additionally, there is little reason to expect that the very modest growth trend in industrial wood use will change in the foreseeable future (Sedjo 2004). Although some markets are growing, others are declining. For example, major segments of the paper market, such as newsprint, have declined markedly in some parts of the world, now that use of the Internet is widespread. Also, paper recycling is reducing demand for virgin fiber. Recent FAO projections as well as models of the global forest sector often assume the continuation of more modest demand growth, to 1.8–1.9 billion m^3 per year for 2010–2015.

World demand is factored into the model but in much less detail than supply. The model assumes that demand will increase very modestly over the next 100 years, growing 0.4 percent annually initially and gradually converging to a stable situation in 100 years. This approach is used for two reasons. First, projections based on population and GDP have proved notoriously inaccurate, on the high side (Sedjo and Lyon 1990; Shugart et al. 2003). Second, since the model is forward looking, with trees growing through multiple decades, mathematical convergence required movement to a long-term steady state.

Although the demand for industrial wood has been stable and predictable over time, the use of raw wood as biofuel, biomass energy, and other energy sources could dramatically change the trajectory of future demand (Sedjo and Sohngen 2009). Wood is a potential substitute for fossil fuels, and wood energy has substantial appeal: it is considered renewable and does not contribute to the long-term buildup of atmospheric carbon. Should wood energy become important, the new demand for wood would invalidate current projections. Although wood energy is technically not an industrial wood use, it would draw from essentially the same natural resource base as industrial wood.

Some model-based estimates project a 10-fold increase in biofuel demand during the next 50 years (Alcamo et al. 2005). In many industrial countries, biofuels, particularly ethanol from grains, sugarcane, and other plant materials, have already become an important source of nonconventional transport energy. Biofuels derived from cellulosic biomass—fibrous and woody portions of trees and plants—may offer an even more attractive alternative to conventional energy sources (Kinitisch 2007). Also, wood cellulose can be used in gasification, such as the integrated gasification combined cycle (IGCC) process to produce synthetic gases, including hydrogen. These gases can be further used to produce energy directly or as feedstock to produce other energy products, including ethanol and biocrude. Wood-fired gasification plants can be constructed as stand-alone projects and are now under consideration in some locations. One possibility is that new gasification biorefineries could replace aging traditional boilers in existing pulp mills (Larson et al. 2006). Pulp mills have large energy requirements and handle large amounts of wood. This study, however, assumes that changes in the demand for wood for energy purposes will be modest and have a negligible impact on overall industrial wood demand.

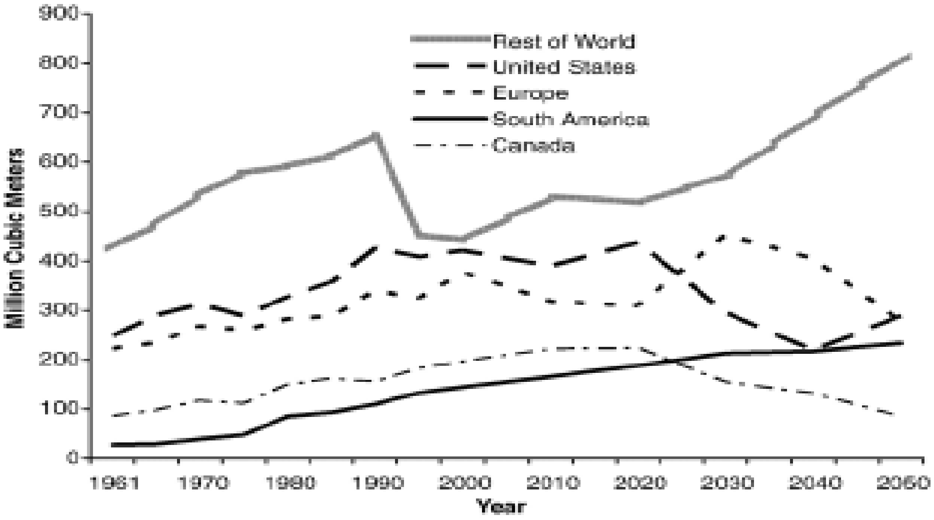
5. Results

Baseline Case: No Climate Change

In the absence of climate change, the world's overall area of forest is projected to decline over the 21st century. Figure 5 provides historical and projected estimates of timber harvests by major global regions in the base case from 1961 to 2050. Even in the absence of climate change, the projections show major changes by region. Harvests from the former Soviet Union states dropped dramatically in the early 1990s and are not expected to return to the levels of the late 1980s until the 2030s. The projections also anticipate that U.S. harvests decline after 2020. Europe follows essentially the same path to about 2020, but production increases thereafter and into the 2030s, after which it declines. Canadian production continues its rise until about 2015, after which it too declines. Throughout the entire period, South American output is projected to increase because of continuing expansion of planted forests and timber production. Production from the rest of the world will not achieve 1990 levels again until after 2030, when the former Soviet states fully recover. The increases in this category also reflect increased timber supply from fast-growing industrial wood plantations in subtropical regions—Australia, New Zealand, the Asia-Pacific countries, and parts of Asia.

The driving force in global timber production and the incremental increases in timber production has been the expanding area of managed subtropical plantation forest. As in recent decades, most of the incremental increases in production are projected to occur in plantations of nonnative species, such as southern U.S. pine, Caribbean pine, Monterey pine, and eucalyptus, established in subtropical regions—most importantly South America, but also parts of Africa, Asia and Oceania.

Figure 5. Timber Supply for Baseline Scenario, 1961–2050, By Region



Source: Daigneault et al. (2007).

Prices are a signal of relative scarcity or abundance. Figure 7 presents wood price projections until 2140 for both the baseline case and the two global warming scenarios (Sohngen et al. 2001). Note that the baseline has the highest prices, reflecting greatest relative scarcity. In this scenario timber prices are projected to rise approximately 0.4 percent per year during the period to 2050 as increases in demand slightly outrun productivity increases. As noted, most of the growth in production is projected to occur in plantations of nonindigenous species established in subtropical regions of South America, Oceania, Asia-Pacific, and Africa.

These areas have been successful in converting marginal agricultural lands and native forestlands to high-value forest plantations. The model conservatively projects subtropical plantations to increase in the baseline by 273,000 hectares (ha) per year on average, with 27 percent of the new plantations in South America, 20 percent in Oceania, 8 percent in Asia-Pacific, and 25 percent in Africa (Daigneault et al. 2007). The baseline plantation establishment prediction is somewhat lower than the recent average annual increase in nonindigenous plantations in subtropical regions, 6 million ha per year for the period 1980 to 1990 (FAO 1995).

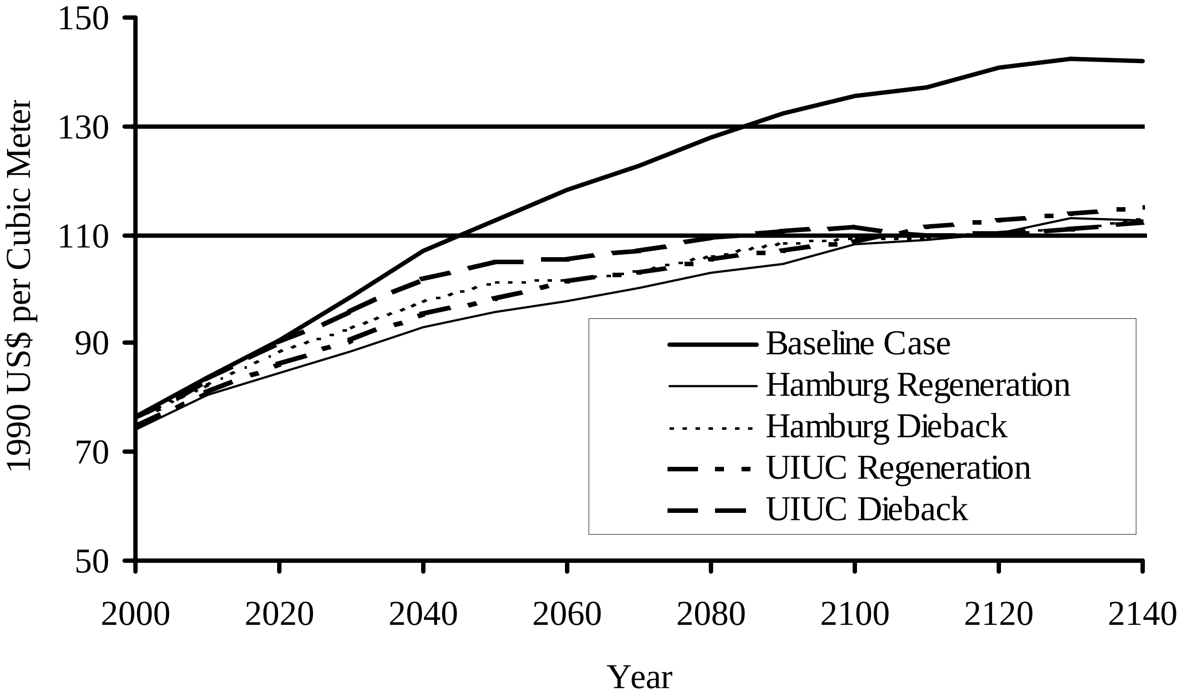
Subtropical plantations have a large effect on the global figures because they commonly grow at rates in excess of 10–15 m^3 per ha per year, whereas many temperate forests grow at only 2–5 m^3 per ha per year (ABARE/Jaakko-Poyry 1999). The total area of fast-growing industrial wood plantations is projected to expand from around 70 million ha currently to around 130 million ha in 2050. Total wood production from these plantations is projected to increase from about 200 million m^3 per year, or about 13 percent of total wood supply, to about 700 million m^3, or about 41 percent of total wood supply, by 2050. Total production from all planted forests is forecast to reach 75 percent of total global production by 2050 (Irland et al. 2007).

Results with Climate Change

The two climate change scenarios (Figure 6) give lower prices than the baseline case, with the dieback scenario price somewhat higher than that of the regeneration scenario. In both cases, however, timber supplies are expected to be enhanced by climate warming.

The projections suggest that global timber prices (denominated in 2000 real southern U.S. softwood log prices) rise from $114 per m^3 to $132 per m^3 from 2000 to 2050, an increase of nearly 0.4 percent per year. However, the total quantity of timber produced globally increases only slightly over this time period, from 1.64 billion m^3 to 1.71 billion m^3 per year. The regional results are reported in Tables 1, 2, 3, and 4 (above) to the year 2045. For all regions except Oceania, the projected changes in direction are the same through time, although the magnitude of the change varies somewhat.

Figure 6. Global timber prices over time



Source: Sohngen et al. (2001)

The economic model predicts that global timber supply increases and prices decline relative to the base under all scenarios (Figure 6). As expected, the regional and temporal effects on timber production for the two climate scenarios are different (Table 3). In the Hamburg scenario, production increases most heavily in low- to mid-latitude regions because climate changes are predicted to be mild and the trees respond well to the higher levels of carbon dioxide. In the near term (1995 to 2045), the Hamburg model anticipates the largest relative production losses in mid- to high-latitude regions of North America, the former Soviet Union, China, Oceania, and Europe—regions that currently supply 77 percent of the world's industrial wood (FAO 1996). These relative declines reflect the large productivity increases in the low- to mid-latitude regions, including South America, India, Asia-Pacific, and Africa. In the long run, productive species replace the lost forests, so productivity increases. Initially, prices are relatively lower in the regeneration scenario. In the long run, however, the period of conversion ends and the same productive forests take over, causing long-run prices to converge in both scenarios. The difference in prices between the dieback and regeneration scenarios declines before the conversion process ends because it takes longer for more productive species to take hold in the regeneration scenario. In the UIUC scenario, production increases are similar for all regions, but larger tropical warming reduces productivity gains in low- to mid- latitude regions.

Although the former Soviet Union is predicted to gain significant production relative to the baseline in either scenario, these increases take many years to affect markets because species grow slowly there. Europe harvests heavily during early periods to avoid economic losses from dieback in its generally older stock of trees. In contrast, North America has relatively younger timber stocks initially, and it reduces harvests initially. In the baseline projections, most of the increase in timber harvests will occur in these subtropical regions, and climate change appears to strengthen this trend as managers adapt quickly with fast-growing, nonindigenous plantation species.

Early forest losses are offset by moving more productive southern species farther north. “Net Area Change” in Table 1 is the prediction of the relative area of forests after climate change by BIOME3. This model predicts relatively large increases in forest area. However, given the low productivity of polar forests, even with climate change, the newly established forest stocks will be small in 2050 and are unlikely to become major industrial forests, for the reasons discussed below. Also, one assumption of the model, that forests are not converted into high-quality agricultural land, limits most of the expansion to conversions of one forest type for another or to shifts of low-value grasslands and tundra to forests. Accessible forests in the economic model consequently increase by only 5 percent. Most of the increase in forestland is predicted to occur in inaccessible boreal and tropical regions (31 to 41 percent) that are never used for timber harvests.

In summary, for the most part, the changes in forest areas are consistent with recent experiences in markets. To the year 2050, most of the losses occur in high-latitude regions, with the lower-latitude developing world generally benefiting. There are slight losses in North America’s accessible forest area. Europe and the former Soviet Union gain forestland.

6. Discussion

In recent decades industrial forestry has undergone major changes as planted forests have been established in an increasing number of countries and regions. Often, these areas are not the traditional wood producers but instead, tropical and subtropical countries (Bael and Sedjo 2006). Indeed, an increasing percentage of the world’s industrial wood comes from planted forests, and the fraction is expected to exceed one-half by 2050, even in the absence of any climate change. Climate change could be expected to accelerate this process.

Forest Managers' Adaptation Options

The timber-producing sector has a high degree of potential for adaptation to climate change (Sohngen 2007; Seppala et al. 2009). In the near term, damaged forests can be harvested and the usable wood commercially utilized. In the longer term, the forest can usually renew itself through natural regeneration, although not always with the same species. In the very long term, the forest can migrate and adapt to a new climate, although not all new conditions will be conducive to forest.

Figure 7 describes how adaptation through harvesting and replanting can substantially reduce losses that would otherwise occur if natural systems were allow to adapt on their own. The dieback regime often assumes that tree mobility is exceeded by the rate of climate change (Davis and Shaw 2001). Dieback per se need not threaten the adequacy of timber supply if a portion of the dying trees can be salvaged; moreover, we currently have huge surpluses of forest stocks over the requirements of industrial wood demand. Note that in a dieback scenario, human management plays a large role in both salvage logging and promoting rapid regeneration. Salvage logging captures some of the timber values that might otherwise be lost, and timely artificial regeneration shortens the time to harvest of future timber. Humans can thus facilitate an accelerated adjustment.

A major set of adaptations is associated with the planted forest. A decision to plant involves considerations of location, species, stock quality, and many other factors. Managers of short-rotation plantations could simply replant with the same species but using seed from a more appropriate provenance. Forests can be regenerated with rapidly growing species chosen for their adaptability, as well as timber production and/or other forest values. Other adaptations that may be useful during climate warming include shortening rotation periods, harvesting target species, salvage harvesting where damage has occurred, replanting of new species, and adjusting future investment levels, including relocation of plantations.

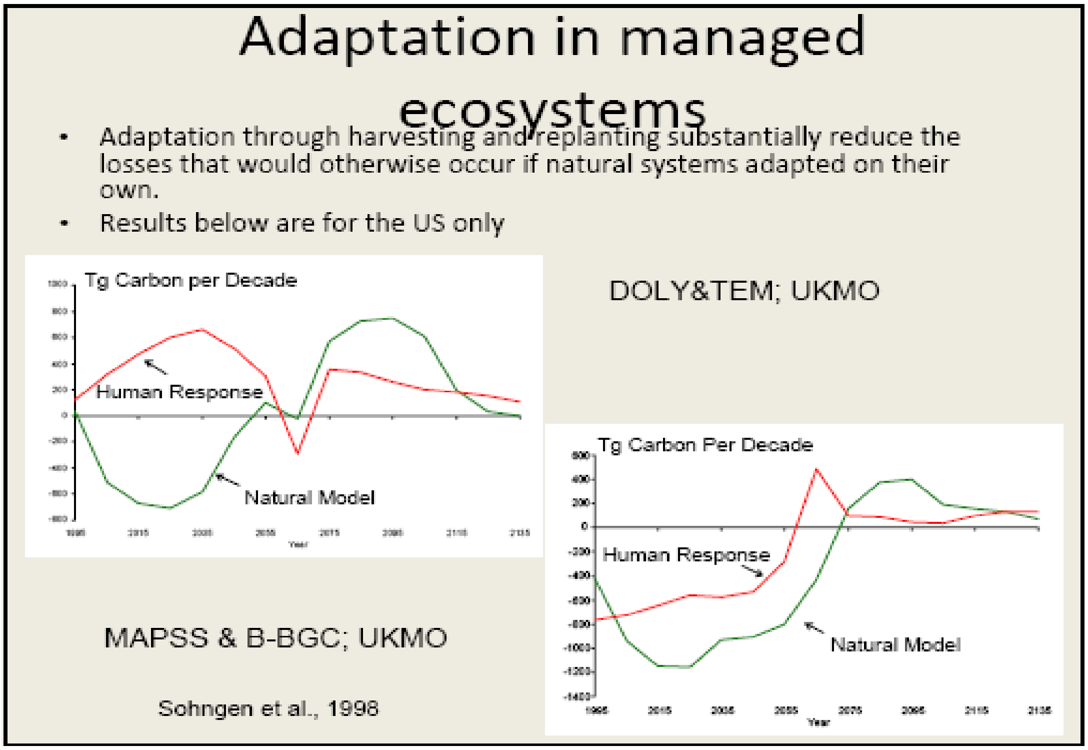
The adjustment problems for mills are generally negligible, since the new species are likely to be similar to the ones replaced; for example, slash pine would be milled the same way as loblolly pine. Thus, where artificial regeneration is practiced, the adaptation costs are likely to be very small. The challenge for managers is replanting with the appropriate species and adjusting the management regime to the new climate situation.

In a recent paper on forest adaptation to climate change, Roberts (2009) points out that policies that serve multiple purposes can be useful in adapting to climate change. He notes that some forest managers are already beginning to anticipate climate change in their management decisions. Also, he points out that existing policies tend to be reactive rather than proactive.

Given the uncertainties of how climate is likely to affect any specific forest, however, one might maintain that a reactive policy with a high degree of flexibility is highly appropriate.

Reactive adaptation would include activities to mitigate any climate-related damage to the forest, such as efforts to control or limit the effects of wildfire. Limiting wildfire may extend the life of the trees until the timber can be harvested. However, wildfire suppression may lead to larger fires in the longer term. Salvage logging is another reactive adaptation: after damage associated with a natural event, such as fire or infestation, the remaining merchantable timber in the forest is harvested and utilized.

Figure 7. Adaptation in Managed Ecosystems



Adaptation in managed ecosystems

- Adaptation through harvesting and replanting substantially reduce the losses that would otherwise occur if natural systems adapted on their own.
- Results below are for the US only

DOLY&TEM; UKMO

MAPSS & B-BGC; UKMO

Sohngen et al., 1998

Source: Reprinted from Sohngen et al. (1998).

Forests compete with other uses for land. Increasing development and growing populations are often associated with forest clearing for agriculture. These pressures on forestland will continue, with or without climate change. However, climate change could modify the comparative productivity of the lands for the various uses. Thus, in some cases forest uses may be benefited by climate change, and in others they will be disadvantaged.

Costs of Adaptation

The costs of establishing a new tree plantation depend on the site and general economic conditions within a country. Establishment costs on a new site, including land, could run about $1,000 per ha—approximately double the cost of replanting a stand after harvest (Sedjo 1983, 2004). Thus, the incremental costs of relocating plantations is roughly $500 per ha. Rehabilitation of an existing forest is likely to be a different type of project. A 1998 World Bank project in India (49477) put the costs of the rehabilitation of 27,000 ha of forest at about $18.8 million, or about $666 per ha. A World Bank fire suppression project in the southern Amazon in Brazil (PO7882) was put at $1.4 million. The extent and thus the costs of the climate damages depend in part on the effectiveness of any mitigating activities.

We calculated the present annual average costs of investment to offset climate-related damage for five-year periods between 2010 and 2050. About 0.5 million ha of forestland is harvested each year in developing countries, yielding approximately 200 m^3 per ha. About 200,000 ha, or 40 percent, is in tree plantations. If 10 percent of the plantations (20,000 ha) need to be relocated each year, at $1,000 per ha, the replanting investment costs would be about $20 million worldwide. However, the incremental costs associated with relocation are estimated at about one-half the replanting costs, since replanting would occur in any event and the incremental costs would be those for accessing and preparing the new site. Thus, total global replanting costs would be about $10 million annually. Incremental fire control costs plus funds for rehabilitation of natural forest could be about $20 million annually. Rehabilitation could cost about $20 million (40,000 ha times $500 per ha). This might have only a minimal effect on harvest levels, since the rehabilitated areas may not be an important part of the timber base. The total global incremental cost for relocation and rehabilitation could be approximately $50 million per year for the developing countries. However, the amount related to timber and fire control is about $30 million, since the replanted costs could be viewed as the responsibility of the plantation ownership.

Although fire suppression costs can be very high, the relevant cost estimates for this report are the incremental costs related to climate change. In the United States, much of the current fire suppression activity is unrelated to timber harvests and involves protecting development in and adjacent to forests.

Public Sector Investment

Forest ownership varies considerably across the globe. Relevant public sector investment could consist of roads and other infrastructure for harvesting, although forest roads are usually the responsibility of the forest harvesting entity. If forests are relocated, some new major roads might be required to facilitate the delivery of raw wood to the mills. Where forests are publicly owned or subsidized, the public investment could take the form of tree planting to replace or anticipate forest losses. In some cases it could involve aerial seeding and other activities to facilitate the more effective migration and regrowth of the forest, although aerial seeding is usually not recommended for commercial forests.

"Soft" adaptation measures refer to reliance on the natural resilience, mobility, and reproductive capacity of the forest. This natural resilience may need to be enhanced. For example, species mobility for natural forests can be facilitated through human activities such as aerial seeding and removal of obstructions that prevent migration. Such actions are probably less appropriate for industrial forests. Fire control might also be viewed as a soft adaptation policy.

What is the proper public sector role in supporting adaptation to climate change? Should international aid agencies provide support or compensation? Public sector support is often viewed as appropriate in the case of catastrophes and disasters. However, the nature of climate change, natural or human induced, is such that we have time to anticipate the consequences and undertake adaptive responses, such as the activities described in this report

One can think of warming as an externality associated with the free or low-cost disposal of a "bad," in this case greenhouse gases (GHGs), into the atmosphere. Emissions have been viewed as costless when, in fact, there are real costs associated with GHG buildup. The generator of a negative externality is typically held liable for its associated damages. Thus, the countries of developed world, which have a long history of releasing GHGs into the atmosphere, would have liabilities for these earlier as well as current emissions. Emerging countries like China and India are also now major generators of GHGs and so also have liabilities. The larger a country and the longer the country has been industrialized, the larger its share of the GHG emissions. The developed versus developing country dichotomy is an approximation of this reality. Thus, in concept, compensation should flow from developed to developing countries in recognition of the source and size of the damages. How should such transfers be allocated between the public and private sector? Using the common law paradigm, both private and public entities are eligible for compensation for damages from externalities. For forestry, natural forest restoration and/or compensation would seem appropriate regardless of ownership. Investments to reduce damages from fires, infestations, wind-throw, and storms should in principle address these problems, regardless of the forest ownership, for the same common law reasons. For plantation owners, public or private, the damages are likely to be modest, for the reasons articulated in this report. However, the loss of the market values of the former forest plantations could be large if those lands have few alternatives uses in the new climate—for example, if forestland becomes arid grassland. Finally, however, the rationale developed above may be overwhelmed by real world economic and political realities.

Limitations

The results of this study are subject to many kinds of uncertainty, given that the model runs must make assumptions about everything from the extent of global warming to the pace of technological change to the behavior of forest managers.

Modest technological change is built into the basic model and is not addressed separately for the industrial forest industry. Technological change could also be part of the adaptation process; for example, tree improvement could facilitate adaptation to the drought conditions or infestations associated with climate change.

No serious cross-sector measures are identified. The obvious one would be the question of alternative land uses for forestry and agriculture, such as pasture and cropland. The Sohngen et al. (2001) approach does not allow for the automatic conversion of useful agricultural land to forest uses as climate changes unless those lands are not being actively managed or a conscious decision is made to convert the land to forest cover. Indeed, much of the newly developed plantation area of the world reflects land-use changes, typically from abandoned and marginal agriculture use to intensive forest plantation management. Climate change, in the form of changing temperature and/or precipitation, could shift the comparative productivity of an unmanaged natural site from some uses to different uses, such as from grassland to forest.

A major limitation of this study is the range of possible climate changes generated by the variousmodels. Under a different model, the results for any of the regions or countries examined could be very different. For forests, precipitation is probably as important as temperature, at least in the temperature ranges under consideration.

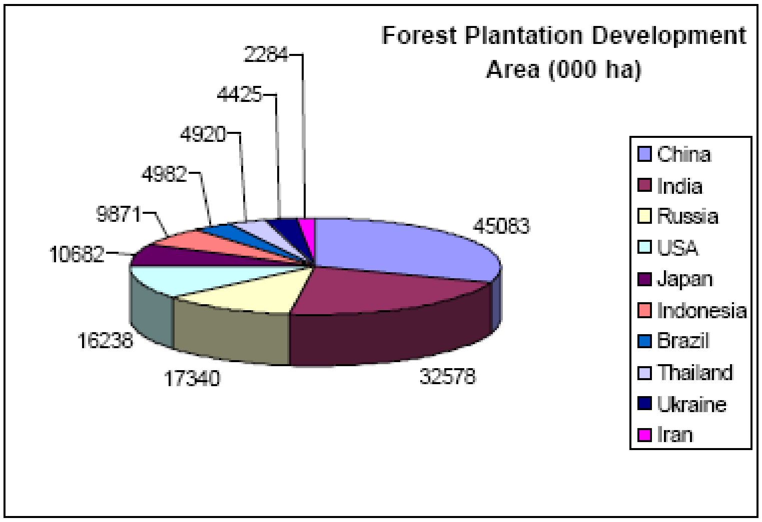
Useful research advances for forest and industrial wood may be found in the development of trees that can flourish under changing climatic conditions. Also, for industrial forestry, short rotations facilitate adaptation. It is likely that future breeding will develop trees customized to the site and that the genetic features of each new rotation will be adapted to the anticipated changing conditions. Short rotations are likely to becommon.

7. Country Case Studies

Three nations—Brazil, South Africa, and China—generate relatively large volumes of industrial wood from planted forests, and all have been expanded their planted forest estates in recent years. How will they fare under climate change?

As Figure 8 shows, China and Brazil are among the leading countries in forest plantation establishment, with China ranked number one, and Brazil, seven. Whereas China has a large portion of its planted forest dedicated to protection functions, however, Brazil has been rapidly increasing its production of industrial wood. South Africa has had a much more modest expansion of planted forest, but its domestic pulp and paper industry is very active in international trade.

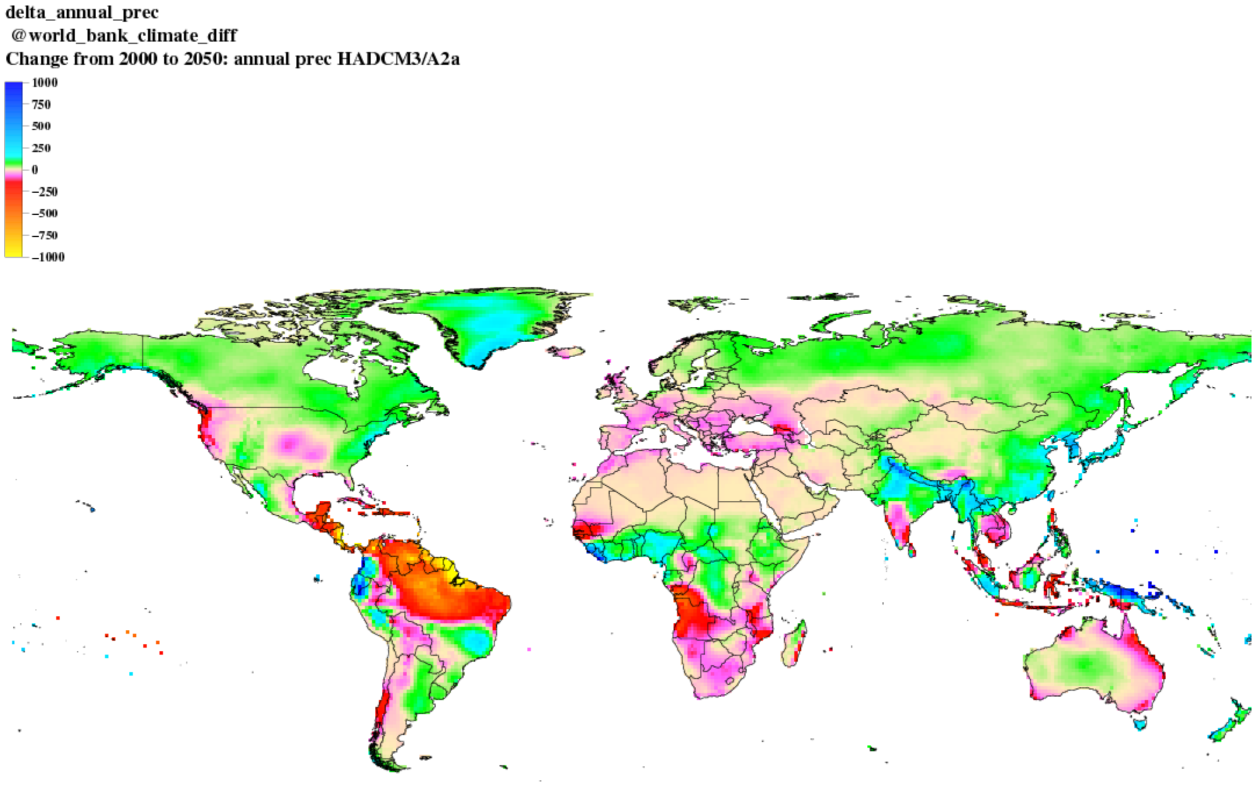
Figure 8. Forest Plantation Area, by Country



Source: Reprinted from Seppala et al. (2009).

Figure 9 provides a global overview of precipitation using the Hadley climate model. Hadley projects very high maximum temperatures and also severe precipitation limitations for some regions.

Figure 9. Expected Change in Precipitation, 2000–2050 (Hadley Model)



Source: Provided by Gerald Nelson.

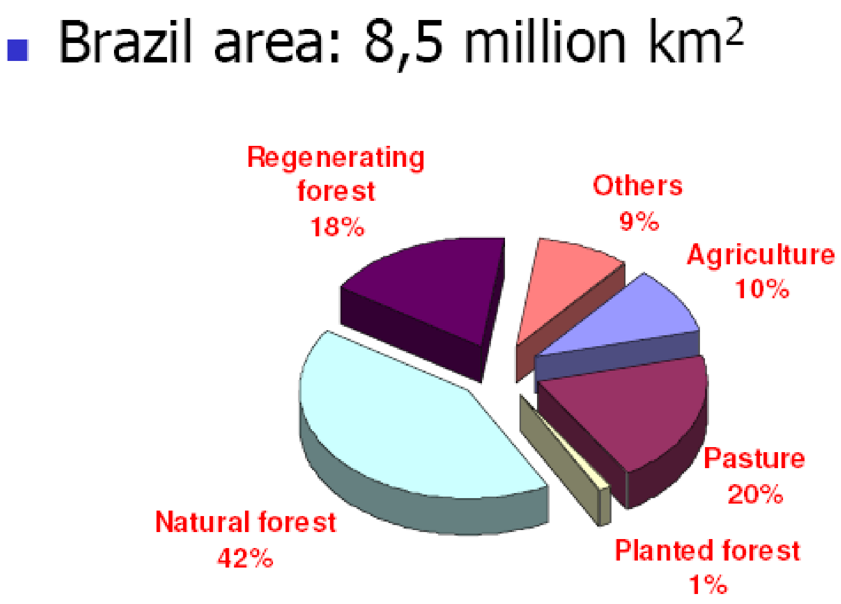
The projected precipitation levels should have positive effects on forestry production in southern Brazil and southeastern China but are not as promising for forestry in South Africa. The following sections describe the status of industrial forestry and the implications of climate change for the forest sector in Brazil, South Africa, and China.

Brazil

Current Forest Resource

Brazil’s tropical forests make up 42 percent of its total land area, and its plantations, 1 percent (Figure 10). It is estimated that the natural forest sector accounts for about one-half of the total value of industrial wood (about $22 billion) but only about 20 percent of the over $10 billion in wood product exports. Brazil also has harvests from its tropical forests. The federal forest is 210 million ha, of which 12 million ha is available for concessions. However, actual forest concessions appear to be only about 300,000 ha. Sustainable systems involve low-intensity selective logging, with only a very few trees harvested per ha. The goal involves harvesting 30 m^3 per ha in large trees every 30 years. This intensity would involve the harvesting of only 1 m^3 per ha per year, on average. The major environmental effects of harvests in these areas relate to roads and the possibility of spontaneous migration that could lead to land-use changes.

Figure 10. Brazil’s Land Area, by Ecosystem Type



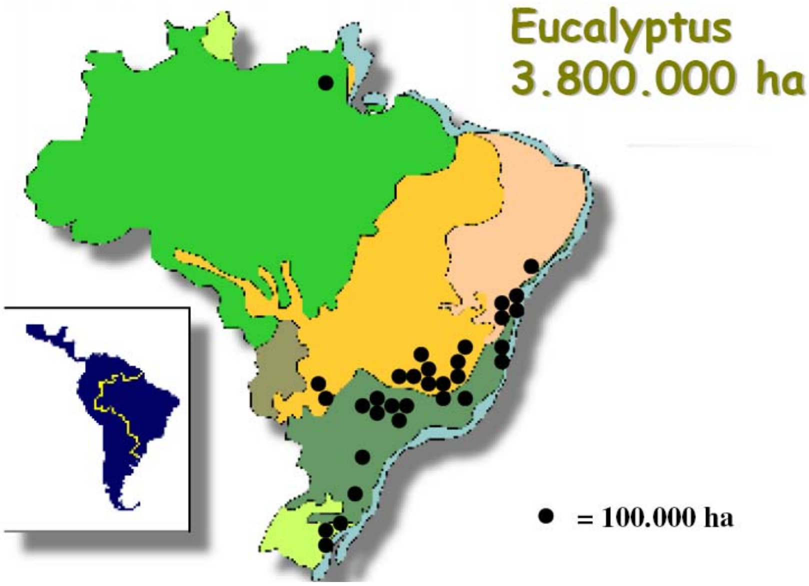
Source: Fernando Seixas, ESALQ/USP, Piracicaba, SP Brazil (2009).

Although important, natural forests are declining in significance as sources of industrial wood as plans continue to establish an additional 500,000 ha of plantation forest annually. About 6 million ha (1 percent) of Brazil’s land area is planted forests (Seixas 2009), but this is the core of Brazil’s forest industry. In recent years about 600,000 ha has been planted or replanted annually, about 40 percent of which involves newly established plantations. Eucalyptus and pine constitute 5.6 million ha (93 percent) of the total planted forest. Eucalyptus is found predominantly in the southeast and pine in the south. Currently, eucalyptus is found in warmer regions than pine, in part because it is frost sensitive (Figures 11, 12). Tree breeding efforts currently underway seek to develop frost-resistant eucalyptus trees. This could expand the area suitable for plantations. Brazil estimates the 2007 sustainable harvests of its pine and eucalyptus plantations at 191 million m^3 annually, with eucalyptus production being more than twice that of pine (Seixas 2009).

As a result of increasing establishment of fast-growing industrial wood plantations, South America generally and Brazil in particular are projected to continue expanding market share, experiencing an annual increase in production of approximately 0.8 percent per year over the next 50 years. Under the baseline, most of these increases are derived from harvests in industrial wood plantations. The area of land devoted to plantations in South America is projected to more than double during the coming half-century, from 10.7 million ha in 2008 to 26.7 million ha in 2050. Although total harvests are expected to increase in the region, baseline harvests from natural tropical and subtropical forests are projected to decline over the next 50 years. Industrial wood plantations are projected to account for as much as 71 percent of the timber harvested from all of South America by 2050 (Daigneault et al. 2007).

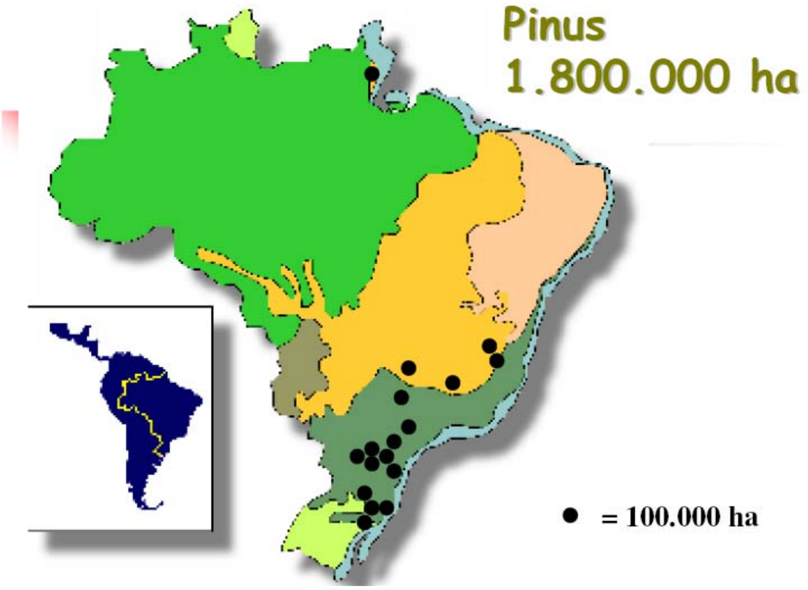
Figure 11 identifies areas of major eucalyptus plantation activity, and Figure 12 identifies the areas with major pine plantations. Most of the plantations are in the area that was formerly the coastal forest, savannah forest, or *caatinga* (dry forest vegetation). Note that the north-south range is somewhat greater for eucalyptus than for pine. Should warming move forest toward the poles, the planted forest would migrate to the south. It is likely that both forest types could be relatively easily shifted to southern Brazil.

Figure 11. Eucalyptus Plantation Areas in Brazil



Source: Fernando Seixas, ESALQ/USP, Piracicaba, SP Brazil (2009).

Figure 12. Pine Plantation Areas in Brazil



Source: Fernando Seixas, ESALQ/USP, Piracicaba, SP Brazil (2009).

In general, eucalyptus is the preferred species because of its very rapid growth. Adaptation to global warming would involve adjusting species and if necessary, relocating plantations. Indeed, warming would probably allow continued, perhaps greater, expansion of the planted area of forest, since few plantation areas would need to be abandoned and cooler areas should warm. Moreover, the large number of eucalyptus species allow, in principle, for substitution of more suitable varieties. Knowledge of the growth habits and likely wood performance properties of eucalyptus and pine is currently limited to a relatively few species, however, and additional research in this area could be important.

Brazil plans to establish more industrial plantation forests than envisioned in the projection model of Sohngen et al. (1999). The government goal is to plant about 500,000 ha annually. Because of the very rapid growth of its planted forest trees, Brazil has a competitive advantage over most other industrial timber-producing countries. Tree improvement has furthered this advantage as biological growth rates have continued to rise. Investment in the forest and wood-processing sectors has been substantial and is expect to continue at a relatively high level. Short rotations, continuing tree improvement, genetically improved stock, and large areas for expansion suggest that the Brazilian forest industry is ideally positioned to adapt to climate change.

Climate Change

Brazil is expected to see warming in the plantation areas of the southeast and south. However, the costs of warming to Brazil’s planted forest industry are likely to be minimal. Warming would expand the frost-free areas suitable to eucalyptus to the south. With warming, appropriate species of southern (yellow) pine could continue to be planted in current locations, or slash pine might be substituted for loblolly pine should the warming be excessive. Also, tropical (Caribbean) pine could be introduced, should temperatures rise substantially. In general, the pine and eucalyptus species currently in use are well suited to be redistributed within the regions of the country. The same species also offer the ability to adjust, within limits, to changing precipitation and moisture conditions.

The changes that climate change will bring to the tropical forest area of Brazil, largely in the Amazon region, remain to be seen. A few climate models suggest major vegetative changes, but most suggest that the tropical forest will persist. In any event, the changes anticipated between now and 2050 appear unlikely to dramatically disturb the overall forest or the timber production drawn from it. Over the longer period, should forests persist, changes in tree species are to be expected in general (Shugart et al. 2003) and also for tropical forests (Sedjo 2003). Should forestland give way to grasslands, attempts to maintain the land in forest would probably be futile and alternative land uses would probably be both low cost and wise. In summary, it is likely that climate change would generate more benefits than damages for Brazil's wood-producing industry, and little public investment is warranted.*Offsetting investments.* Although the relocation of planted forest might best be left to the private sector investors in those forests, some sensible types of public investments could mitigate the impacts of climate change on Brazilian forests. A system of forest fire control is probably desirable both in the plantation regions and for natural forests. Indeed, fire is a continuing problem in parts of the Brazilian forest, independent of climate change, and the World Bank has a history of supporting fire control capacities. (See the project appraisal document, Brazil – Amazon Fire Prevention and Mobilization Project March 2001.) Although natural forests could provide an useful agent facilitating fire adaptation to the new climate (Sedjo 1993), a fire control capacity is desirable to limit damage to infrastructure and development around the forest. Also, projects to promote forest rehabilitation on a selected basis, especially in the natural forest, may be desirable. Since wildfires in subtropical Brazilian forests are common, a program with an annual additional budget of perhaps $2 million, based on earlier World Bank fire projects, might be appropriate.

South Africa

Current Forest Industry

South Africa has a very small area of natural forests, largely in scattered patches. The total area of 327,600 ha constitutes only about 0.2 percent of the land area of the country. However, open natural savanna woodlands occupy another 28 million ha (DWAF 1996).

Establishment of forest plantations in South Africa was initiated in the late 19th century with exotic tree species, and the areas planted increased rapidly after 1920. Plantation species consist largely of eucalyptus and pine. Trees were planted on high-lying grassland areas with acceptable precipitation and other conditions suitable for forest plantations. Afforestation expanded more rapidly after the middle of the 20th century, and a domestic pulp and paper industry emerged. The annual rate of planting during 1981–1990 was about 18,000 ha, and the total planted area was 1,487,000 ha in 1995. The pace of planting has varied, decreasing from its peak of 45,000 ha in 1991. More recently, new afforestation has proceeded at a level of around 11,000 ha per year, constrained largely by the availability of suitable land, which is limited by either water-use regulations or insecure tenure.

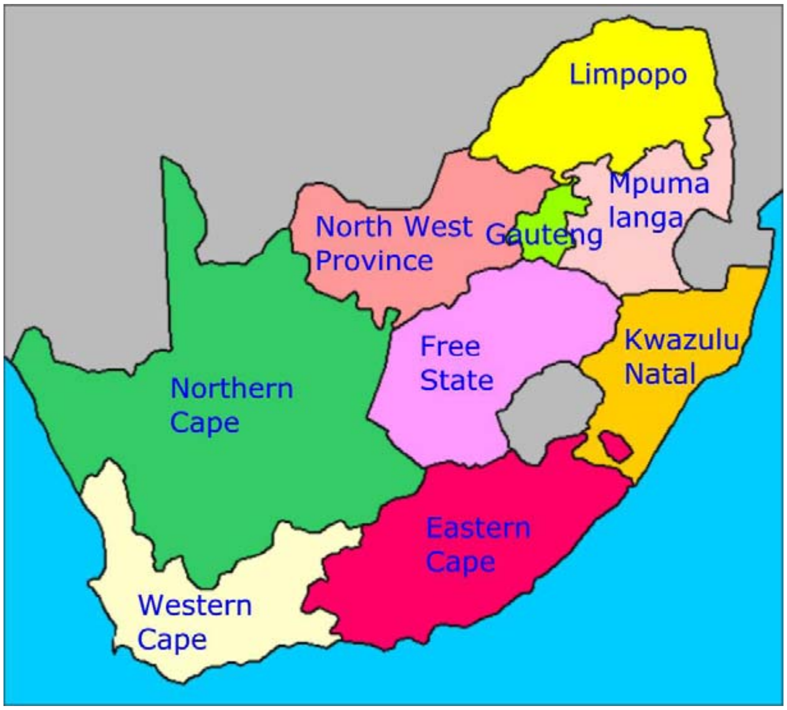
Several large private companies together own about one-half the plantation area; of the remainder, a large portion is owned by the state and the rest by some smaller private companies. South Africa's forest plantation area has continued to increase. The state-owned plantations have primarily been geared to the production of sawlogs, whereas the privately owned plantations are mainly used for the production of pulpwood. The South Africa pulp and paper industry is easily the largest in Africa and it is an important international producer and exporter.

Growth rates of pine in South Africa are about 16 m^3 per ha per year, with harvest rotations varying from 15 to 25 years depending upon the intended use (Sedjo 1983). Eucalyptus growth is more rapid and rotations shorter. The country's plantation estate consists of 52 percent in pine, 39 percent in eucalyptus, and 7 percent in wattle, with the balance comprising other species, such as poplar. Because of water shortages and consequent regulations, the forestry sector has been put under tighter control and the cost of planting has increased (SH 1999). The current strategy is to enhance the annual production of roundwood from the existing plantation areas by applying genetic improvement and better silviculture to all plantation areas.

Climate Change

A major constraint on planted forest in South Africa is water. The country is arid and semiarid in the west, becoming wetter as one moves eastward. Plantations are concentrated in a region where rainfall exceeds 800 mm per annum, specifically, in a swath of running from West Cape in the south to the northeast and parallel to the southeast coast of South Africa to Limpopo in the northeast. Other provinces with substantial tree plantation are Mpumalanga, Kwazulu Natal, and Eastern Cape (Figure 13). Exacerbating the uncertainty about water supplies, South Africa is subject to drought (Vogel 2003). The viability of South Africa's forest plantations would likely depend more on global climate change's overall effects on precipitation and moisture rather than on temperature. A number of climate studies suggest that South Africa is likely to have drier winters, and the Hadley model projections (Figure 9) suggest moisture difficulties by 2050. However, some of the land limit constraints could be relieved with more secure tenure rights.

Figure 13: South African Provinces



Source: Department of Water Affairs and Forestry, South Africa.

Timber production would likely suffer if the climate turns drier, with little possibility of investments to offset the decline: irrigated planted forests rarely make financial or economic sense. The land would likely revert to grasses, with grazing being perhaps its most economically attractive use. Alternatively, should moisture increase, the area suitable for plantation forests would likely grow, even independently of temperature, resulting in increased industrial wood and wood products from South Africa. Moreover, increased moisture could potentially open the savannah lands of South Africa to planted forestry, since moisture often determines whether the vegetation is forest or grasses.

Should the tree plantation value be lost, the financial cost would be the value of the plantation as an asset. The present value of 1 ha of South African plantation forest was estimated to be about $3,700 in 1983 (Sedjo1983). Adjusting for inflation, the current value could be in the neighborhood of $10,000 per ha. The costs of establishing additional plantations, where suitable, are estimated to be quite low in South Africa because of the relative ease of site preparation costs and low labor costs (Sedjo 1983).

The role of public investment to offset climate impacts on industrial forests appears limited. Many of the forests are public, although the large paper industry is private. A sensible approach, should climate disadvantage and undermine forest plantations, might be to focus investments on retraining of the displaced labor force.

China

Forest Resource

China has a variety of geographic and ecological and climatic conditions (Figures 14, 15). Since the late 1970s, China's forests have made a remarkable recovery in large part because of the government-sponsored program to establish large areas of planted forest. Indeed, China has been the world's leading country in the planting of new and restored forests, both to increase industrial wood production and for other reforested and afforested purposes. FAO (2005) reports that China's man-made forests have increased from 28 million ha in 1986 to 48 million in 2001, or an average of about 1.33 million ha annually. About 45 million ha of China's forest area is planted (FAO 2005, Figure 6.3), and China's forested land area increased from 107.2 million ha to 158.5 million ha between 1986 and 2005. In a separate study that draws on the FAO data, Kauppi et al. (2006) estimate that China's forest area has been increasing by about 1.5 percent annually in recent years, among the most rapid worldwide. These numbers suggest that forested area in China has expanded from about 11 percent of the total area in the mid-1980s to about 16 percent today.

Figure 14.Ecosystem Areas by Type: China

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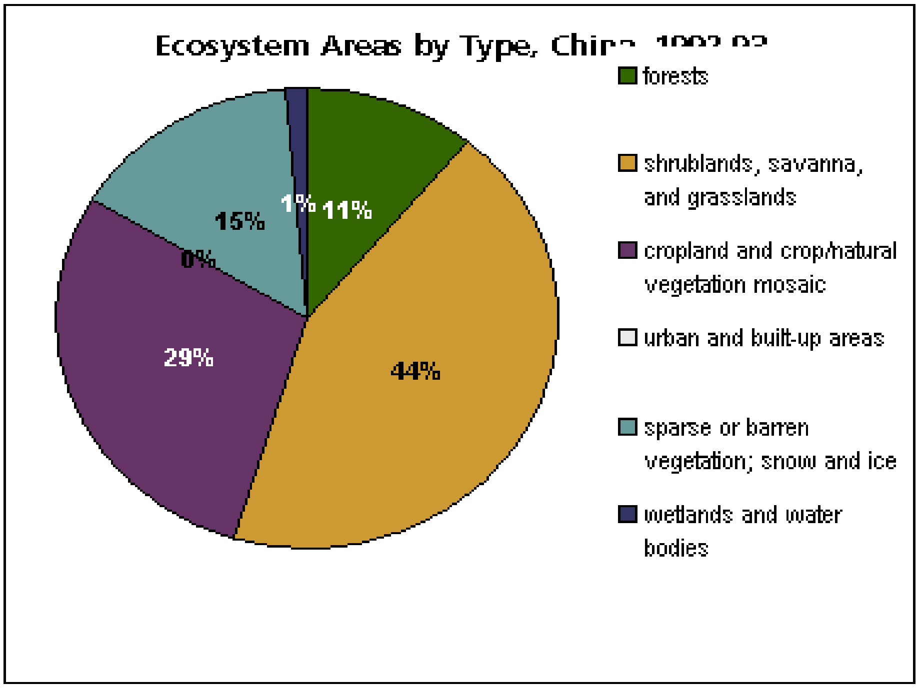
Source: World Bank.

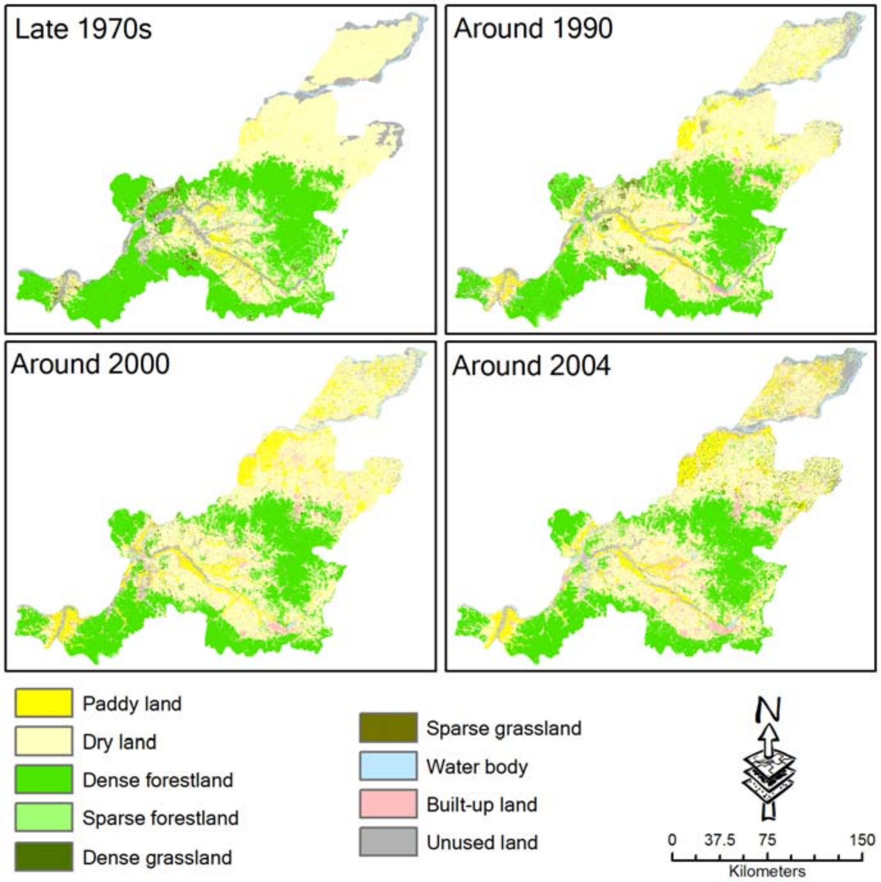
Figure 15. China's Land Area by Ecosystem Type



It is anticipated that China will continue to expand its forest even in the absence of climate change. FAO data reveal that China estimated about 86 million ha of timber forest and 62 million of protection forest for 2005; the protection forest has increased more rapidly than the timber forest. A declining portion of the forest was dedicated to firewood.

China's forests are located largely in the northeast, which is temperate, and the southeast, which is subtropical. The Haldey map (Figure 9) suggests that both regions will be modestly advantaged by climate change to the mid-21st century. More generally, IPCC (2007) projects that most of China will experience increased precipitation, the west being the exception. This view is consistent with the estimates of Sohngen et al. (2001). Figure 16 depicts the land cover of Heilongjiang Province, in the northeast. This assessment discloses forest decline through the 1990s but a modest recovery since then.

Figure 16. Land-Use Change in Heilongjiang Province



Source: Shen et al. (2009).

Although China is an important producer and exporter of industrial wood products, it is a relatively modest producer of raw industrial wood. Much of its wood used for processing is imported from a variety of suppliers, including Russia, the Asia-Pacific, and North America (http://www.woodmarkets.com). Even though its forest planting programs target production of more industrial wood (protection forests being the other main goal), increasing the amount of domestic wood for domestic processing is not critical, provided that wood imports continue unobstructed.

Climate Change

For China, the challenges of climate change to its industrial wood producing forests appear modest. The exception could be insect infestations, which have tended to affect largely the non-timber-producing poplar forests in the interior. China is responding to this threat with generically engineered poplar trees that are resistant to the infestation. Most timber trees have not been seriously affected. However, infestations and genetic adaptations could raise the costs of adaptation. The effects of climate change on forestry anticipated by 2050, as reflected in Sohngen et al. (2001) and in the IPCC map, suggest an overall improving situation for forestry and industrial wood production in China. This situation should be enhanced by the active policies of forest establishment, management, and protection being undertaken by the Chinese government. Adaptation costs that might be required by climate change may be modest. Productivity in the relevant regions is anticipated to increase, benefiting regions currently in forest cover. Additionally, China is continuing to establish planted forests for both environmental and industrial wood purposes. Thus, should climate-related problems occur in forest production, modest changes in the choice of new tree planting stock should be sufficient to adjust to the modified climate.

In recent years the World Bank has provided financial assistance to China for at least two forestry development projects that involved planting trees. However, the impacts of climate change on China’s industrial forestry sector through 2050 appear to be minimal. There seems to be little reason to anticipate any serious investments in offsetting the effects of climate change on China’s industrial forests, since it is unlikely that China’s industrial wood situation will deteriorate significantly over the next 50 years because of climate change.

8. Conclusions

This report has reviewed the literature on how climate change will affect the world's forest sector. Overwhelmingly, research suggests that overall forest area will probably change little and most likely expand modestly. Forest productivity (net primary productivity) is expected to increase in most regions. As climate changes, tree species are expected to migrate poleward. Carbon fertilization will probably increase growth rates at least marginally for most forests, although this issue is scientifically less certain. However, forest damage will occur as existing trees become less suitable for the new climates. The anticipated trends are captured in this report by using the projections of Sohngen et al. (2001). Although these projections were done several years ago, no new detailed, comprehensive projections are available, and there are no new scientific findings that would lead us to expect that these projections would change appreciably if updated.

The general finding is that the future overall availability of industrial wood is likely to be more than adequate despite climate change, although the location of some forests and some supply sources could change. Forest stocks and anticipated growth are more than adequate to meet anticipated future industrial wood demand. Plantation forests are projected to increasingly supply industrial wood requirements. These forests have short rotations and can be planted in the species of choice, which can be revised to fit changing conditions, thereby allowing maximum flexibility.

The three countries examined in detail, Brazil, South Africa, and China, generally show different capacities to adapt. Brazil has a large and growing forest plantation sector. With short rotations, a relatively large number of species to draw from, and large land areas available for new or replacement sites, Brazil is in a strong position to adapt its timber-producing forests. Most climate models suggest that moisture will be adequate, but should aridity become widespread, future supply could be compromised.

Although most of its industrial wood is imported, China appears to be in a strong position to maintain and expand its forests and increase domestic wood harvests even in the face of climate change. China has a very aggressive tree-planting program. Most of the industrial forest planting is anticipated to occur in the southeast, a region that is expected to receive adequate precipitation with climate change.

The third country, South Africa, is more problematic. Plantation forestry has done well in South Africa, and the country has built a successful pulp and paper industry oriented toward export markets. However, the areas of tree plantations are near the edge of an adequate moisture regime, and there is little room to relocate them within the borders if the climate turns dry. Some models project decreased precipitation, which suggests problems for the existing plantations.

Over the next 50 years the forest industry as a whole could probably adapt without major relocation of its processing facilities. Over long periods of time, assuming appropriate foresightedness, processors could adjust gradually by phasing out obsolete facilities (which often have 50-year lives) and adjusting the locations for new investments, thereby keeping additional climate-induced costs very modest.

Most industrial forest plantations are owned by private entities. However, there are many exceptions. In South Africa, for example, although the pulp plantations are privately owned, sawtimber plantations are typically owned by the state. In China, large areas of plantations were established and are managed by the state, but private international forest companies are now beginning to establish tree plantations. In Kenya, government plantations provide wood for both sawmills and pulp operations, while small-scale private tree growing for industrial purposes is also encouraged (Sedjo 2004).

The income vulnerabilities probably reside mostly with the forestry labor force, which is largely unskilled and low income. Although tree growing is a relatively modest user of labor, workers are needed both for planting and for harvesting. More importantly, wood-processing facilities often use substantial amounts of labor. Thus, any climate-induced disruptions in the industrial forest resource are likely to generate employment losses in the processing industries, as well as in the forest.

Fire, disease, and infestation may help clear away the old forest as part of the process of bringing in the new. Even if they part of the adaptation process, however, control of these forces is probably desirable, both to allow for increased salvage and to minimize damage to development in the forest. Costs could include programs and training in fire, pest, and disease control. Also, the costs of the relocation of a plantation are likely to be higher that the costs of replanting at an existing site. Finally, there are losses associated with tree damage, even if salvage is successful: fewer trees are harvestable, and trees exposed to fire have more limited uses than harvested healthy trees. Obviously, these are mitigating and adapting activities, and real losses will result. Good management, however, can reduce these costs and losses.

Despite the generally optimistic assessment found in the report, uncertainty persists. Unanticipated problems related to climate change could take the form of widespread infestation of forests. However, plantations offer many dimensions for flexibility and adaptability. Even with infestations, for example, managers can replant with trees that are genetically resistant to the pests (either through traditional breeding or through genetic engineering) or with different species altogether. Thus, plantations, the growing source of industrial wood, provide more options in addressing an infestation problem than would be available in most natural forests.

One of the larger uncertainties relates to new sources of demand for wood. Although wood was once a major source of energy, most harvested wood today is used as industrial wood—for lumber, solid wood material, and pulp and paper. However, wood is commonly mentioned as an alternative to fossil fuels and. Wood can be combusted directly or converted into various forms of energy including biofuels. The potential demand for energy sources is huge and could dramatically alter the balance between wood production and demand. This issue is beyond the scope of this report but cannot be dismissed.

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