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DEVELOPMENT AND CLIMATE CHANGE

Adaptation of **Forests** to Climate Change

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Adaptation of **Forests** to Climate Change

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All dollars are U.S. dollars unless otherwise indicated.

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1. CONTEXT

This study is part of a World Bank effort intended, first, to help decision makers in developing countries to better understand and assess the risks posed by climate change and to better design sector strategies to adapt to climate change. The second objective is to develop a "global" estimate of adaptation costs to inform the international community's efforts, including UNFCCC and the Bali Action Plan, to provide access to adequate, predictable, and sustainable support, and to provide new and additional resources to help the most vulnerable developing countries meet adaptation costs.

To meet these two objectives, the broad World Bank effort will proceed on two tracks, a case study and an aggregate track. This study is part of the aggregate track, which has two objectives. The first is to ensure the availability of developing country/regional adaptation cost estimates to contribute to the discussion on climate change leading up to the Copenhagen conference in late 2009. The second objective of the aggregate track to begin to develop procedures that will be needed to generate aggregate adaptation cost numbers once the country case studies are completed. Within that track, the forestry component focuses on the industrial wood sector. Traditional fuelwood is also of interest. However, since a significant amount of fuelwood is not traded in markets, there is not much data. In general, we would expect that conditions favorable to an expanding forest would also be favorable to the creation of fuelwood, and vice versa.

The approach of this forestry study is to draw from the considerable existing literature (see Table 1) to provide perspective, as well as estimates and projections of the impacts of climate change on forests and forestry in various regions and countries. Based on the assessment of these projections, adaptation measures are suggested to mitigate damages likely to be incurred and identify adaptations that might be made. Preliminary cost estimates are made. The approach will not involve a new model or new projections. Rather, the study draws from the literature and the results of earlier investigations. These are reported and the most comprehensive results fused into a single report. These do not perfectly fit the precise guidelines—for example, GDP and population—applied to some of the other World-Bank-sponsored studies. However, the models often do not calibrate to GDP or population. Rather, they make some simplifying assumptions on the demand side with the focus of the analysis being on the supply side. The results are, to a large extent, invariant to demand-side projections that are only modestly varied.

The results of this study are consistent with the general findings of the IPCC Fourth Assessment of Climate Change, WG II (2007), 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 increases will shift from low-latitude regions in the short term to high latitude regions in the long term." This correspondence is not surprising, since this study draws in part on the IPCC findings and on the literature that went into developing those findings.

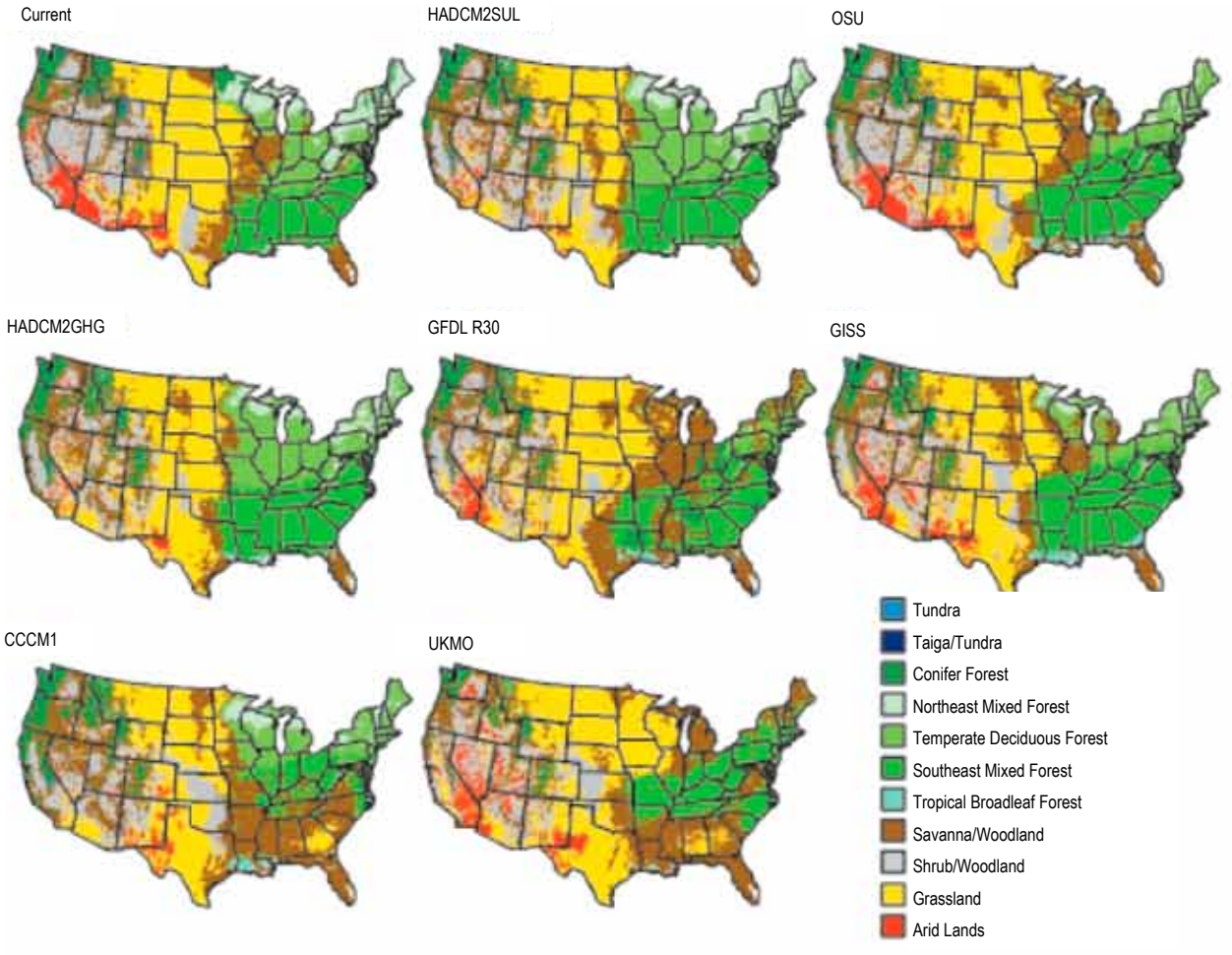
1.1 WHAT ARE THE POTENTIAL IMPACTS OF CLIMATE CHANGE, INCLUDING EXTREME WEATHER EVENTS, ON THE SECTOR?

The ecological literature suggests that warming is likely to result in an expansion of forest in the

high-latitude areas that were previously devoid of forest. In the mid-latitudes, some species are likely to experience dieback of some forest species and types, while others migrate to areas with more friendly climates (Smith and Shugart 1993; Easterling and Aggarwal.). Ecological studies suggest that tree species at the edge of their ecological range may persist even if they are not able to regenerate in those conditions (Clark 1998).

Figure 1 provides projections of forest configuration under several alternative GCMs. Note that there are large differences in the location of forests and other vegetative types across models. For example, while some models—for example, CCCM and UKMO—predict the forests of the U.S. Southeast to be replaced by grasslands, others— for example, HADCM2SUL and HADCM2GHG—expect forests to flourish (Figure 1). This is probably due largely to predicted differences in moisture. Although models now project on subcontinental scales, it is still well-recognized that GCMs do less well when predicting regional climate effects (Climatewire 2009).

FIGURE 1. MODELED VEGETATION DISTRIBUTION



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: Neilson 1995, reproduced from Shugart et al. 2003.

In addition to a changing temperature, the amount and pattern of precipitation and moisture is critical to forests. In general, getting warmer and wetter will enhance forest growth, while warmer and drier is likely to be detrimental to growth. If drying is significant, grasses will often replace forests in natural systems (Bowes and Sedjo 1992). A number of biogeographical models demonstrate a polarward shift of potential vegetation for the 2xCO_2 climate by 500 km or more for the boreal zone (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 result in forest expansion and replacing of up to 50 percent of current tundra area. There is, however, a concern that the lagged forest migration (compare the tree species migration rates after the last glacial period of a few kilometers per decade or less to a projected future 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 correspondent large carbon pulse (Malcolm et al. 2002). However, such a result could also lead to an increased rate of harvest to allow the capture of the value of the trees before it is lost to mortality. For timber production, which typically relies on managed forests with migration facilitated by human actions, this negative effect of lagged migration might be of lesser importance than for natural forests.

Carbon Dioxide Fertilization. Increasing concentrations of atmospheric CO_2, aside from modifying the temperature and precipitation pattern, may also increase production through the "carbon fertilization effect" as noted above. Earlier 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 concentrations on tree growth. Long-term FACE studies suggest an average NPP increase of 23 percent in response to doubling of the CO_2 concentration in young tree stands, with a range 0–35 percent (Norby 2005.) However, in another FACE study of mature 100-year-old tree stands, little long-term increase in stem growth was found (Korner et al. 2005). This 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 the Sohngen et al. (2001) study, which used projections that increased NPP by 35 percent under a 2xCO_2 scenario. Regardless of the contradictory effects of variations in CO_2 concentrations, however, empirical evidence indicates that forest growth rates have been increasing since the middle of the 20th century, as noted by Biosvenue and Running (2006).

1.1.1 Disturbances and extreme events

Natural disturbances are an integral part of the environment in which most forests flourish and evolve. Wildfires, outbreaks of insects and pathogens, and extreme events such as high winds, are often an integral part of the forest environment. These disturbances often precipitate stand-replacing events. Ecological systems adapt to their climate. Changing climates create new conditions less consistent with the current ecosystems, thereby creating increasing stress on the systems. 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 (van Mantgem et al. 2009; Westerling et al. 2006). Modifications of temperature and precipitation, which weaken the forest and can increase the frequency and intensity of infestation and fire, may be as important as the direct impact of higher temperatures and elevated CO_2. An example of such a situation may be the extreme beetle outbreak in the Canadian western forests (Kurz et al. 2008). Many observers believe the beetle population has flourished due to the warmer winters, and thus insect mortality has been dramatically reduced.

Indeed, some have argued that extreme events in forestry are often the vehicle for facilitating the replacement of an established forest with a new, perhaps more suitable forest, should conditions change (Sedjo 1991). Although extreme events could well increase due to climate change, few forest production models include these effects. However, from a timber production perspective, one response would be to anticipate the disturbances with shorter and/or more targeted harvests.

1.2 WHO (ACROSS AND WITHIN COUNTRIES) IS LIKELY TO BE MOST AFFECTED?

1.2.1 Geographically

In general, climate change is likely to shift natural forests toward the poles. The same shift is likely for planted forests, although it would probably be propelled by forest management decisions that involved the replacement of harvested plantation stands into new areas. Most GCMs indicate that temperature changes will be least at the equator and increase as the poles are approached. Thus, for forests, the locational changes should be greatest in the boreal and temperate countries, most of which are developed. This suggests the likely migration of boreal forest into areas that formerly were devoid of trees—for example, parts of the tundra—accompanied by temperate forests moving into some areas that were formerly occupied by boreal forests, assuming soils, photoperiod, etc. are appropriate. Although not often discussed, tropical forests may be impacted 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. However, climate models are not generally regarded as good predictors of regional precipitation changes. In general, however, interiors of continents tend to be dry, and this tendency should be exacerbated under climate change and warming.

Over the next fifty years, the forest industry could probably adapt without major relocation of its processing facilities for reasons discussed below. Over long periods of time, assuming appropriate foresightedness, processing facilities could adjust gradually though the phasing out of obsolete facilities, often with 50-year lives, and adjust the location for new investments, thereby keeping additional climate-inducted costs very modest.

1.2.2 By income or vulnerability class

Forest assets have a variety of ownerships. 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. However, 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, labor is needed both for planting and for harvests. 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.

1.3 WHAT EXPERIENCE IS THERE WITH ADAPTATION IN THE SECTOR?

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 have not been traditional wood producer countries, but tropical and subtropical countries in which forest planting has occurred (Bael and Sedjo 2006). Indeed, the changes have been so great that an increasing percentage of the world's industrial wood comes from planted forests. The share is expected to be over one-half by 2050, even in the absence of any climate change. Climate change could be expected to accelerate this process.

A host of approaches and tools may be used to adapt to changing conditions such as climate change (Sohngen 2007; Seppala et al. 2009), with a major set of adaptations associated with the planted forest. A decision to plant also involves considerations with respect to location, choice of species, and quality of the stock to be planted. The planting approach allows regeneration to be for the species of choice, which is often a rapidly growing species appropriate for intensively managed industrial forests. This choice can be desirable for timber production and/or for other forest values. Adaptations that may

be useful during climate warming include changing rotation periods, salvage where damage is incurred, replanting of new species if conditions warrant, and adjusting future investment levels, including relocation of selected plantations if warranted.

In a recent paper on forest adaptation to climate change, Roberts (2009) points out those 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. He also points out that existing policies tend to be reactive rather then 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.

1.3.1 Autonomous adaptation

The evidence indicates that natural forests have been migrating at least since the last glacial period, as the earth warmed and moisture patterns changed. In the absence of very rapid climate change, tree species have shown that they are able to migrate and adapt to the changing environment, in some cases creating forests with a new combination of tree species (Shugart 2003). Figure 2 shows the migration of some forest species in North America in the post-glacial period. Figure 2 shows that the forest changes will depend upon the specifics of the climatic change. However, climate changes have accelerated in recent decades, and some observers anticipate an increase in die-back toward the end of this century (IPCC 2007).

For managed and planted forests, human actions may facilitate the transition. For short rotation plantations, the optimal approach may be simply to replant a site after harvest with a more appropriate provenance. The adjustment problems for mills are generally negligible, since the species are likely to be similar to the ones replaced; for example, slash pine replacing loblolly as the temperature rises. Thus, the adaptation costs are likely to be very small, since artificial regeneration would occur anyway. The only serious question regards replanting with the appropriate species and adjusting the management regime to that new climate situation.

Public sector investment. Forest ownership varies considerably across the globe. Relevant public sector investment could consist of roads and other infrastructure that allows harvesting to take place, although forest roads are usually the responsibility of the forest harvesting entity. In the context of climate change and forest relocation, some major new roads might be required to facilitate the delivery of raw wood to the mills. In addition, forests are often publicly owned or assisted by public funds. In this context, the public investment could take the form of tree planting to replace or anticipate forest losses. In some cases, the public investment could take the form of aerial seeding and/or other activities to facilitate the more effective migration and regrowth of the forest, although aerial seeding is usually not recommended for commercial forests.

1.3.2 "Soft" adaptation – policies and regulations

"Soft" adaptation might include policies and regulation to facilitate the "natural" migration and regeneration of the forest, such as those discussed above. Fire control might also be viewed as a soft adaptation policy. However, the broader implications involve short-term emissions releases, and fire control could be difficult

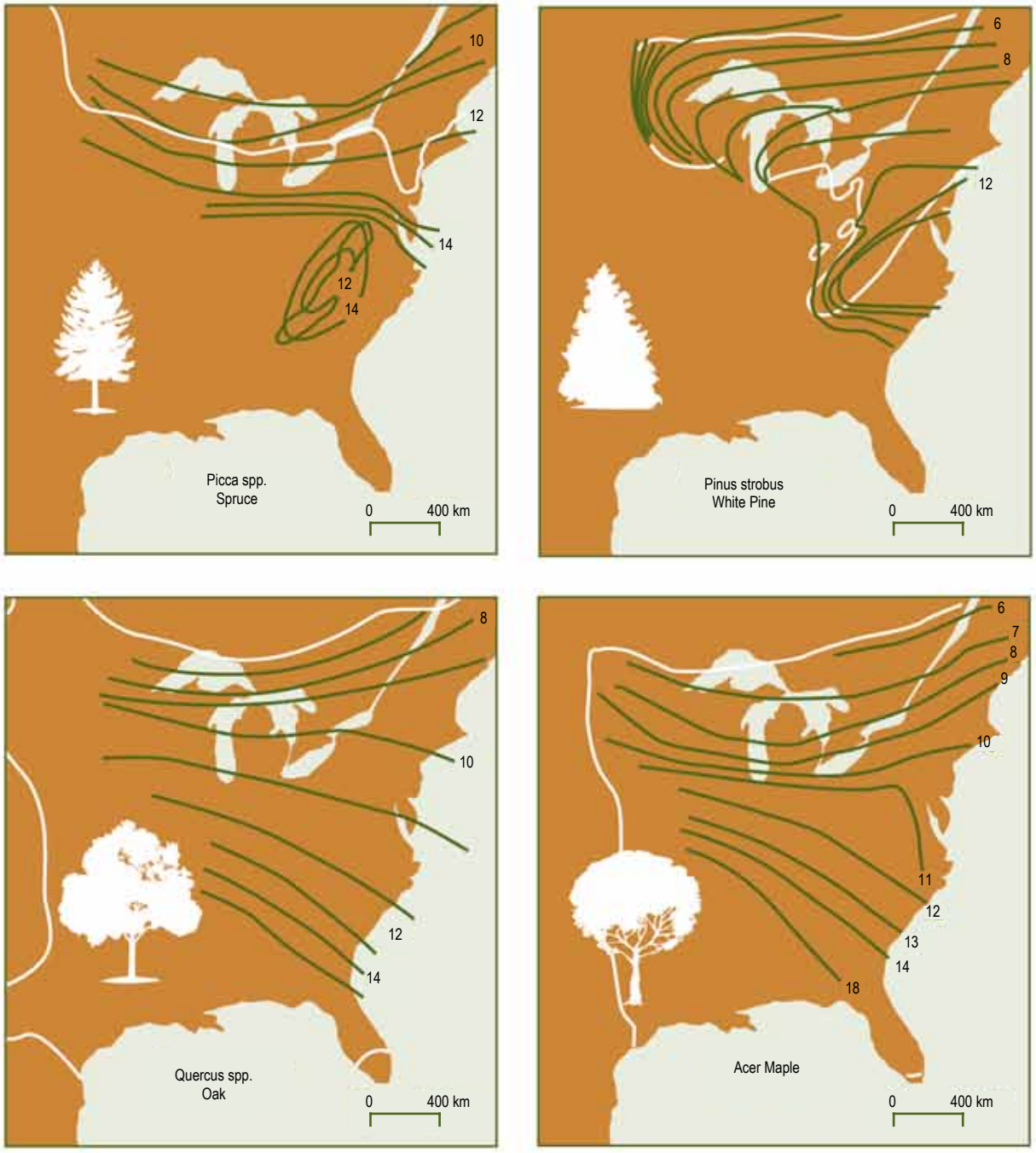
1.3.3 Reactive adaptation

Reactive adaptation could probably involve activities that might be undertaken should damages be occurring in the forest. An example might be attempts to control or limit the effects of wild fire. Limiting wildfire may result in extending the life of the trees, thereby allowing the harvest of the timber before it is destroyed. However, early wildfire control has often been cited as a cause for larger firers in the longer term. In addition, salvage logging is common, whereby after damage associated with a nature event, such as fire or infestation, the remaining merchantable timber in the forest is harvested and utilized.

1.4 WHAT IS THE NATURE AND EXTENT OF THE ADAPTATION/DEVELOPMENT DEFICIT IN THIS SECTOR?

The timber producing sector has a high degree of potential for adaptation. In the near term, damaged forests can still be harvested and the usable wood commercially utilized. In the longer term, the forest can usually renew itself through natural regeneration,

FIGURE 2. CHANGES IN THE RANGES OF FOUR TREE SPECIES SINCE THE LAST ICE AGE



The lines in the map 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 climate due to climate change. The species clearly displayed marked differences with respect to their migration patterns and rates.

Source: Davis 1981, reprinted from Shugart et al. 2003.

although not always with the same species. In the very long term, the forest can migrate and adapt to new climatic conditions, although not all new conditions will be conducive to forests.

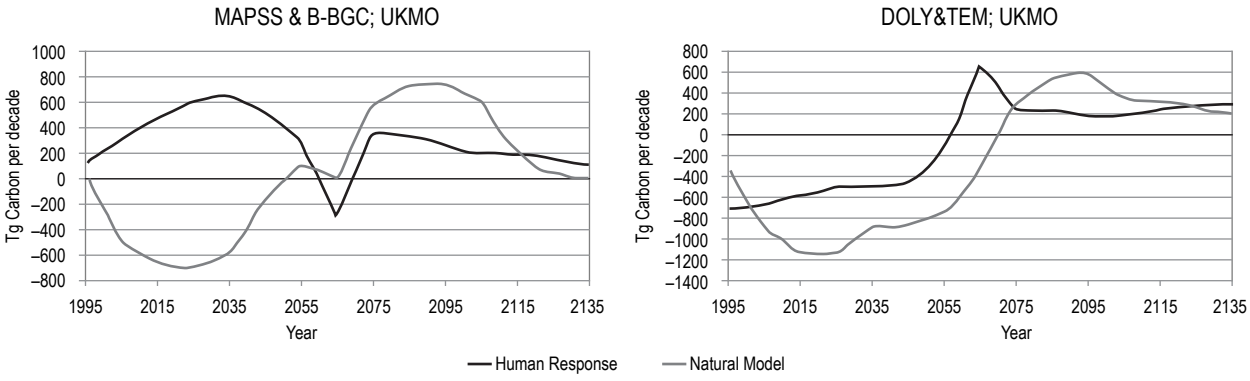
Figure 3 describes how adaptation through harvesting and replanting can substantially reduce losses that would otherwise occur if natural systems were allowed to adapt on their own. The die-back regime often assumes that tree mobility is exceeded by the rate of climate change (Davis and Shaw 2001). Note that in a die-back scenario, human management plays a large role in both salvage logging and in promoting rapid regeneration. Salvage logging captures some of the timber values that might otherwise be lost, and timely artificial regeneration provides for more future commercial timber at an earlier time that would be the case relying on natural regeneration. The major consideration is that humans can facilitate an accelerated adjustment.

1.5 HOW WILL EMERGING CHANGES IN DEVELOPMENT AND DEMOGRAPHICS INFLUENCE ADAPTATION?

Forests compete with a variety of other uses for land. Increasing development and growing populations often involve forest clearing, which could involve greater use of previously forested land for agriculture. These alternative pressures will continue to compete for land 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, while in others they will be disadvantaged.

FIGURE 3. ADAPTATION IN MANAGED ECOSYSTEMS

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



Source: Reprinted from Sohngen et al. 1998.

2. LITERATURE REVIEW

2.1 PREVIOUS STUDIES RELEVANT TO THE SECTOR AND THEIR MAJOR CONCLUSIONS.

A number of studies have examined the implications of climate change on forests and sometimes on industrial wood production (Table 1). The usual modeling approach is to combine general circulation models (climate models) and ecological models to provide a representation of the climate-modified environment. Economists then treat this as the underlying production function, upon which economic models can and are imposed to make their assessments. However, since different GCMs are used and different ecological models, 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 examined impacts of warming on aspects of terrestrial vegetation.

The basic approach of any analysis of the economic impact of climate change on forests requires the integrated use of three types of models: economic, climate models (GCMs), and ecological models. A number of economic models have been developed to examine long-term timber supply. Some of these models have been modified to estimate the effects of forestry on climate change, as forest activities can sequester and release carbon. A major focus of recent work has been on the ability of forests to capture carbon, thereby offsetting or mitigating to some degree global warming. Some of these models also have been modified to examine the effects of climate change on forestry. This study has a major interest in this last set of models; their projections form the basis of this current study.

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 areas in a region in the U.S. to adapt to a new and changing climate, with mobility of crops and forests playing a major role. A country-focused effort (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), which focused on forestry's response to climate, used a simple regression approach. Darwin et al. (1995) examined the adjustment of agriculture and forest markets to climate change in the U.S. However, the computable general equilibrium (CGE) approach used did not capture the intertemporal adjustment process so critical in forests. More recent global efforts include those by Perez-Garcia et al. (1997, 2002). A quite recent effort was that of Irland et al. (2007). These efforts used a global forest economic model to examine the effect of climate change on forest growth and its effects on timber markets. However, while the analysis uses the TEM, the approach ignores the dynamic migration aspects of tree species.

Finally, the economic study that most directly and comprehensively examined the effects of climate change on forests is that of Sohngen et al. (2001). The approach utilizes 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

TABLE 1. EXAMPLES OF SIMULATED CLIMATE CHANGE IMPACTS ON FORESTRY

Reference; location	Scenario and GCM	Production impact	Economic impact
Schngen et al., 2001; Schngen 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-altitude gain. • 2145: prices increase up by up to 80% (no climate change), high-latitude gain, low-latitude loss. Benefits go to consumers.
Solberg et al., 2002. *Global*	Baseline, 20–40%, increase in forest growth by 2020	• Increased production 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 (2XCO_2 in 2060), TSM 2000, BIOME 3, Hamburg model	• 2060s, 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 increases 21% With climate change: • Pulpwood price decreases 25% • Solid wood decreases 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 A1F1, A2, B1, B2 upto 2100. Few management scenarios	• Increased forest growth (especially in N. Europe) and stocks, except for A1F1. • 60–80% of stock change is due to management, climate explains 10–30% and rest due to land use change.	In the A1F1 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 HadCN2+TEM CGCM1+VEMAP HadCM2+VEMAP IS92a	• Increase in the 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 evaluation and northern forests decline, southern forests expand.	• Reduction in log prices • Producer welfare reduced compared to n climate change scenario • Lower prices; consumers will gain and forest owners will loose

Source: Reprinted from IPCC 2007, Easterling et al. WG 2.

base and climate change deviations from that base. Related efforts, including some subsequent follow-on efforts using variants 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. Other studies that are part of the literature and are particularly involved in this current study include Shugart et al. 2003 and Kirilenko and Sedjo 2007.

2.1.1 The results

Tables 3–6 below 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 in wood prices. All the large developing regions show net benefits over the period to 2050 and generally beyond. However, forest stocks cannot increase indefinitely, and at some future time stocks must stabilize or decline. However, this need not imply a decrease in industrial wood supplies.

Table 3 provides the estimates of Sohngen et al. (2001) of the percentage change in forest areas in the longer term (by 2145), based on the projections of the

TABLE 2. SUMMARY: TIMBER MARKET RESULTS TO DATE

Region	Output 2000–2050	Output 2050–2100	Producer returns
North America	–4% to +10%	+12% to +16%	Decreases
Europe	–4% to +5%	+2% to +12%	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

Source: Alig et al. (2002), Irland et al.(2007), Joyce et al. (1995, 2001), Perez-Garcia et al. (1997, 2002), Sohngen et al. (2001), Sohngen Mendelsohn (1998, 1999), Sohngen and Sedjo (2005), Karajaianen et al. (2003), Nabuurs et al. (2002), Perez-Garcia et al. (2002), Sohngen et al. (2001), Lely et al. (1997). Adaptation to Forests and People to Climate Change. 2009. Alexander Buck, Pia Katila Risto Seppala, (eds.). IUFRo World Series Volume 22. Helsinki, 224 p.

Hamburg and IIUC climate scenarios of the late 1990s used for ecological projections. Note that for each GCM, eight of the nine regions experience a net area change over this longer period. Additionally, all of the regions experiencing a decline are developed regions. The next table, Table 4, 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 5 presents the percentage change estimates in regional timber production for 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 projection for Oceania and the tow projections for North America. Finally, Table 6 draws the summary results from Table 5, adjusted to the year 2050. Note that projected timber production in North America and Oceania has declined modestly under the Hamburg scenario, while only North America has declined under the UIUC scenario.

TABLE 3. PERCENTAGE CHANGE IN FOREST AREAS IN LONGER TERM (BY 2145), BASED ON THE HAMBURG AND IIUC CLIMATE SCENARIO USED FOR ECOLOGICAL PROJECTIONS

	Hamburg[3]			UIUC[3]		
	Net Area Change	Access[1] Net Change	Inacess. Net Change	Net Area Change	Access[1] Net Change	Inacess. 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[2]	33	(3)	39[2]
Africa	71	5	74	38	(4)	41
Total	27	5	41	19	5	31

Source: Sohngen et al. 2001.

[1] Accessible forest areas are forests used for industrial purposes. For the low- to mid-latitude forests, accessible includes only industrial plantations or highly managed forests.

[2] For the Asia-Pacific region, inaccessible forests are the valuable dipterocarp (tropical hardwood) forests of that region. Inaccessible forests also expand in both ecological scenarios for that region, but those changes are suppressed here in order to show changes for the most important market species.

[3] Hamburg and UIUC refer to the climate scenarios used for the ecological predictions.

TABLE 4. PERCENTAGE CHANGE IN TIMBER GROWTH RATES BY 2145.

	Hamburg		*UIUC*	
	BIOME 3 Predicted % Change in NPP	*% Change in Merchantable Timber Yield*	*BIOME 3 Predicted % Change in NPP*	*% 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

Source: Sohngen et al. 2001.

To summarize, all the developing regions show positive growth in timber production to the year 2050. Additionally, all the regions with non-negative 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 ecological scenario. Note that all the developing country regions have exhibited timber harvest production increases both to 2050 and continuing to 2145.

For the period under consideration up to the middle of the 21st century, total global forest timber harvests

TABLE 5. PERCENTAGE CHANGE IN REGIONAL TIMBER PRODUCTION FOR 50-YEAR TIME 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
Total All Forests	6	21	30	5	18	29

Source: Sohngen et al. 2001. * time periods each cover a 50 year period.

TABLE 6. PERCENTAGE CHANGE IN REGIONAL TIMBER PRODUCTION TO THE YEAR 2050, BASED ON THE CLIMATE SCENARIOS USED FOR ECOLOGICAL PROJECTIONS

*Region**	*Hamburg 1995–2050*	*UIUC 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
Total All Forests	**6**	**5**

Source: Adapted from Sohngen et al. 2001. * time period cover a 55 year period.
Note: The results of the period 1995–2045 were straight-line extended to 2050.

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 being experienced in only North American. Oceania has a decline under one climate model and an increase in another.

2.2 HOW OUR STUDY COMPLEMENTS EXISTING WORK

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 most comprehensive results are fused into this single report. These do not fit perfectly the precise guidelines—for example, GDP and population—that were applied to some of the other World-Bank-sponsored studies. However, the basic models used are not calibrated to either GDP or population. Rather they make some simplifying assumptions on the demand side with the richness of the model and the focus of the analyses being on the supply side. Earlier sensitivity analysis shows that the projections are, to a large extent, only minimally impacted by modest demand-side changes (see Sedjo and Lyon 1990). Based on the assessment of these projections, the study suggests some adaptation measures to mitigate for damages likely to be incurred, and makes preliminary estimates of costs.

The results of this study are consistent with most of the studies of this question, as well as with the general findings of the IPCC Fourth Assessment of Climate Change (Easterling et al. 2007), which states that the changes globally range from "a modest increase to a slight decrease, although regional and local changes will be large." It also notes that "production increases will shift from low-latitude regions in the short term to high-latitude regions in the long term." The similarity with the findings of this study is not surprising, since this study draws in large part on the IPCC findings and on the literature that went into developing those findings. On average, most of the studies find forest productivity and area increasing modestly

Uncertainties increase over the longer term, which raise concerns about the possibilities over the longer term. The IPCC (2007) anticipates "significant forest dieback toward the end of the century." However, forests cannot expand indefinitely even in the absence of climate effects. Indeed, dieback occurs as mortality overtakes a forest. The dieback exacerbated by climate change is likely to be different—and indeed more severe—as the process of replacing earlier forests by forests more appropriate to the changing climate are established. However, dieback need not threaten the adequacy of timber supply, given the ability to salvage a portion of the mortality and the huge surpluses of forest stocks over the requirements of industrial wood demand.

2.3 METHODOLOGY

The basic approach of an analysis of the economic impact of climate change on forests requires the integrated use of three types of models: economic, climate models (GCMs), and ecological models. Specifically, a number of global general circulation models (GCMs) exist. These models provide climate change scenarios. Ecological models are also needed to estimate the response of vegetation to whatever climate change is

anticipated. Together these models estimate changes in vegetative composition, location, and productivity, which are driven by temperature and precipitation change.

Ecological models project the extent to which a specific climate change is expected to shift the geographic distribution of plants and particularly tree species (Emanuel et al. 1985; Shugart et al. 1986; Solomon et al. 1996; Neilson and Marks 1994). Responses by forests to past climate change have consisted of the independent movements of the ranges of important tree species (Shugart et al. 2003). A critical issue in the location of natural forests is the rate at which tree species migrate. This issue is less important for plantation forests, because people can be involved in the replanting of the appropriate species for the new climate conditions. In addition, climate change is projected to alter tree productivity—in the aggregate in a positive direction—through temperature and precipitation changes (Melillo et al. 1993). Although these studies are relatively old, there are no new studies that undermine these results over the period to 2050.

Finally, the carbon dioxide fertilization effect may be an important enhancer of productivity. Although the science is still inconclusive and size of the effect appears to vary considerably (see Shugart et al. 2003, pp. 19–20, for a more complete discussion of the literature), these effects are usually introduced. Supporting the use of a carbon fertilization factor are the findings of Boisvenue and Running (2006), which indicate that tree productivity generally has increased in recent periods.

This report, although not developing a new methodology, 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 utilized together with two climate models and an ecological model. The approach uses the climate change predictions of two general circulation models: the Hamburg T-106 model (Claussen 1996; Bergtsson et al. 1996) and the UIUC model (Schlesinger et al. 1997). Again, there are no new studies that undermine these results over the period to 2050.

The analysis assumes that climate changes linearly until 2060, at which time it stabilizes at an atmospheric CO_2 level of approximately 550 ppm, which is a doubling of the 1998 atmospheric CO_2 level of 340 ppm. Specifically, the models used for climate change predict from two equilibrium general circulation models (GCMs). Steady-state forecasts from the Hamburg T-106 model (Claussen; 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, the Hamburg model 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 compared to 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 have different regional impacts on timber supply.

2.3.1 Capturing ecological changes in the economic model

An ecological model, the global terrestrial biosphere model BIOME3 (Haxeltine and Prentice 1996; Haxeltine 1996), is used to predict vegetative changes that would be expected to be precipitated by the climate changes predicted by the GCMs. The climate predictions are used by a global terrestrial biosphere model (BIOME3) to estimate equilibrium changes in the distribution of timber species and the productivity of those species across the globe. Biomes are ecological types that represent accumulations of different species, referred to as forest types. While some models predict net primary productivity (Melillo et al. 1993) and some models predict global changes in the distribution of forest types (Neilson and Marks 1994), most models do not capture the two effects simultaneously.

The approach of Sohngen et al. (2001) considers two types of transition and optimizes over both effects. The first involves forest dieback where some portion of the forest dies due to climate change. The second makes the transition without the dieback as forest regeneration more quickly fills in the gaps without a high disruption due to mortality. The dieback scenario also involves salvage logging, where the timber in the dead forest is salvaged and gradually replaced by regeneration. Under

dieback, the prices are slightly higher as the value of the salvage is lower than if salvage timber were replaced by high-value timber from live trees.

The stock of forests also depends on the movement of species across the landscape. Two different and likely extreme scenarios of dynamic processes that govern the movement of species are used to capture this movement: dieback and regeneration. As forest types move because of climate change, the dieback scenario predicts the loss of a large fraction of the existing stock (King and Neilson 1992; 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 salvaged. This salvage enters the market through harvests. The proportion of salvage in each timber type varies by region.

This approach assessing two effects is important because changes in net primary productivity (NPP) can affect species dominance within a forest type, and the species present can affect NPP. BIOME3 also includes carbon fertilization through the physiological effects of increased carbon dioxide on water use efficiency of plants.

In the long run, the yield of forests is likely to rise because of these two 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; and McCarl et al. 1999). Second, BIOME3 predicts that more productive species move poleward. In the long run, 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 predictions. For example, the prediction for North America from the NPP increase alone is that long-run timber yield should increase 17 percent, 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 (that is, a 23 percent change in NPP and 4 percent change in merchantable timber yield; see Table 2) because Hamburg suggests that species movement in Europe causes mostly an expansion of forests into marginal shrublands in Mediterranean areas. While 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 conversions of northern species to southern species and less forest expansion (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 for a period after a period of initial increase. Thus the two statements in the IPCC 2007 report cited above earlier (pp. 227 and 275), 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 southern timber types that grow faster, landowners may have an incentive to harvest even young trees to make way for new species that grow more quickly.

The results are reported in Sohngen et al.(2001) for the two climate GCMs: Hamburg and UIUC. In the Hamburg scenario, BIOME 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). From this approach, which includes net primary productivity changes and the carbon dioxide fertilization effects, the projected changes in the distribution of timber species and the productivity of those species by location is obtained.

2.3.2 The economic model

The economic model (TSM) of Sohngen et al. (1999) provides the base case (no climate change) results. This model is applied to the vegetative changes to project

changes in industrial wood availability and costs that are reported in Sohngen et al. (2001). The period examined is that up to 2060, approximately the same as the 2050 target called for in the World Bank's terms of reference. The results of Sohngen et al. (2001) are adjusted in this report to fit the 2050 time frame. The model focuses on net primary productivity (NPP) and assumes a carbon fertilization enhancement of 35 percent (Haxeltine 1996). Although some believe this to be too high (Norby et al. 2005), the consensus is that fertilization is positive and the direction of forest growth in recent decades is empirically borne out by the results of Boisvenue and Running (2006).

BIOME3 provides more disaggregated results than the economic model can use. The data is aggregated and provides 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.

The basic economic model utilized was developed as an optimizing control theory model designed originally to focus on industrial timber supply. The model is designed to examine carefully the various aspects that go into timber supply by region and land class. Supply is provided by a number of regions that have varying locations, species, site conditions, and harvesting and transport costs. Initially, the supply regions consisted of twenty-two homogeneous land classes; substantial detail on the various supply sources of timber can be found in Sedjo and Lyon (1990). Initially, a large nebulous area of land, much unmanaged with limited details, 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. About fifty regions were used in the 2001 version, which generated the result utilized in this study. The model is designed to capture the inter-temporal 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. Additional areas of plantation also can be added gradually, subject to the availability of suitable land and economic returns.

The model includes consideration of forest management and silvicultural practices, alternative species, as well as various growth rates, harvest costs, and delivered costs to mills. The model adjusts the level of management to economically optimum levels, and provides for the introduction of new lands to establish new plantation forests through time where economically justified. Since the model includes many different land classes and a variety of site and climatic conditions, these give rise to a host of individual regional supply curves. Locational considerations and transport costs are built into the model, 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 (rationale expectations) and thus considers current demand and supply conditions in the context of future conditions. It maximizes the sum of producers' and consumers' surplus for each period and for the system.

Given the supply of various producers and regions together with global demand, the model determines optimal harvest levels and forest management investments through time. This model has appeared and been utilized in a number of published papers and reports to address not only timber supply issues (Sohngen et al. 1999), but also the 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 utilized in this study is that which examined forest modifications in response to climate change (Sohngen et al. 2001). That methodology used climate change estimates of GCM, to which the ecological literature was applied to create projections of the forest ecosystem around 2050. The underlying economic projections model for this period is applied to this 2050 forest. The approach reports and compares the situation under two "climate change scenarios" with the projections of the "base case," i.e., without changes due to climate change.

2.4 DEMAND

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

World demand is imposed in this model, but in much less detail than supply. The model assumes that demand will increase very modestly over the next 100 years. Demand is initially position to clear the market in the base period. It is then shifted out through time at a decreasing rate asymptotically approach a steady level at a period 100 years out. This approach is used for two reasons. First, projections based on population and GDP have provided notoriously inaccurate projections on the high side (Sedjo and Lyon 1990, Shugart et al. 2003). Second, since the model is forward looking with trees growing through multi-decades periods, mathematical convergence required movement to a long-term steady state. The model used assumes demand is shifting at 0.4 percent annually initially gradually converging to a stable situation in 100 years.

Although traditional fuelwood is not model in the model or this analysis, it is unlikely to upset the projections. Global fuelwood use appears to have already peaked at 1.9 billion m^3 and is stable or declining (Goldammer and Mutch 2002).

2.4.1 Possible changes in demand

Although the demand for industrial wood has been stable and predictable over time, the expansion in the use of raw wood to energy uses in the form of biofuels, biomass energy, and other energy uses could dramatically change the trajectory of future demand (Sedjo and Sohngen 2009). Wood is clearly a potential substitute for fossil fuels and, since carbon dioxide can be viewed as recycled in the biological system, wood energy has substantial appeal. Should wood energy of this type become important, this would almost surely escalate the demand for wood, thereby invalidating all of the current projections regarding the future demand for industrial wood. Although wood energy is not technically an industrial wood demand, it would draw from essentially the same natural resource base as industrial wood. Wood is viewed as renewable and as recycling the emitted carbon and thus not contributing to the long-term buildup of atmospheric carbon. Although it appears unlikely that traditional fuelwood will expand significantly, some model-based estimates project an increase in biofuel demand during the next 50 years by as much as a factor of ten (Alcamo et al. 2005). In many industrial countries, biofuels, particularly ethanol from grains and other plant materials—such as sugarcane—have already become an important source of nonconventional transport energy. Biofuels derived from cellulosic biomass—fibrous and wood portions of trees and plants—may offer an even more attractive opportunity as an alternative to conventional energy sources. In addition, wood cellulose can be used in gasification processes—for example, 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 a feedstock to produce a variety of energy products, including not only ethanol but also biocrude, using processes such as Fisher-Tropsch. Wood-fired gasification plants can be constructed as stand-alone projects, as is now under consideration in some locations. An intriguing possibility is that new gasification biorefineries replace aging traditional boilers in existing pulp mills (Larson et al. 2008). Pulp mills have large energy requirements and are designed to facilitate the flow of 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.

2.5 HOW WE REPRESENT THE FUTURE—2010 TO 2050

2.5.1 The baseline results without climate change

Using the dynamic global timber market model results developed by Sohngen et al. (1999) to project future timber supply in the absence of climate change, the model maximizes the net present value of consumer plus producer surplus in global timber markets. It optimally manages harvest rotations, timberland area, forest management investments, and age-class distributions of forest types in about 50 land classes, which are reported in 10 regions worldwide to 2145. A slightly updated version of the model was used by Daugneault 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 6. The global model covers all major timber producing regions of the world.

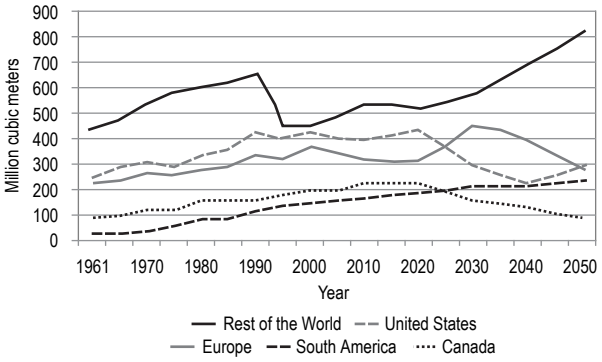
In the absence of climate change, the world's overall area of forest is projected to decline over the 21st Century. Figure 4 provides historical and projected estimates of timber harvests by major global regions in the base case from 1960 to 2060. Even in the absence of climate change, the projections show major changes by region. This includes the historical data that show the harvests from the former Soviet Union states, which dropped dramatically in the early 1990s. Projections estimate that harvests of those states will not reach levels of the late 1980s until the 2030s. The projections also anticipate U.S. harvest leveling off in the 1990s and declining 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, reflecting the continuing expansion of planted forests and timber production from that region. The projections indicate that production from the "rest of the world" will not achieve 1990 levels again until after 2030, reflecting the full recovery of the forest Soviet states. The "rest of the world" increases also reflect increased harvests from a host of countries, including not only the former Soviet Union states, but also increased timber supply derived from fast-growing industrial wood plantations located in subtropical regions, and including Australia, New Zealand, the Asia-Pacific, 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 has been true in recent decades, most of the incremental increases in production are projected to occur in plantations of non-native species—such as southern U.S. pine, Caribbean pine, Monterrey pine, and eucalyptus—established in subtropical regions of the world, including most importantly South America, but also parts of Africa, Asia and Oceania.

In Figure 5 higher (real) prices for the no-climate-change scenario (base case) are projected. In the baseline scenario, timber prices are projected to rise approximately 0.4 percent per year during the period to 2050 as increases in demand are anticipated to slightly out-run productivity increases. As noted, most of the growth in production in the base case is projected to occur in plantations of non-indigenous 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

FIGURE 4. PRESENTS PROJECTIONS OF TIMBER HARVESTS BY REGION FOR THE BASELINE SCENARIO



Source: Daigneault et al. 2007.

forest plantations. The model conservatively projects subtropical plantations to increase in the baseline by 273,000 hectares per year on average, with 27 percent of the new plantations predicted to occur 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 used in the base case is somewhat lower than the recent historical average annual increase in non-indigenous plantations in subtropical regions of 6 million hectares per year for the period 1980 to 1990 (FAO 1995).

The effect of subtropical plantations is understood when it is recognized that they commonly grow at rates in excess of 10–15 m^3 per hectare per year compared to many temperate forests, which grow at only 2–5 m^3 per hectare per year (Bazett 1993). The total area of these fast-growing industrial wood plantations is projected to expand from around 70 million hectares currently to around 130 million hectares in 2050. Total wood production from these subtropical fast-growing 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 [per year, or about 41 percent of total wood supply by 2050. Total production from all planted forests is forecast by some to reach 75 percent of total global production by 2050 (Irland et al. 2007).

2.6 GLOBAL RESULTS:

2.6.1 With climate change impact on the forest sector

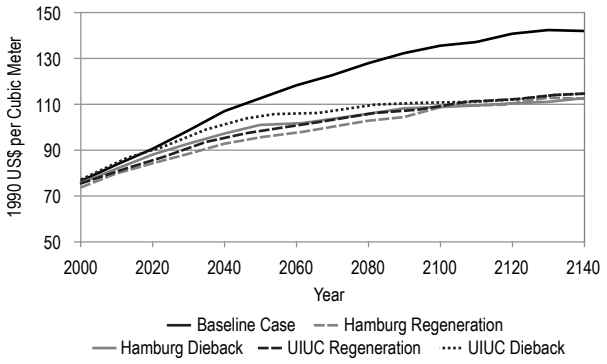
Prices are a signal of relative scarcity or abundance. Figure 5 presents wood price projections until 2140 for both the baseline case and for the two global warming scenarios (Sohngen et al. 2001). Note the baseline with no climate change has the highest prices, reflecting greatest relative scarcity. The two climate-ecological scenarios give lower prices, with the dieback price somewhat higher than that of the regeneration scenario. In either case, the implication of the study is the timber supplies will be enhanced by anticipate climate warming.

These 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 to the year 2045. For all regions except Oceania, the projected changes in the direction are in the same through time, although the magnitude of the change varies somewhat.

With climate change, the ecological model BIOME3 predicts large conversions from one forest type to another, large conversions of non-forest land to forest-land, 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, these ecological results are broadly consistent with the literature (Watson et al. 1998; Gitay et al. 2001).

Four transient ecological change scenarios are developed to provide decadal predictions of the ecological variables described above. These include a dieback and regeneration scenario 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,

FIGURE 5. GLOBAL TIMBER PRICES OVER TIME



Source: Sohngen et al. 2001.

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, as market forces can facilitate change by harvesting slower growing trees or trees destined for dieback and planting trees designed for the new climate.

2.6.2 Regional impacts

The economic model predicts that global timber supply increases and prices decline relative to the base under all scenarios (Figure 5). 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 projects the largest relative production losses will centered 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 that long-run 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. The baseline projections predict 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, non-indigenous plantation species.

Early forest losses are offset by moving more productive southern species further north. "Net Area Change" in Table 1 is the prediction of the relative area of forests after climate change by BIOME3. BIOME3 predicts relatively large increases in forest area. However, given the low productivity of these polar forests even with climate change, the newly established forest stocks will be small in 2050. In any event, they are unlikely to be major harvested forests for the reasons below. In addition, model's assumption—that forests do not shift 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 percent 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 in accessible forest area. Europe and the Former Soviet Union gain forestland.

2.6.2 Global "wet" and "dry" scenarios

In general, a warmer and wetter climate is likely to promote forest growth under many real world conditions (Bowes and Sedjo 1993). In both of the GCM models used, the warming scenarios showed an increase in average NNP over the base, and forest growth in the aggregate benefited. The Hamburg results might be viewed as the "wet" results, with this model giving generally higher productivity (NPP) outcomes, while the UIUC results are modestly less productive and can be viewed as the "dry" outcomes. The Hamburg scenario generates an average increase in forest NNP above the base of 38 percent, while the UIUC generates an NNP increase of 29 percent above the base.

Of the two GCMs used, the Hamburg scenario consistently generated more favorable timber grow results than the UIUC. Although they vary a bit by region, the results probably reflected more substantial precipitation and a more favorable distribution of moisture. The overall results of both models suggest that precipitation and moisture may have been slightly improved in the aggregate. However, carbon dioxide fertilization also was a major contributor to the positive results. One effect of carbon dioxide fertilization is that it allows the plant to use water more efficiently, thereby providing the potential to offset some declines in moisture.

2.7 HOW CLIMATE CHANGE IMPACTS ARE CALCULATED

- Events that damage forests could include fire, infestation, disease, and wind-throw. All of these might be expected to be exacerbate in a major climate warming. In many cases the event need not be unusually extreme, but might simply represent a situation where the forests, under stress due to the changing climate, are increasingly susceptible to the various events above. Under stress from climate change, the forest could experience dieback due the changes, thereby increasing the probably of wildfire, wind throw, etc.
- Additionally, extreme events generated by climate change could put healthy forests at greater risk. This would be particularly true for windstorms and adjacent wildfire. These concerns are considered below.

2.8 HOW COSTS OF ADAPTATION ARE DEFINED

Adaptation for forests to climate change could occur naturally, though natural regeneration and tree migration. However, for timber forests, adaptation to maintain continuous industrial wood production may require salvage logging of disturbed forest. Additionally, disturbed forests could be replanted in species more suitable to the changed climate, and the plantation forests could be relocated by establishing new plantations in more suitable locations as replacements for the old. Finally, tree breeding could be undertaken to develop more resilient trees to better adapt to the changing or new climate.

Fire, disease, and infestation could be part of the adaptation process by clearing away the old forest as part of the process of bringing in the new (Sedjo 1991). Although these may be part of the adaptation process, control of these forces is probably desirable, both to allow for increased salvage and to minimize damage to development in the forest. The relevant types of 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 growing trees. Obviously, these are mitigating and adapting activities and real losses will result. Good management, however, can reduce these costs and losses.

2.9 HOW COSTS OF ADAPTATION ARE CALCULATED

The costs of establishing a new tree plantation depend upon the site and general economic conditions within a country. Establishment costs, including land, could run about $1,000/ha for a new site. Replanting a stand after harvest is approximately one-half of that (Sedjo 1983, 2004). Thus, the incremental costs of relocating plantations is roughly $500/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/ha. A World Bank fire suppression project in Brazil (PO7882) was put at $1.4 million in the southern Amazon. Obviously, anticipation of climate change induced events and mitigating actions will not always prevent damages, and the extent of the climate induced damages can still be substantial.

3. RESULTS OF DAMAGE OFFSET INVESTMENTS

3.1 INVESTMENT COSTS (UPFRONT AND MAINTENANCE) IN THE BASELINE (NO CLIMATE CHANGE) SCENARIO

About 0.5 million ha are harvested each year in developing countries (assumes 200 M^3/ha), of which about 200,000 ha or 40 percent are in tree plantations. If 10 percent of the plantations, 20,000 ha, need to be relocated each year, at $1,000/ha, the replanting investments 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 area could be about $20 million; that is, 40,000 ha @$500/ha. This might have only a minimal effect on harvest level, 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.

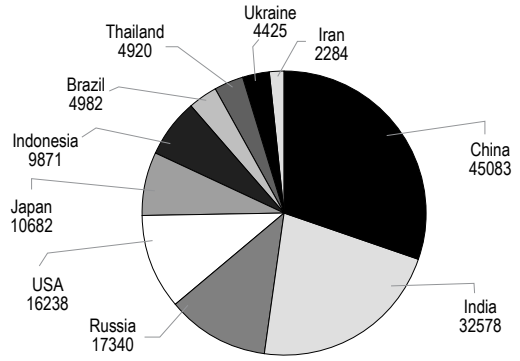
Although fire suppression costs can be very high, the relevant cost estimates for this report are incremental costs related to climate change. In the U.S., much of the current fire suppression activity is unrelated to timber harvests and relates to protecting development in and adjacent to forests

3.2 COUNTRY CASE STUDIES: BRAZIL, SOUTH AFRICA, AND CHINA

The climate effects on forests and industrial wood production in Brazil, South Africa, and China, countries chosen by the World Bank, are discussed below. The focus in these countries is on planted forests. All three countries have substantial volumes of timber produced from their planted forests, and all three have expanded their planted forest estates in recent years.

Figure 6 shows that China and Brazil are both among the leading countries in forest plantation establishment, with China leading the world and Brazil ranked number seven. Brazil has been concentrating on wood-producing forest; and unlike China, which has a large portion of its planted forest dedicated to environmental and protection objectives, Brazil has been rapidly

FIGURE 6. FOREST PLANTATION DEVELOPMENT AREA (000 HA)



Source: Reprinted from Seppala et al. 2009.

increasing its production of industrial wood. South Africa, the third case study country, has had a much more modest expansion of planted forest, but it has provided the base for a domestic pulp and paper industry, which is very activity in international trade.

Figure 7 provides a global overview of precipitation using the Hadley GCM. Hadley has one of the largest increases in maximum temperatures and also has severe precipitation limitations for some regions. Note that for the regions examined in this study—Brazil, South Africa, and China—precipitation is positive for forestry production in southern Brazil and southeastern China, but not as promising for forestry in South Africa.

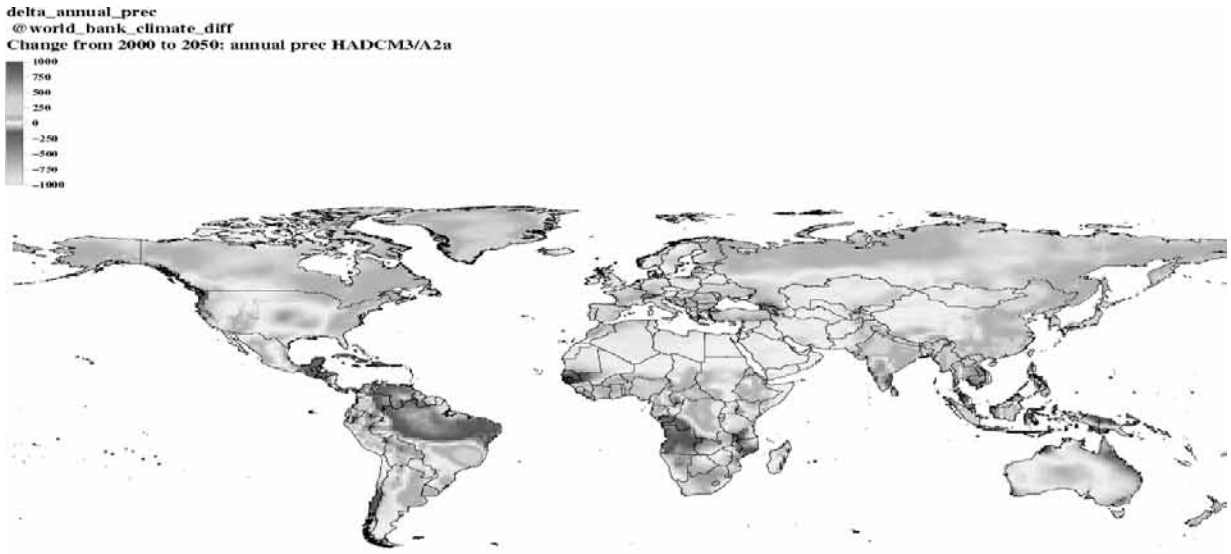
3.2.1 Brazil

The forest resource

Brazil's tropical forests make up 42 percent of its total land area, compared to 1 percent for plantations (Figure 8). It is estimated that 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—comes from the natural forest sector. Brazil also has harvests from its tropical forests. There are 210 million ha of federal forest, 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/ha in large trees each 30 years. This intensity would involve the harvesting of only 1 m^3 ha/yr on average. The major environmental effects of harvests in these areas probably involves the creation of roads and the possibility of spontaneous migration that could lead to land-use changes.

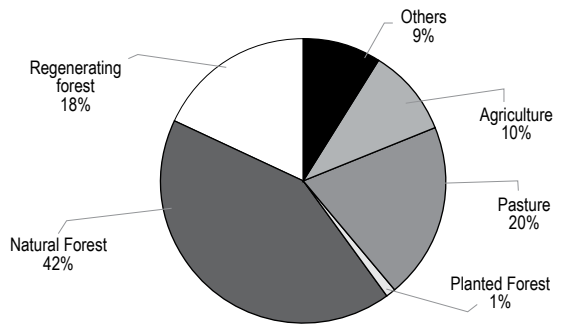
Although important, natural forests continue their decline in significance as sources of industrial wood, as Brazil plans to continue to establish an additional 500,000 ha of plantation forest annually. About 1 percent of Brazil's land area—or about 6 million ha (Seixas 2009)—is planted forest, but this is the core of Brazil's forest industry. In recent years, it has planted or replanted about 600,000 ha annually, about 40 percent of which are newly established plantations. Eucalyptus and pine constitute 5.6 million ha, or about 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 9 and 10). Tree breeding is currently under way toward the

FIGURE 7. CHANGE IN PRECIPITATION, FROM 2000 TO 2050



Source: Provided by Gerald Nelson.

FIGURE 8. BRAZIL AREA: 8.5 MILLION KM^2



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

development of frost-resistant eucalyptus trees. This could expand the area suitable for plantations. Brazil estimates the 2007 sustainable harvest of its pine and eucalyptus plantation 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 is projected to continue expanding its 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 hectares in 2008 to 26.7 million hectares 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 9 identifies areas of major eucalyptus plantation activity, while Figure 10 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). The north-south range is somewhat greater for the eucalyptus than the pine.

FIGURE 9. EUCALYPTUS 3,800,000 HA

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

Should a warming occur that moved forest, or forest suitability toward the poles, the movement of the planted forest would be toward the south of Brazil. Thus, both forest types could likely be relatively easily shifted to the area of Brazil toward the south. In a country the size of Brazil, there appears to be adequate room for movement to the south while still remaining within Brazil.

In general, eucalyptus is the preferred species due to its very rapid biological growth. Global warming could be met by adjusting species or, if necessary, relocating

FIGURE 10. PINUS 1,800,000 HA

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

plantations. 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. The existence of a large number of eucalyptus species would allow, in principle, the substitution of a more suitable variety. A word of caution, however, since knowledge of the behavior and likely wood-producing performance of the various eucalyptus and pine species is currently limited to a relatively few species. Additional research in this area could be important.

Brazil's recent planning and performance indicate they plan to establish far more industrial plantation forests than envisioned in the projections model of Sohngen et al. (1999). The government goal is to plant about 500,000 ha annually. Brazil has very rapid biological growth of planted forest trees and views itself with a substantial competitive advantage over most other industrial-country forests. 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 expected to continue at a relatively high level. Short rotations, continuing improvement and adaptation of genetically improved stock, and large areas for expansion suggest the Brazilian forest industry is ideally positioned to adapt to climate change.

Global change

Global change in Brazil is expected to involve warming in the plantation areas of the southeast and south. However, the cost of warming to Brazil's planted forest industry is likely to be minimal. Warming would expand the frost-free areas suitable for eucalyptus, thereby allowing them to be established further to the south. With warming, pine could continue to be planted and producing where it is currently located. Adjustments could be made to the warming either by continuing to use the appropriate species of southern (yellow) pine. Slash pine might be substituted for loblolly pine should the warming be excessive. Also, tropical pine—for example, Caribbean pine—could be introduced should temperatures rise substantially. In general, the array of pine and eucalyptus species currently in use and available are well-suited to be relocated within these regions to address a regional warming. The same sets of species also offer the ability to adjust within limits to changing precipitation and moisture conditions.

The alterations 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. However, 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, for this report, the timber production drawn from it. Over the longer period, should climate change be such that forests persist, changes in tree species are to be expected in general (Shugart et al. 2003) and also for tropical forests (Sedjo 2003). Should forest land change fundamentally, such as to grasslands, attempts to maintain 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, there are some sensible types of public investments to mitigate the impacts of clime change on Brazilian forests. A system of forest fire control is probably desirable both in the plantation regions and for natural forests. 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 entitled "Brazil—Amazon Fire Prevention and Mobilization Project March 2001"). Although natural forests could provide a useful agent to facilitate adaptation to the new climate (Sedjo 1993), a fire control capacity is desirable to limit damage to infrastructure and development around the forest. In addition, 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.

3.2.2 South Africa

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

Forest plantations in South Africa were first initiated in the late 19th century Exotic tree species were tried, and the area 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 1981–90 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 hectares in 1991. In recent years, new afforestation has proceeded at a level of around 11,000 hectares per year, constrained largely by a limited availability of suitable land, either in terms of water use regulations or in terms of insecure land tenure.

Several large private companies together own about one-half the plantation area, with a large portion owned by the state and some smaller private companies. South Africa's forest plantation area has continued to increase. 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.

Biological growth rates of some species—such as pine—are about 16 m^3/ha/year, with harvest rotations varying from 15 to 25 years depending on 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. Water concerns have resulted in 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.

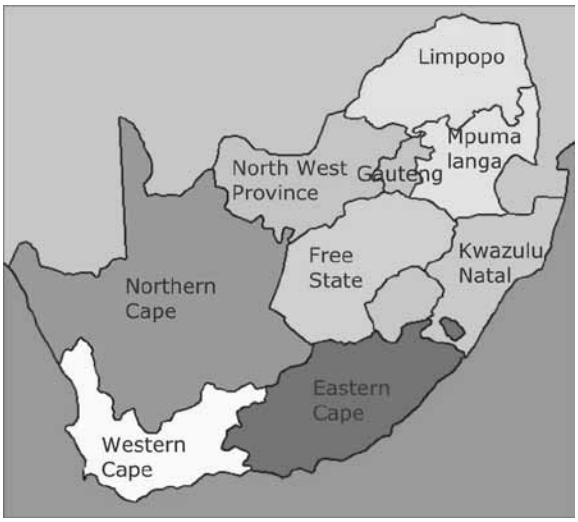
Climate change

As noted, a major constraint on planted forest in South Africa is water. South Africa climate configures into arid and semi-arid in the west, becoming wetter as one moves eastward. Plantations are concentrated in an area of the country in provinces where rainfall exceeds 800 mm per annum, specifically in a swath running from West Cape in the south to the northeast and parallel to the southeast coast of South Africa to Limkpopo in the northeast. Other provinces with substantial tree plantations are Mpumalanga, Kwazulu Natal, and Eastern Cape (Figure 10). Worsening the uncertainty, South Africa is subject to drought (Vogel 2003). Under a situation of global warming, the question of the viability of South Africa's forest plantations would likely depend more on the overall effects on precipitation and moisture, rather than temperature. A number of climate studies suggest that South Africa is likely to have drier winters. In addition, some of the land-limit constraints could be relieved with more secure tenure rights. Furthermore, the Haley GCM (Figure 7) projections suggest moisture difficulties as climate changes to the year 2050.

Given that a constraint to forest plantations is water, should the climate turn toward greater dryness, forestry and timber production would likely suffer. Should dryness increase significantly, the likely outcome is a substantial decline in South African timber production, with little possibility of investments to offset the decline (irrigated planted forests rarely make financial or economic sense). The lands 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 increase, 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 a lost 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 of a wooded ha could be in the neighborhood of $10,000 per ha. The cost of establishing additional plantations is estimated to be quite low in South Africa due to the relative ease of site preparation costs and low labor costs (Sedjo 1983).

FIGURE 11. SOUTH AFRICAN PROVINCES



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

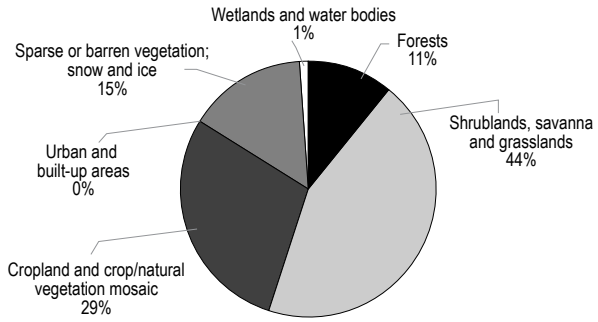
The role of public investment to offset climate impacts on industrial forests appears quite limited. Many forests are public, although the large paper industry is private. If climate were to undermine forest plantations, a sensible approach might be to focus investments on retraining of the displaced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

3.2.3 China

China is a large country with a variety of geographic, ecological, and climatic conditions (Figures 12, 13). Since the late 1970s, China's forests have made a remarkable recovery, in large part due to 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 (Figure 7). Some of these are aimed at increasing industrial wood production, but large areas are also dedicated to other reforested and afforested purposes

FIGURE 12. MAP OF CHINA

FIGURE 13. ECOSYSTEM AREAS BY TYPE



(Figures 12, 13). An FAO report (2005) indicates 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. Figure 6.3 of that report presents an estimate that about 45 million ha of China's forest is planted. The FAO report (2005) also indicates that China's forested land area has 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 China's forest area increased by about 1.5 percent annually in recent years, among the most rapid worldwide. These numbers suggest that about 11 percent of China's area was forested in the mid-1980s, and that the portion in forests today is about 16 percent, given the recent forest area estimates.

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, with protection forest increasing rapidly while timber forest expanded only modestly. A declining portion of the forest was being dedicated to firewood.

China's forests are located largely in the northeast and southeast sections of the country. Fortuitously, the Haldey map (Figure 7) suggests that both those regions—the Northeast temperate region and Southeast subtropical region—will be modestly helped by climate change to middle of the 21st century. More generally, IPCC (2006) 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 (Table 6).

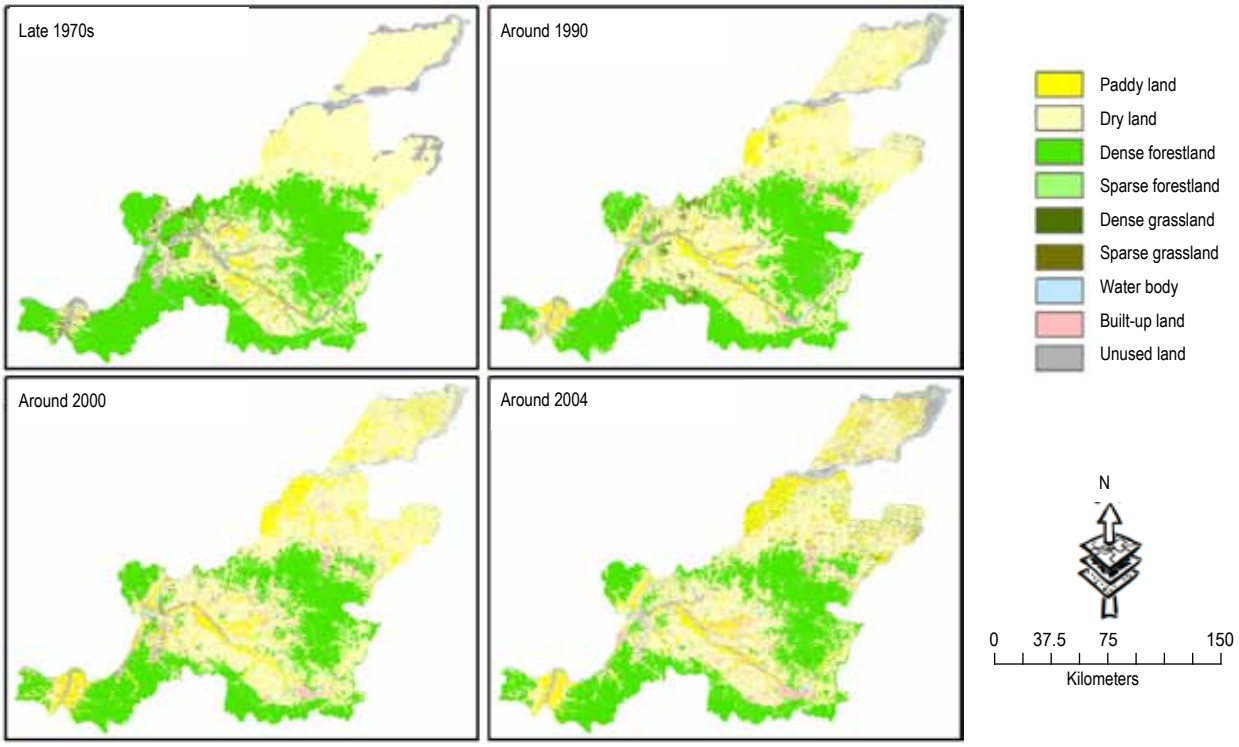
Figure 14 provides a focused look at the land cover of Heilongjiang province in the northeast. This assessment shows forest decline through the 1990s, but a modest recovery since then.

Costs of adaptation

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). As noted, its forest planting programs have at least two purposes: environmental protection and the production of more industrial wood. Thus, while the reforestation program is directed at adding more domestic wood to domestic processing, this consideration is not critical for continued wood processing provided that wood imports are allowed to continue in a relatively unobstructed manner.

For China, the challenge of climate change to its industrial wood producing forests appears modest. The exception could be infestations, which have tended to plague largely non-timber-producing poplar forests in the interior. China is responding to this threat with genetically engineered poplar trees, which are resistant to the infestation. Most timber trees have not been seriously adversely affected by the insects. However, infestations and genetic adaptations could increase the cost of adaptation. The overall 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 further be improved due to 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 so that regions currently in forest appear likely to benefit from climate change. 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.

FIGURE 14. LAND COVER OF HEILONGJIANG PROVINCE



Source: Shen, Yin, and Qi 2009.

In recent years, the World Bank has provided financial assistance to China for at lease two forestry development projects, both of which involved planting trees as a component. However, the impacts of climate change on China's industrial forestry sector through 2050 appear to be minimal. There appears to be little concrete reason to anticipate any serious investments in offsetting the impacts of climate change on China's industrial forests. In summary, it is difficult to see China's industrial wood situation deteriorating significantly over the next 50 years due to climate change.

4. LIMITATIONS

4.1 TREATMENT OF EXTREME EVENTS

Damages to wood-producing forests associated with extreme events seem to be largely limited to the type of threats common to forests, such as fire and windthrow. These in turn could become more serious either due directly to the extreme events or due to reduced forest health, such as infestation or disease related to the changing climate. These threats could be manifest as forest dieback. As discussed above, these types of problems can be addressed in part through salvage logging, which reduces the financial losses. In addition, regeneration, either natural or artificial, could be promoted to facilitate the recovery of a forest. Note, however, that for forests extreme events generally are not independent, but rather associated with forest system biological weakness. This weakness can reflect either the age and/or health of the forest, and may be associated with the unsuitability of the forest types that became established under the earlier climate regime. New types may need to accompany climate change.

4.2 TREATMENT OF TECHNOLOGICAL CHANGE

Modest technological change is built into the basic model and is not addressed separately for the industrial forest industry. Technical change could also be part of the adaptation process, such as tree breeding designed to facilitate adaptation to drought conditions or to resist infestations associated with climate change.

4.3 TREATMENT OF INTER-TEMPORAL CHOICE

Inter-temporal choice with forests and forest plantations could be associated with harvesting before the optimal rotation age, where conditions suggest that climate change threatens to reduce or destroy the timber crop. An early harvest may avoid most of this loss (Shugart et al. 2003).

4.4 TREATMENT OF "SOFT" ADAPTATION MEASURES

I would take "soft" adaptation measures in the context of the forest industry to refer to reliance on the natural resilience, mobility and reproductive capacity of the forest. This natural resilience may need to be facilitated through, for example, efforts to ensure the absence of obstructions to natural mobility. In addition, mobility can be facilitated through more active human activities to promote mobility—such as aerial seeding—which although probably inappropriate for industrial forests, could facilitate mobility among "natural" forests.

4.5 TREATMENT OF CROSS-SECTORAL MEASURES

No serious cross-sectoral measures were identified. The obvious one would be the question of alternative land use among forestry and agricultural uses such as pasture and cropland uses. The Sohngen et al. approach does not allow for the automatic conversion of useful agricultural land to forest uses as climate changes, unless those lands are not actively being managed or though a

conscious human decision to promote the land use change to forests. Indeed, much of the newly developed plantation area of the world reflects land use changes, typically from abandoned and marginal agricultural 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 grasses to forest.

4.6 AREAS FOR FOLLOW-UP WORK AND RESEARCH ADVANCES

A major limitation of this study is the range of possible climate changes generated by the various GCMs. Any of the regions or countries examined could have different results with a different GCM. For forests, precipitation is probably as important as temperature, at least in the temperature ranges under consideration.

Regarding forest and industrial wood, useful research advances may be found in the development of trees that have the ability to flourish under changing climatic conditions. In addition, 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 be an element of the customized tree.

5. INVESTMENTS AND COMPENSATION: SOME THOUGHTS

The question arises as to what the proper public sector role should be in addressing climate-change-induced adaptation and/or compensation. This question focuses particularly on the appropriateness of external support to the country—such as from the World Bank—for investments in adaptation and/or compensation. Let me share a few thoughts. Public sector support is often viewed as appropriate in the cast of severe catastrophic or near-catastrophic disasters. Climate change, natural or human induced, would probably fit. However, the nature of the event is such that substantial time is probably available to anticipate and undertake adaptive responses to many of the shocks so as to mitigate the size of the direct damages. Obviously, something like the Kyoto Protocol is a move in the direction of mitigating warming and its consequences. Some of the activities suggested in this report are intended to reduce the damages by adaptation, perhaps involving investments, from the warming that is not successfully mitigated.

One can think of warming as an externality associated with the free or low-cost disposal of a "bad," in this case GHGs, into the atmosphere. This approach to disposal has been viewed as costless when, in fact, there are real costs in the form of damages associated with GHG build-up. In common law, the generator of a negative externality is typically held liable for damages associated with the externality. Thus, the countries of the developed world, which have a long history of releasing GHGs into the atmosphere, would have liabilities for these earlier as well as current emissions. More recent transition countries, such as emerging countries like China and India, also are now major generators of GHGs and so also have liabilities. The larger a country and the longer the country has been industrialized, the larger share of the GHG emissions are probably its responsibility. The developed vs. 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 the transfer be allocated between the public and private sector? Using the common law paradigm, both private and public entities alike are eligible for compensation for damages from externalities. For forestry, natural forest restoration and/or compensation would seem appropriate regardless of ownership if the source of the damages were identified. Investments to reduce damages from fires, infestations, wind-throw, storms, etc., should in principle address these problems regardless of forest ownerships 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 market values of the former forest plantation lands could be large if those lands have few alternatives uses in the new climate; for example, with permanent moisture reduction, as could occur in South Africa. Finally, however, the rationale developed above may be overwhelmed by real world economic and political realities.

6. SUMMARY AND CONCLUSIONS

The main components of the study are as follows:

- Establish a baseline and projected timber and fuel harvests for the period 2010 to 2050. These estimates will be drawn from the existing literature.
- Describe the nature of the different climate risks faced by the forestry sector.
- By major timber producing regions, establish the quantitative and economic impact of climate change on the forestry sector.
- Develop a data base of adaptation measures, with estimates of their costs and benefits, allowing for variations in costs by country, or by region. Draw on information from relevant World Bank projects and/or other sources.
- By developing region, use the data base to estimate costs of adaptation as the minimum level of investment required to partially offset or restore the timber and fuel productivity of forests to their without-climate change levels, recognizing that in many cases one country or region's comparative advantage in forestry activities may be reduced or lost while another's is enhanced.
- In addition, the TOR called for the utilization of existing methodology and literature to a major country in each of the three regions. The major countries agreed to were Brazil, South Africa, and China.

The report extensively reviewed the literature. Overwhelmingly, the literature suggested that the world's overall forest area would probably change little most, likely expanding modestly. The tables show that forest productivity (NPP) is expected to increase in most regions. As climate changes, tree species are expected to migrate to areas more conducive to their needs. 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 utilizing the projections of Sohngen et al. 2001. Although these projections were done several years ago, no new comprehensive projections of this detail are available. Also, there are no new scientific findings that would lead us to expect 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. Plantation forests have short rotations and can be planted in the species of choice, which can change to fit changing conditions, thereby allowing maximum flexibility to adapt to climate change.

Three countries are examined in detail: Brazil, South Africa, and China. They 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. However, should it have widespread moisture problems, its future supply potential could be compromised. However, most GCMs suggest moisture will be adequate. Although most of China's industrial wood is

imported, China appears to be in a strong position to maintain and expand its forests and increase future 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 generally expecting adequate precipitation with climate change.

The third country, South Africa, is more problematic. Plantation forestry has done well in South Africa, as the country has built a successful pulp and paper industry oriented toward export markets. However, moisture is inadequate for trees in much of South Africa. The areas of tree plantations are near the edge of an adequate moisture range. A number of GCMs project decreased precipitation, which suggests problems for the existing plantations. The opportunities to relocate are limited and could be further reduced by precipitation problems.

Despite the generally optimistic assessment found in this report, uncertainly persists. Unanticipated problems related to climate change could take the form of widespread infestation of forests in any of these countries or more broadly. However, plantations offer many dimensions for flexibility and adaptability. Even with infestations, for example, plantations provide potential adaptability by allowing the replanting of species not favored by the pests. Furthermore, planting allows for the introduction of genetically altered trees resistant to the pests, either through traditional breeding or through genetic engineering. 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; that is, lumber and solid wood material, and pulp and paper. However, there are growing demands for alternatives to fossil fuels, and wood is commonly mentioned. Wood can be combusted directly or converted into various forms of energy, including biofuels. The potential demand from 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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