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Wood Production under Changing Climate and Land Use

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CONTENTS

EXECUTIVE SUMMARY

The fundamental question on which this chapter focuses involves forest resource availability and resource consumption: Will the resources from future forests be adequate to meet future needs? Although all forest amenities are of interest, this chapter concentrates primarily upon those for which data are most available, reliable, and measurable: wood and wood products. All of the conclusions depend upon uncertain climate model simulations (resource availability), uncertainty in adaptive changes in forest product use, and uncertain regional human population growth scenarios (resource consumption). Assuming all of these variables change as projected by their respective scenarios, the following forest resource responses are likely (note that none of the conclusions summarized below were considered in the 1990–1992 IPCC Assessments):

- Tropical land use will be much more important than change in climate and atmospheric chemistry in affecting forest product availability there, at least until the middle of the next century (High Confidence). Growing stock in the tropics is projected to decline by about half from anthropogenic deforestation, while consumption is predicted to expand because of a threefold increase of population. The projected standing stock decline appears even after calculation of concomitant changes in climate and atmospheric chemistry, which could increase both productivity and the areas where tropical forests can potentially grow.
- Under these circumstances, tropical forests of densely populated countries in Africa and Asia would be most vulnerable to loss (High Confidence). These areas contain rapidly expanding human populations and concomitant increasing needs for forest products, especially but not entirely for fuelwood. Fuelwood consumption is expected to increase throughout the 55-year study period (High Confidence).
- Temperate-zone wood requirements are likely to continue being met for at least the next century (Medium Confidence). This conclusion is based on assumed climate and land use changes that leave temperate forest covering about as much land by the year 2050 as today. Also, current harvests from plantations and wildland forests are expected to increase only marginally. Additionally, annual growth increments are assumed to remain constant through 2050. Finally, an increasing proportion of requirements for wood is expected to be met by imports from outside the temperate zone.
- Future wood availability in boreal regions is uncertain at best, based on current data, scenarios, and models (High Confidence). Future production is expected to be controlled by increases in climate-induced irregular and large-scale mortality events, which cannot be simulated or predicted with current models. These could generate considerable surplus wood from salvage fellings, but would severely decrease standing stocks over the long term. In addition, current and future harvests in boreal forests are expected to be largely determined by needs outside the zone. The models underlying future projections contain no consideration of these forest economic or trade processes or their implications, a particularly critical omission in boreal regions. Therefore, the available information does not support realistic analysis of future boreal forest product demand.
- Total global wood consumption will exceed the availability expected by the year 2050 (Medium Confidence). Analysis of increasing human populations, with the assumption of constant per capita wood use, suggests that the annual need for timber will exceed the current 2% annual growth increment before the year 2050. Although we assume that the annual increment will remain constant, it could increase slightly from warming and enhanced atmospheric CO_2 concentrations, or it could decrease greatly from growth declines and mortality brought on by climate change.
- Future temperate and possibly tropical zone requirements for boreal forest products may result in serious shortfalls of boreal industrial roundwood during the 21st century based on the analysis of temperate and tropical zone forest standing stocks and requirements (High Confidence).
- The livelihood of indigenous tropical peoples will be adversely affected if climate and land-use change induce forest losses (High Confidence). These peoples depend on a large diversity of forest products that are expected to undergo declines in biodiversity and forest regeneration due to climate change and may be subject to forest degradation apart from land conversion.
- Options for adapting to and ameliorating potential global timber supply shortages in the future include the following actions: In the tropics, the greatest progress may be achieved by reducing social pressures driving land conversion (e.g., by increasing crop and livestock productivity on current agricultural lands) and by development of large tree plantations (High Confidence). In temperate areas, use of modern forestry practices to reduce harvest impacts on ecosystems, combined with substitution of nontimber products for forest products, could reduce climate impacts

significantly (Medium Confidence). In boreal regions, the most useful focus may be on adapting to potential climate-induced large-scale disturbances, such as by rapid reforestation of disturbed areas with warmth-adapted seed provenances (Medium Confidence).

- Research needed to conduct a more accurate assessment of climate change impacts on future forest product availability includes (1) obtaining new data needed to demonstrate and quantify direct effects of atmospheric CO_2 on ecosystem productivity and tree growth (High Confidence), and (2) uniform reporting and assembly of national forest inventory data sets (High Confidence). New mathematical models will be needed especially to (a) simulate transient (lagged) responses of forests to rapid climate change, (b) integrate relationships among climate changes, ecological responses, and economic forces and responses, and (c) simulate regional climate changes and their effects (High Confidence).

15.1. Introduction

This chapter examines the changes induced in human-valued properties and products of forests (primarily wood and wood products) by potential shifts in vigor, productivity, and geographic distribution of tree species populations and of forest ecosystems. These shifts are expected to arise from global changes in climate and atmospheric chemistry. In addition, this chapter examines the roles of other forces—particularly of land use, which may modify or mask effects of changing climate and atmospheric chemistry. The changing commodities and amenities derived from forests are a tertiary response to the initial forcing caused by increased atmospheric concentrations of greenhouse gases. As such, the commodities cannot be estimated reliably until accurate forecasts are made of the intermediate processes and outcomes (climate, atmospheric chemistry, and resulting forest density and growth patterns). On the other hand, we can and do assess the socioeconomic responses to quantitative estimates of changing climate, land use, and forest ecosystem responses that are expected to arise from current practices and processes and from potential future ones.

This chapter focuses on the fundamental question of forest resource availability and resource needs: Given that the availability of growing stocks and related amenities from today's forests are adequate to meet today's needs under today's climate, will the availability from future forests be adequate to meet future needs under predicted future climates? The analysis avoids the more complex issues of economic responses to changes in potential growing stocks (as expected in decreasing prices because of enhanced harvests from use of new technologies, increasing prices from decreasing supplies, and changing prices from product substitution resulting from increasing prices). It concentrates instead on estimating the quantity of growing stock to which economics must be applied and the size of the population needing forest products.

Chapter 1 of this volume evaluates forest geographical, ecological, and productivity responses to changing climate and atmospheric chemistry. Chapter 24 of this volume examines the need for and effects of actions taken to mitigate increasing atmospheric CO_2 concentrations. These include forests subjected to unplanned and nonsustainable forest management practices. A third related chapter in the Scientific Assessment (Chapter 9, *Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate*, of the IPCC Working Group I volume) defines expected changes in global carbon cycling from shifts in forest geography and productivity under future changes in climate and atmospheric chemistry.

This chapter encompasses wood and wood products and amenities from all forests, whether or not they can be used by humans. Although all forest amenities are of interest, the chapter concentrates primarily upon those for which data are most available and reliable: wood products [roundwood (i.e., that portion of wood and bark removed from forests), industrial roundwood (i.e., that portion of roundwood to be processed further), and fuelwood and charcoal (i.e., that portion of roundwood to be consumed for cooking, heating, and so on)].

The term "availability" of roundwood is used throughout this report, rather than the economically significant term "supply." Roundwood availability (as distinguished from supply or production) depends on the amount of growing stock and on annual growth increments. These are determined by climate, soils, management, and forested area. Only a fraction of growing stocks is normally considered as commercial forest, and only a fraction of commercial forest is available for harvest (supply). Even if harvested wood equalled growing stock—say, by application of advanced technologies—wood products can only be harvested up to the amount of available growing stock. Hence, growing stock is a more conservative estimator of the fundamental limit to harvests than is some smaller quantity, such as sustainable harvest level (see Section 15.5.2).

In the current assessment, we assume that even intensive management will not increase potential harvests beyond the maximum potential natural growing stock. Although the assumption is probably safe, the role of management in increasing future forest biomass (= growing stocks) is examined in detail by Brown *et al.* in Chapter 24. They conclude that during the next 55 years, about 20 Gt (Table 24-4) could be added by forestation to the approximately 1000 Gt (Table 24-1) already present in above- and belowground biomass stocks of forests. This potential 2% contribution by management may not be realized within the realities of limited forest management budgets.

In contrast to variables controlling growing stocks, harvests from forests will depend on the technology available to harvest and market roundwood, and demand for the resulting wood products (and hence, price of the products), as well as the amount of growing stock itself. Demand for wood products ("need" and "consumption" are noneconomic terms used in this report in place of "demand") and related amenities will change with shifts in size and geographic distribution of population, with technological and financial prosperity of end users, with price of the products, with availability of alternative products, and so on. Assessment of these variables is beyond the scope of the current chapter, although they could be profitably examined in the next IPCC assessment report. Here, we assume that per capita consumption remains constant and that population size increases as in the IS92A population projection (IPCC, 1992). In developed countries (e.g., Australia), per capita consumption actually declined during the last decade (FAO, 1992) and could do so in other countries in the future.

15.1.1. 1990 IPCC Forestry Assessment Results

The 1990 IPCC assessment of forestry (IPCC, 1990a) was confined to managed forests—difficult entities to assess because forest areas or volumes are rarely measured as "managed" or "unmanaged," and when they are so divided, the definitions of "managed" vary widely. As a consequence, the 1990 assessment contained few quantitative conclusions. However, it did define uncertainties and issues of importance. In particular, it suggested that forest plantations are probably much more vulnerable to environmental change than are mixed-species and mixed-age stands. The latter contain species and developmental stages that may be less vulnerable to chronic climate change at any given point in time or space, whereas the former are easier for forest pests to invade.

The assessment recommended that impact analysis focus upon transitional climate and forest responses that may be with us for several decades, rather than on a single future long-term "equilibrium" climate. Finally, it recommended that "in the face of great uncertainties about rates and magnitudes of climatic changes, forest responses to potential climate change, and socioeconomic repercussions of climate-induced forest changes, it is prudent to prepare for severe undesirable impacts to ensure that viable and flexible options are implemented to maintain sustainable forest ecosystems." The results of our report are consonant with these two fundamental recommendations. However, unlike earlier efforts, our assessment was developed to go a step further in documenting the level of predictability in future forest production and consumption as constrained by projected changes in climate and land use.

15.1.2. 1995 IPCC Forestry Assessment Strategy

The current chapter approaches the assessment first by quantifying present and future roundwood availability and potential consumption as accurately as possible with available data and models (Section 15.2). Then the validity of these estimates is assessed, first for the globe as a whole (Section 15.2), then within tropical, temperate, and boreal forest regions (Sections 15.3, 15.4, and 15.5). Both validity assessments are based upon less quantifiable but relevant estimators of timber availability and consumption that are not included in the models. These analyses generate definitions of certainties, uncertainties, and unknowns regarding future availability of and needs for timber. Adaptation measures to reduce effects of specific changes are then discussed (Section 15.6). Last, monitoring and modeling products needed to resolve identified uncertainties and unknowns in future IPCC forest product assessments are presented (Section 15.7).

15.2. Present and Future Global Forests

Kirschbaum *et al.* (see Chapter 1) describe the distribution and characteristics of natural forests and discuss the expected responses by forest ecosystems to changing atmospheric chemistry and climate. In Chapter 24, Brown *et al.* examine the potential gain in forest area and density that forest management potentially can provide. In addition, we examine the possibility that forestry and forest management, and several other kinds of land use, may be as important or more important than climate in determining the future spatial and temporal distribution of forests. The interactions of these climatic and management changes will generate impacts that are not necessarily intuitively obvious. Therefore, to be useful, the assessment must at least quantify the changes in wood products should current conditions of change continue unabated (business as usual).

15.2.1. Present Characteristics of Forests

Globally, forests in 1990 covered one-fourth to one-third of the earth's land surface (34 million km^2, FAO, 1993a; 41 million km^2, Dixon *et al.*, 1994; see Chapter 1 for a detailed description). Although the great majority of these forests can be considered as managed to some degree, only about 4% of forests consist of intensively managed plantations (1.35 million km^2, Kanowski *et al.*, 1990; 1.12 million km^2, Dixon, *et al.*, 1994). WRI (1994) cites a doubling of forest plantations during the decade from 1980 to 1990, with three-fourths of all plantations being in Asia. The plantations may produce a disproportionate amount of forest products. About 30% of industrial timber production (industrial roundwood, i.e., non-fuelwood raw logs) in Latin America, for example, may have originated on plantations (McGaughey and Gregerson, 1982). Brown *et al.* (Chapter 24) point out that about 11% of the world's forests undergo active management; this includes 20% of mid-latitude and 17% of high-latitude forests but only about 4% of low-latitude forests.

FAO estimates that globally, forest products were worth about $418 billion in 1991; this amounted to 4% of the gross domestic product (GDP) of developing countries and 1% of the GDP in developed countries (FAO, 1993a). Although most forest products were consumed locally, total annual exports of logs and wood products between 1986 and 1988 were estimated at $68 billion, of which $10 billion was earned by developing countries (Sharma *et al.*, 1992). Many developing (tropical) countries rely heavily on their forest resources for obtaining capital. For example, 1991 forest product exports from Cambodia represented 43% of all trade; from the Congo, 16%; and from Indonesia, 12% (FAO, 1993a).

15.2.2. Projecting Future Forest Characteristics

Numerical projections of forest area and growing stocks require us to combine a spatially explicit mathematical model of forest response to climate and land use with a quantitative scenario of climate and land-use change. Few vegetation models are available from which to choose. There currently are no forest response models that simulate the processes controlling the change of forest productivity or geography over time ("transient" models), and that are globally comprehensive (see Chapter 9, *Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate*, of the IPCC Working Group I volume).

Static responses of forests—those that would be expected at some time following cessation of directional environmental change (Prentice and Solomon, 1991)—can be projected by several available models. Their fundamental flaw is that dynamic equilibrium of forests cannot be expected for centuries

Box 15-1. Use of Static Models to Estimate Future Forest Production

The application of the BIOME or IMAGE model (Tables 15-1 through 15-4) or other static vegetation models (see Chapter 1 of this volume, and Chapter 9, *Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate*, of the IPCC Working Group I volume) to estimate potential forest changes under different but stable modeled climate omits potential variables that could be critical to future forest distributions and productivity. The following weaknesses are most important:

- There is no indication that a stable climate will appear in the foreseeable future. Indeed, the global change problem to be assessed involves rapidly changing climate, not stable climate, during the next 50 to 100 years. The static models do not simulate impacts of rapid climate change on slowly responding forests, and current efforts aimed at parameterizations of the process will beg the question.
- Static models do not simulate tree mortality. In a warmer and potentially drier world, the geography of forest ecosystems is expected to shift, as it has many times during climate changes of the past (e.g., Huntley and Webb, 1989). This may be detected initially as negative or positive changes in seedling survival, growth and productivity of established trees, and eventually by forest decline as the environmental variables exceed species tolerances. Such forest decline is likely to be amplified by increases in tree mortality events (dieback), disease and insect outbreaks, fire, and damage associated with extremes in weather, none of which are simulated by the static models.
- Static models assume that trees instantaneously occupy new, climatically suitable areas. However, current projections of climate change appear to be too rapid to allow population geography to adjust: If the Holocene tree species migration rate of 0.2–0.4 km/yr (Davis, 1976, 1983; Huntley and Webb, 1989, suggest 0.1 to 1 km/yr based on examination of extant paleoecological data) records maximum tree migration rates, trees may be unable to attain the 4–6 km/yr rate of climate change expected (Solomon *et al.*, 1984). As a result, large areas of low productivity or degraded forest (forest lacking a full complement of growing stock and tree species, consisting instead of slowly growing and dying trees made ecologically inappropriate by climate change) could be present for centuries.
- Static models assume that new forested areas instantaneously grow to maturity and can be harvested. Thirty to 50 years or more of relatively stable climate are required to reach a harvestable condition of most species once the tree is established. Therefore, most of the new areas capable of supporting forests may consist of young, immature trees. Establishment of these trees under the expected regeneration-unfriendly conditions is potentially an even more serious problem.
- Static models do not account for differences in short- and long-term forest productivity. However, a forest in decline in the short run (50–70 years) will increase the available wood supply. If there are large areas of dead or dying trees, much of this wood probably will be harvested or salvaged. In the long run (>75 years), however, roundwood availability could decrease because of the immaturity of new species populations.
- Static models assume that the soil conditions will be suitable for new tree invasions. However, in boreal regions, permafrost and excess surface water dominate many landscapes, prohibiting uptake of nitrates. Recent glaciation at high latitudes has endowed large areas with thin soils or bare rock. In many tropical areas, prior intensive agriculture has so depleted the soil of phosphorus that tree growth is exceedingly slow. These soil features could form major barriers to immigration and growth even at the slow rates projected by models, making it unlikely that the forest tree populations will be able to migrate at their measured rate of 0.2–0.4 km/yr or reach maturity at their natural rate of 20 to 50 years.

(e.g., Solomon, 1986; Bugmann, 1994), following an environmental equilibrium which itself is not likely in the foreseeable future (see Box 15-1).

Although the static models cannot be used to identify what vegetation units will replace current ecosystems, the models can define which ecosystems will be inappropriate for the new climates and hence are vulnerable to climate change (e.g., Solomon and Leemans, 1990; Chapter 1). This requires only the very simple and robust assumption that climatic limits to forest growth implied by current geography will operate similarly in the future as well. Even this simple assumption may not be entirely correct because of potential changes in climate response patterns of plants induced by increased atmospheric CO_2.

One static model (BIOME 1.1, hereafter BIOME; Prentice *et al.*, 1992,1993) was conceived specifically for assessing geographically distributed responses of vegetation types to expected climate changes. BIOME is unlike other static models in that it is based on specific physiological responses of plants to climate. These responses define a set of plant functional types (PFTs). Each PFT is characterized by a minimal (and different) set of known climate thresholds (minimum winter temperatures, summer warmth, evapotranspiration). BIOME was modified to include climate-dictated potential

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BIOME cannot be used to assess interactions among forestry, land use, and climate change. However, the BIOME vegetation classification has been incorporated into a model of interacting population (including associated natural resource utilization), land use, vegetation, and climate (IMAGE 2.0, hereafter IMAGE; Alcamo, 1994). Land use (agriculture) is modeled as a function of food demand by populations that vary in density over time, and in resource demand from one region to another. Land use is further modeled as constrained by climate and soils.

IMAGE has been used to project the implications of these population-land use-climate interactions on the geography of forests (Zuidema *et al.*, 1994; Leemans and van den Born, 1994). The IMAGE projections generate an annual climate change from greenhouse gas concentrations; by the year 2050, this produces a climate essentially indistinguishable in its forest effects from those produced by the IS1992a future scenario (IPCC, 1992). However, IMAGE has been applied without feedbacks between changed climate and changed wildland vegetation (i.e., BIOME-dictated wildland vegetation does not respond to climate change). Therefore, its effectiveness is reduced where land use is unimportant. Hence, we projected global wood product availability into the future with both BIOME vegetation responses from Solomon *et al.* (1993) and IMAGE land cover change scenarios from Zuidema *et al.* (1994).

15.2.3. Projecting Future Availability of Forest Products

The forest area of ecosystems projected by BIOME for the present and for the year at which climate reflects a doubling of greenhouse gases (GHGs) is shown in Figures 1-5 and 1-8 (see Chapter 1) and is presented in Table 15-1. Note that estimated present forested areas (Dixon *et al.*, 1994) and modeled present forested areas (Solomon *et al.*, 1993) are similar except for a serious discrepancy in the tropics. There, the differences are in both definition (each defines "forest" differently) and in model capability (BIOME is less accurate at distinguishing between tropical forest and tropical savanna; Prentice *et al.*, 1992).

Table 15-1: *Tropical, temperate, boreal, and global forested areas in 10^6 km^2 under different future climate scenarios, at the year of a doubling of atmospheric CO_2, and percentage differences between current and future climates—projected by the BIOME 1.0 model.*

	Present Area Est.[1]	Present Area Modeled[2]	GFDL Area	GISS Area	OSU Area	UKMO Area
Tropical Forests	17.6	36.8	40.6	42.9	41.3	41.4
Temperate Forests	10.4	10.6	15.7	15.7	13.3	16.1
Boreal Forests	13.7	16.7	8.4	11.5	13.5	9.1
All Global Forests	41.7	64.1	64.7	70.1	68.1	66.6

[1]From Dixon *et al.*, 1994.
[2]From Solomon *et al.*, 1993.

Table 15-2: *Tropical, temperate, boreal, and total global forested areas in 10^6 km^2 under a single, self-generated future climate and land-use scenario, at different years, projected by the IMAGE 2.0 model (from data of Zuidema et al., 1994).*

	Area of Forest at Year 1990	2000	2020	2050
Tropical Forests	27.6	25.0	21.0	14.4
Temperate Forests	5.4	4.1	4.9	5.3
Boreal Forests	13.8	14.3	15.2	15.3
All Global Forests	46.8	43.4	41.1	35.0

The major pattern to emerge from comparison of all four climate scenarios with modeled present area is a moderate increase in area occupied by tropical forests, a strong increase in area occupied by mid-latitude temperate forests, and a similarly severe decline in area occupied by boreal forests. The simulated increase of temperate forest area is almost entirely at the expense of boreal forest area, which is reduced by a lack of very high latitude area to occupy, by loss of area to invading temperate forests at lower latitudes, and by the expansion of agriculture into areas now possessing too short a growing season to allow agriculture.

Table 15-2 presents forested areas in tropical, temperate, and boreal zones projected by IMAGE at 1990 and at 2000, 2020, and 2050. The singular climate scenario is generated within IMAGE, based on annual increments of GHGs generated by modeled energy use, land use fluxes, ocean uptake of CO_2, and so on.

The areas of tropical, temperate, and boreal forests estimated for the present by the two models differ substantially. BIOME initially estimates that 37% more land is in forests than does IMAGE. The differences appear to arise from a much larger agricultural area calculated in IMAGE than in BIOME. It seems likely that BIOME results are less accurate in temperate and tropical areas because IMAGE agricultural area of 1990 is very similar to that measured in FAO statistics (Zuidema *et al.*, 1994), and the current forested area of IMAGE is much closer to that estimated by Dixon *et al.* (1994; see Table 15-1). As one would therefore expect, the greatest difference in 1990 zonal composition between BIOME and IMAGE areal projections is in temperate regions (16.5% vs. 11.6% of forests, respectively) where the greatest density of agricultural land use is found, followed by boreal regions (26.1% vs. 29.6% of forests, respectively) where the lowest density of agricultural land is found. Even if land use were simulated similarly in both models, one would expect the proportions of land in each zone to differ because IMAGE defines the current zones based on national boundaries as well as on the climatic criteria used by BIOME.

The area and geographic distribution of forest changes projected by IMAGE at the year 2050 (Table 15-2) are in sharp contrast to those generated by BIOME at a doubling of GHGs (a point that might be reached by the year 2050; Manabe and Wetherald, 1993). Where BIOME indicates a total global increase in forested area from 1 to 9%, IMAGE calculates a decline of 25%. The large increase in temperate forest area in BIOME simulations becomes a slight decline in IMAGE. Both models project forest gains in temperate regions of North and South America and Europe, but in IMAGE, much land is lost to increased agriculture in Asian temperate regions. A decreasing demand for agricultural land in the developed countries of temperate regions results from slow population growth in Europe and North America and the projection into the future of increases in agricultural efficiency encountered during the past few decades (Zuidema *et al.*, 1994).

The contrast between IMAGE and BIOME projections for the future is greatest in the tropics. Tropical Africa and Asia, where human population growth is greatest, are simulated by IMAGE as losing large amounts of tropical forests and woodlands (Table 15-2). Moderate increases in tropical forests projected by BIOME (Table 15-1) disappear when the need for agricultural land is factored into the calculation, as it is in IMAGE.

Differences in projected boreal forest area are also great. The BIOME losses of 20–50% (Table 15-1) become increases of 10% in boreal forest land (Table 15-2) by IMAGE. BIOME assumes that 50% of the area in which climate permits agriculture will be farmed and that climate changes redistribute mature biomes on the remaining land. IMAGE assumes that declining agricultural demand will allow regrowth of climatically appropriate forests on abandoned farmland but that forests will not be redistributed on undisturbed lands regardless of new climate conditions. This has the effect of eliminating instant forest migration/maturation on lands undisturbed by intensive land use—which are the vast majority of lands in boreal regions, much less in temperate regions, and the minority of lands in many tropical regions. This assumption should be more correct than the assumption of instantaneous migration during the simulated 60 year period (see Box 15-1). Few tree populations in the past 10,000 years have required less than a century to migrate latitudinally across even one of the 55 km pixels simulated by both BIOME and IMAGE (Davis, 1976, 1983; Huntley and Webb, 1989; Huntley, 1990). Fewer still can be expected to form mature, dense populations and forest ecosystems in new locations during that same 55 years.

The land cover and use changes projected by IMAGE appear far more important during this transition period of 60 years than do the effects of concurrent climate change in BIOME. This reflects in part the weak response to climate that IMAGE generates and its assumption that a significant amelioration of climate impacts will result from strong effects of carbon fertilization, water use efficiency, and other feedbacks (Zuidema *et al.*, 1994). This assumption is not included in BIOME. Although there is no definitive evidence that this effect occurs in forest ecosystems, even the greatest benefits claimed for the effect may not be significant (Chapter 1).

Instead, land use must be the most important agent of change in any vegetation replacement scheme based on the relationship between the large magnitude of current global vegetation replacement induced by the current population and the doubling of human population every 35–40 years. We know of no processes (technological or natural) that have been quantified (i.e., that can be included in a simulation) that would ameliorate this enormous impact. Using "back of the envelope" calculations, Sharma *et al.* (1992) conclude that population pressures could reduce forest area 30% by 2025, a value similar to the 24% decline by 2020 estimated by IMAGE (Table 15-2). No other published research of which we are aware takes this land use impact into account in projecting future characteristics of the global terrestrial biosphere.

In sum, without accounting for human demographics and agricultural land use, climate change alone would be responsible for an increase of 1–9% in land suitable for forests, with the largest gains in temperate regions. Projections that simulate future human needs for agricultural land but lack significant impacts of concomitant climate change generate a decline of 25% in forest area by the year 2050, with the greatest losses in the tropics. Because vegetation presence or absence within the envelope of appropriate future climate will be determined by land use at that time, it is the land use projections that must be given the most serious consideration.

The IMAGE projections of forest area have been used to estimate the potential supplies of forest products (from growing stock volume) by assuming that the ratio of forest area to growing stock today will also apply in the future (Table 15-3). We emphasize that the inaccuracies induced by the transient processes discussed in Box 15-1, and those detailed in the following paragraphs, are likely to change this ratio in the future. It is impossible to estimate, however, whether growing stock per unit area will increase or decrease.

Because the volumes in Table 15-3 are related to areas in Table 15-2 (data for the tropical, temperate, and boreal regions in

Table 15-3: *Current and future timber availability (growing stock) in 10^9 m^3, based on 1980 productive forest volume (Sharma, 1992) and percentage changes in forest area in IMAGE (Zuidema et al., 1994).*

	Volume of Forest at Year			
Region	1980	2000	2025	2050
Tropical Forests	146.7	132.8	111.6	76.5
Temperate Forests	41.3	31.4	37.5	40.6
Boreal Forests	90.0	93.2	99.1	99.7
All Global Forests	278.0	257.4	248.2	216.8

Table 15-2 are drawn from individual countries, and in Table 15-3 from the 13 groups of countries), patterns of change are also similar: tropical forest growing stocks decline by almost a half; temperate forests initially decline, then recover by the year 2050; and boreal forests increase slightly over time, with global growing stock volume down by about 22% in the year 2050 (Table 15-3).

The estimates of potential wood availability do not include enhancement of standing stocks from annual forest growth and from tree plantations developed to mitigate atmospheric CO_2 concentrations (see Chapter 24). Measurements of current annual forest growth in tropical regions average 2% of standing stocks (DeBacker and Openshaw, 1972), about 3% of exploitable growing stock in temperate countries, and 1.5% in boreal countries (FAO, 1992). These values would result in an increase in availability of wood products of about 2% (4.24 x 10^9 m^3) above the 216.8 x 10^9 m^3 presented in Table 15-3 by the year 2050.

The annual growth increment assumed in the wood availability projection is unlikely to remain constant. For example, Chapter 24 points out that tropical forest productivity may continue to be degraded by illicit and selective fellings. Also, forest growth may decline and mortality may increase from increasingly inappropriate climate (Solomon and Leemans, 1990; see also Chapter 1). This growth loss also was not included in the calculations that produced Table 15-3. Solomon (1986) used a transient forest response model to calculate an approximate 10% decrease in annual biomass increment at 21 locations in temperate and boreal forests of eastern North America at the time of CO_2 doubling. There were 50% decreases in simulated temperate forests, while boreal sites had increases of severalfold where forests replaced open shrublands.

The opposite effect on annual growth increment is also quite possible (see Chapter 9, *Terrestrial Biotic Responses to Environmental Change and Feedbacks to Climate*, of the IPCC Working Group I volume). Annual growth increment may increase in all zones from the fertilization effect of increasing atmospheric CO_2; increased efficiency of water use; and, particularly at high latitudes, globally warmer temperatures. These enhancements are discussed in detail in Chapter 1, which provides no estimate of the impact on growth increment. However, others (e.g., Melillo *et al.*, 1993) have calculated from carbon flux models that growth increases of 16% may accrue by the time a doubling of atmospheric CO_2 concentrations is reached.

Growing stock volume also might be significantly enhanced through concerted national and international programs to mitigate atmospheric carbon emissions through development of forest plantations for carbon storage and for substitution of fossil fuels with biomass. The maximum increments would vary each year over the life of any proposed program. Chapter 24 uses these estimates, aimed at generating the maximum possible biomass increment (Nilsson and Schopfhauser, 1995), to project potential carbon storage from mitigation measures. Nilsson and Schopfhauser (1995) estimate that about 1.8 x 10^9 m^3 could be incremented annually by the year 2025 (0.7% of supplies shown in Table 15-3), with a peak value of 3.11 x 10^9 m^3 by the year 2055 (1.4% of supplies in year 2050, Table 15-3). This assumes that annual increments will remain constant rather than declining from stress or increasing from CO_2 fertilization.

If the growing stock enhancement for the year 2050 produced by extension of current annual growth increment (4.24 x 10^9 m^3) were combined with that produced by optimum management for the year 2055 (3.11 x 10^9 m^3), forest volumes would decline 19% from 1980 levels by about 2050, rather than declining 22% as calculated in the absence of these factors. Present research results are inadequate to determine whether one should accept or reject either or both of the enhancement factors.

15.2.4. Projecting Future Need for Forest Products

The annual need for forest products must be determined differently from the availability of forest products. One can assume that the need for forest products will be largely independent of climate change and land use effects, at least until available timber supplies have been nearly consumed, forcing prices so high that users cannot afford to purchase them. The simplest assumption is that the need for wood is proportional to population size and associated regional prosperity, although FAO (1993a) depends on gross domestic product (GDP) in more complex and assumption-laden demand models for forest products (Baudin, 1988).

Considering the uncertainties associated with projecting forest product needs to the year 2050, we chose the simpler assumption. Future need for fuelwood/charcoal and industrial roundwood (the two components of roundwood) was calculated (Table 15-4) based on future population estimated for each of the 13 global regions in the IMAGE conventional

Table 15-4: *Current and future need for forest products in 10^9 m^3, based on regional population projections (Alcamo et al., 1994) and regional forest product consumption (FAO, 1993a).*

	Year			
	1990	2000	2025	2050
Industrial Roundwood				
Tropical Regions	0.28	0.35	0.52	0.65
Temperate Regions	0.89	0.95	1.04	1.04
Boreal Regions	0.43	0.45	0.49	0.49
Total Global Volume	1.60	1.75	2.05	2.19
Fuelwood and Charcoal				
Tropical Regions	1.37	1.70	2.63	3.41
Temperate Regions	0.37	0.42	0.49	0.51
Boreal Regions	0.01	0.01	0.01	0.01
Total Global Volume	1.75	2.12	3.13	3.93
Total Volume	3.35	3.88	5.18	6.12

wisdom scenario (Alcamo *et al.*, 1994; Table 3), and the current per capita consumption of forest products in each of these regions (FAO, 1993a).

Current annual global need is approximately 1% of potential global growing stocks (derived from values for product availability in Table 15-3 and for product need in Table 15-4), comparable to values for individual regions calculated by others (e.g., Kauppi *et al.*, 1992; Dixon *et al.*, 1994; Nilsson and Schopfhauser, 1995). Need is projected to reach nearly 3% of global productive standing stocks by the year 2050 (6.12 x 10^9 m^3), as need almost doubles and global growing stock declines by one-fourth or one-fifth. In tropical regions, where as much as 90% of forest production is consumed as fuelwood (FAO, 1993a), need for fuelwood reaches nearly 5% (34.1 x 10^8 m^3) of growing stocks by 2050.

The projected annual need for industrial roundwood and fuelwood/charcoal is well within annual increments projected for growing stocks in boreal and temperate countries. In tropical countries, however, a wood product availability shortfall of some 2% of total standing stocks occurs by 2050; that is, 2% more wood is needed than is being grown each year. If fossil fuels are substituted with fuels from biomass, the shortfall is likely to be more severe. The need for forest products will not necessarily coincide with demand for forested land for agriculture. For example, trees felled for agriculture in Table 15-3 will not all be used to meet the need for forest products in Table 15-4. Hence, the need estimated here is a minimal value and is probably a significant underestimate of growing stock losses to consumption of both roundwood and agricultural land.

Shortages will be more severe in densely populated countries like India, Bangladesh, Pakistan, and China. Shortages may be insignificant in sparsely populated countries such as Brazil, Zaire, and Tanzania. Obviously, continuation of the shortfall would eventually consume the tropical forests in the most impacted regions. Before that occurred, increased value from decreased availability would drive fuelwood prices beyond the reach of all but the richest users, resulting in replacement of fuelwood by less satisfactory products (crop residues, dried livestock dung, etc.) in those areas.

A more sophisticated approach to estimating need—utilizing economic, technological, and political developments to define economic supply and demand, excluding effects of climate-controlled standing stock changes—was generated for the current chapter based on several data sources (Table 15-5).

The economy-based estimates of demand include only industrial roundwood, projected to the year 2020. The approach began with the same current global need (1.60 x 10^9 m^3) as did Table 15-4. By the year 2010, however, economy-based estimators project a much greater need for industrial roundwood than does Table 15-4 (1.75 x10^9 m^3), amounting to 2.15–2.67 x 10^9 m^3 (FAO, 1993a, also projected a consumption of 2.67 x 10^9 m^3 by the year 2010). Need projected by the economy-based method is 2.55–3.16 x 10^9 m^3 by 2020 (compared with the much lower estimate of need of 2.05 x 10^9 m^3 by 2025 in Table 15-4).

Table 15-5: *Economic supply and demand for industrial roundwood to the year 2020 in 10^9 m^3, based on analysis of several authors by Nilsson (1994).*[1]

	Year 1991	2010	2020
Global Demand	1.60	2.15–2.67	2.55–3.16
Tropical Supply	0.28	0.27–0.29	0.31–0.33
Temperate Supply	0.81	1.0–1.12	1.14–1.18
Boreal Supply	0.51	0.56–0.73	0.64–0.79
Global Supply	1.60	1.83–2.14	2.09–2.3

[1] Arnold, 1992; Backman, 1994; Backman and Waggener, 1991; FAO, 1991, 1993a, 1993d, 1994; ITTO, 1993; Kallio *et al.*, 1987; Kuusela, 1994; Nilsson *et al.*, 1992a, 1992b, 1994; Perez-Garcia, 1993; Sedjo and Lyon, 1990; Shvidenko and Nilsson, 1994; Thunberg, 1991, 1993; USDA Forest Service, 1990, 1993.

Although the FAO (1993a) consumption projections only extend to the year 2010, they also are based on economic, technological, and political criteria. The FAO generated global fuelwood and charcoal need increases of 31% by 2010 (compared to the 21% increase at 2000, and a 79% increase by 2025 derived from data in Table 15-4). Thus, the economy-based estimates do not disagree, and suggest that population-based estimates of need may be conservatively low.

In summary, the availability of forest products in the year 2050, as limited by climate and land use, appears to be adequate to meet projected needs in temperate and boreal regions but not in tropical regions. There, calculated consumption appears to define a serious shortfall of future availability. This conclusion is based on an obvious increase in demand, especially for fuelwood. Also, an increasing population may convert forests to farms to provide food and may be forced to rely on industrial roundwood for export income. The fuelwood forest resources are primarily of benefit to less-developed tropical countries, and their loss may well be important for populations in the most crowded countries. The developed countries of temperate and boreal regions may not be significantly affected by losses of the roundwood supplies they purchase from the tropics because these can be obtained from regions of low population density (and, hence, of low fuelwood consumption). Additionally, the developed countries are able to substitute other products for the wood products in current use. For example, timber in residential and commercial buildings currently is being replaced by styrofoam blocks filled with reinforced concrete and by steel structures in some parts of the United States and Europe.

15.3. Evaluation of Tropical Wood Availability and Consumption

Analyses of environmental change scenarios presented in Section 15.2 indicate that land use will be very important for tropical forest product availability during the next century. They suggest that the availability of forest products could decline by about one-half from land-use pressures, even though changes in climate and atmospheric chemistry during this period appear likely to increase the area where tropical forests can potentially grow. The analyses in Section 15.2 contrast the potential decline in forest volume with the more than three-fold increase in need for forest products, especially, for fuelwood, to support local subsistence. The scenario indicates that by the year 2050, tropical regions could be subject to serious deficiencies—up to 2% of standing stocks—between annual availability and need. The discussion in Sections 15.3.1 through 15.3.3 evaluates those conclusions.

15.3.1. Critical Considerations

Two primary forces are currently involved in tropical forest change and are likely to continue in importance in the future. First, human population growth in developing countries, which are primarily tropical countries, is 2 to 3% annually, and population is expected to reach 8.7 billion by the middle of the next century (UNFPA, 1992). If tropical regions undergo economic prosperity during the twenty-first century, the need for forest trees and products could increase drastically to generate urban structures and jobs for increasing urban populations. On the other hand, if prosperity falters and large numbers of destitute people seek subsistence unavailable in cities and urban areas, forests and wood supplies are likely to undergo considerable degradation as humans migrate into forests. No matter what future changes in climate and uses of tropical forests occur, effects of the rapidly growing and dense populations in tropical regions will amplify those changes.

Second, the rate of deforestation is very rapid and likely to continue so. It was 15.4 Mha annually (of 1,756 Mha, or 0.8%) for the period 1981–90—higher than in the previous decade (FAO, 1993b). Degradation of remaining forests (such as change from closed to open forests) due to grazing, fires, excessive logging, and fuelwood gathering leads to loss of plant diversity and standing biomass (i.e., forest degradation; Brown *et al.*, 1991; Flint and Richards, 1991). For example, in Africa, much of the change in closed forest cover of 1.5 Mha from 1981 to 1990 was directly attributable to local population growth (FAO 1993b): 34% was from conversion of forests to short fallow agriculture, which reflects the needs of rural populations; 25% was change of closed forests to open forest or forest degradation resulting in loss of tree canopy due to human pressure; 19% was change from forests to fragmented forest interspersed with agrarian land uses, which represents gradual deforestation because these fragments are eventually converted to agriculture; and 16% was change of forest area to other forest cover.

15.3.2. Availability of Tropical Forest Products

Estimates of deforestation rates vary but are uniformly large. FAO (1993a) calculated annual deforestation of 15.4 Mha 1981–90. The IS1992a scenario projected a forest clearing rate of 20 to 23.6 Mha per year by 2025. In that scenario, 73% of all tropical forests were expected to be cleared by 2100 (IPCC, 1992).

In addition, future forest decline may be accelerated by state control over forests and the collapse of traditional community control and management systems over forests (Gadgil and Guha, 1992). This has contributed to forest degradation in the past, and there is no reason to suspect that it will decline in the future. These forces will shape the expected uses of tropical forests for hundreds of years.

The increasing human activity in tropical forests will affect more than just the current standing stocks. Tree felling and wood extraction in the tropics commonly destroy one-tenth to one-third of the advance regeneration and growth in remaining trees (FAO, 1993b). Fragmentation and degradation of forests due to expanding agriculture, need for wood by human population, and livestock grazing pressure will seriously affect forest regeneration, particularly in tropical Asia and Africa. Soil moisture deficits projected for Africa and part of Brazil (IPCC, 1992) will severely hamper forest succession. Increased frequency of forest fire will also reduce the chances of forest regeneration.

Domestic animals are an important factor, reducing forest regeneration by browsing on seedlings and by trampling seedlings and compacting soils. Livestock, including cattle, sheep, and goats, are increasing in Africa and Latin America. In India, for example, the density of domestic livestock is 6 animals/ha of forest (405 million animals in 1982 on 64 Mha). In Africa there is 1 animal/ha of forest (see Figure 15-6 and FAO, 1993b). The total livestock population globally is expected to increase by a factor of three by 2050 (Zuidema *et al.*, 1994). Thus, the total livestock population in Africa would be 1.69 billion by 2050, grazing on declining forests and pasture land.

The IPCC (1992) Response Strategies Working Group has estimated that the need for cropland will increase along with the world's rising population. Such an increase might require about 50% more land to be in crop production by 2025, a figure considerably higher than the estimates generated by the IMAGE model and used in estimating growing stock volume in Section 15.2.3. The cropland in Africa alone is projected to increase from 163 Mha in 1990 to 347 Mha by 2025 (Sauerbeck, 1993).

15.3.3. Need for Tropical Forest Products

Tropical forests provide a range of economic, social, and environmental services to humans. For simplicity, only the major economic products are included below. The product functions could be classified as subsistence (e.g., wood and charcoal used for cooking) and commercial (e.g., industrial wood and sawn wood). Among subsistence products, only in Brazil is charcoal used as a commercial fuel in industry on a large scale. The commercial products, however, are traded within and between countries.

The forest product consumption values estimated in Section 15.2.4 have been expanded in Table 15-6.

Note that estimated need for fuelwood in the tropical countries increases by about 2.5 times to 2050, but in Africa it increases by 3.3 times (Table 15-6). Yet fuelwood availability in Africa, like the rest of the tropics, is expected to decline by about half during the same time period (Table 15-3). Hence, the projected deficit of need over availability of tropical fuelwood may be most critical in tropical Africa. In addition, export of industrial roundwood, which might be used to offset fuelwood deficits, is already very low (Table 15-6), with 89% of African forest harvest being devoted to fuelwood (FAO, 1993a). Examination of tropical forest area changes projected in Table 15-2 and population changes used in the IMAGE projections (Alcamo *et al.*, 1994) indicates that the fuelwood need problem will increase in severity, as the current 0.84 ha of forested land per capita (FAO, 1993a) declines to 0.13 ha per capita by 2050.

The projections made in Table 15-6 do not consider various factors like tropical forest destruction, much of it for increases in livestock, or forest degradation (legal and illicit removal of trees). The projections also do not include afforestation/reforestation, slowing of land needed for agriculture by enhanced crop productivities, or changes in rates of use of different forest products as countries industrialize (such as decline in fuelwood use but increase in use of industrial wood).

Non-timber forest products are particularly important in tropical regions. The tribal and rural communities in tropical countries gather a large range of non-timber forest products for subsistence consumption as well as for commercial purposes (e.g., food, fodder, oil seeds, gum, nuts, rattan, bamboo, and raw material for a range of industrial products, as well as locally used products like baskets, mats, tools, leaf plates). For example, the value of rattan extraction in Southeast Asia was $275 million in 1990; the value of Brazilian nuts was $72 million (FAO, 1993c).

The impacts of climate change itself (forest dieback, retreating forest boundaries, increased insect pest and fire incidence; see Chapter 1) and the adaptation measures to mitigate the effects of climate change such as short-rotation forestry (Chapter 24, this volume), will reduce the availability of non-timber forest products. Declines in biodiversity in tropical forest due to climate change through increased variance in seasonality (Hartshorn, 1992) and increased turnover rates (Phillips and Gentry, 1994) also may reduce the availability of the large diversity of plant and animal products from forestry. This latter process may not occur universally, as shown in certain limited areas of Venezuela (Carey *et al.*, 1994).

The replacement of tropical forests with non-forest land uses, coupled with increased need for forest products, will not necessarily generate losses in tropical forest volumes. For example, a conservation and large afforestation effort has stabilized the area under forest in India at about 64 Mha since 1980 even though the population is growing at more than 2% annually (see Box 15-2).

Plantation forestry for all purposes (mitigation of atmospheric CO_2, wood for pulp, sawnwood, fuelwood, etc.), using degraded lands, could become one of the most important counteragents to deforestation. Estimates in Table 24-4 (Chapter 24) indicate that potential added tropical forest wood stocks could average 300 Mt/year (16.42 Gt over 55 years beginning in 1995).

Section 15.2.3 notes that between 18 and 31 x 10^8 m^3 annually (0.7 to 1.4 % of standing stock at the time of measurement) is the most one can expect from plantations designed to mitigate atmospheric carbon. Yet plantations may be much more significant in alleviating the need for forest products in the future. The area established as plantation in 90 tropical countries by 1990 was 44 Mha (FAO, 1993b), with India accounting for nearly 40% of the total area, followed by Indonesia and Brazil. Tropical countries are implementing large afforestation programs. India averaged 1.44 Mha annually in the decade 1981–1990 (FAO, 1993b) and now is planting about 2 Mha

Table 15-6: *Current and projected forest product needs in the tropics (10^3 m^3), based on per capita consumption estimates from FAO (1993a) projected to 2020 and 2050 with UN (1993) population estimates.*

Product	Region	1991	2010	2020	2050
Industrial Roundwood	All Tropics	237	485	555	791
	Africa	39	55	70	113
	Asia	102	172	193	313
	Latin America	96	258	292	365
Fuelwood and Charcoal	All Tropics	1348	1829	2164	3389
	Africa	446	729	924	1496
	Asia	619	800	900	1496
	Latin America	283	300	340	424
Sawnwood	All Tropics	68	140	159	229
	Africa	5	8	11	18
	Asia	37	59	66	108
	Latin America	26	73	82	103

Box 15-2. Forest Conservation in India

Tropical deforestation for the period 1981–90 is estimated to be 15 Mha annually (FAO, 1993b). In addition, the IMAGE 2 model projects increasing deforestation (Table 15-2) from the simple assumption that larger populations will increase the demand for land, thus increasing deforestation of that land. However, the reality in India presents a contrasting picture.

Since 1980 India has periodically assessed its area under forests through its National Remote Sensing Agency (NRSA). The area under forests was assessed for the periods 1981–83 (FSI, 1988), 1985–87 (FSI, 1990), 1987–89 (FSI, 1992), and the latest for 1989–91 (FSI, 1994).

The area under forest in India since 1982 has been stable at 64 Mha (Table 15-7). The forest conservation achieved in India is significant because the population density in India is high (257 persons/km^2) with a large rural population (627 million in 1991) depending on biomass, and an annual population growth rate of 2.12% during 1981–91.

Notably, the area under dense forest (>40% tree crown cover) increases in each assessment, suggesting an increase in carbon stocks sequestered by Indian forests. Responsible factors include the Forest Conservation Act of 1980, which bans all conversion of tropical forest land to non-forest uses, and the world's largest afforestation program (FAO, 1993b). This exemplifies the adaptation potential of tropical countries to declines in forest areas and demonstrates the limitations of projections of future forest area based on population growth rates, such as those from IMAGE (used to construct Tables 15-2 and 15-3).

Table 15-7: *Area under forest in India, in 10^3 ha, according to assessments of the National Remote Sensing Agency (the year refers to the mid-year of assessment; Ravindranath and Hall, 1994).*

Forest Category	1982	1986	1988	1990
Dense Forest (Crown Cover >40%)	36.1	37.8	38.5	38.6
Open Forest (Crown Cover 10–40%)	27.7	25.7	25.0	25.0
Mangrove Forest	0.4	0.4	0.4	0.5
Total Forested Area	64.2	63.5	63.9	64.1

annually (IPCC, 1992). The dominant species planted in India are largely short-rotation exotics, as they are elsewhere in the tropics (Ravindranath and Hall, 1995).

In India and Brazil, the choice of short-rotation forestry will only meet the need for industrial wood and fuelwood (and charcoal), not for sawn logs for structural uses. Thus, forest plantations (largely softwood) are no substitute for logging in forests for hardwoods. Climate change can worsen the situation by affecting forest regeneration due to warming and decreased availability of soil moisture. There is a possibility that a large area could be planted to hardwoods and long-rotation plantations such as teak.

In summary, the shortfall of wood during the 21st century, projected for tropical areas in Section 15.2.4, appears to underestimate the potential problem. Tropical countries will face serious shortages in forest products required for subsistence (fuelwood, wood and fibers for construction, fruits and nuts for food). However, wise land-use policy may mitigate some of the forest losses.

15.4. Evaluation of Temperate Wood Availability and Consumption

The scenarios discussed in Sections 15.2.3 and 15.2.4 suggest that temperate forests could cover about as much land by 2050 as they do today, and that current consumption (3.1% of standing stock, based on Tables 15-3 and 15-4) may increase only slightly by 2050 (3.8% of standing stock). With a 3–3.5% annual growth increment in temperate zone trees (FAO, 1992), and with an increasing proportion of need being met by imports from outside the temperate zone (FAO, 1993a), the scenario analysis in Section 15.2 indicates that temperate-zone forests are likely to continue meeting the need for forest products on a sustainable basis for at least the next century. The discussion in Sections 15.4.1 through 15.4.3 examines that conclusion in detail.

15.4.1. Critical Considerations

Perhaps the most important characteristic for defining forest product availability in temperate zones, now and in the future, is that temperate zones are most appropriate for mechanized agriculture of monospecific crops; hence, mankind has altered the natural vegetation there both intensively and over a relatively long time. Consequently, at 0.71 billion ha (compiled from FAO, 1993a; Puri *et al.*, 1990; World Bank, 1993; Chadha, 1990; Khattak, 1992; Helvetas and Swiss Development Corp., 1989; Goskomles SSSR, 1990; Kurz *et al.*, 1992; Xu, 1994), temperate forests cover only about half of their potential area, and the remaining forests often differ quite considerably from the original state (Stearns, 1988; Deutscher Bundestag, 1991; Röhrig, 1991).

The prosperity of the developed countries which permits development of mechanized agriculture also gives most countries of the temperate zone greater capability than those in other zones to manage forests to avoid future disturbances (fire, insect attack, mortality from rapid and chronic climate change, and so forth) and to enhance growth (artificial tree migration, plantation establishment, post-establishment thinning and fertilization, and so on).

The capabilities of developed nations which buffer temperate forest product availability from environmental threats also provide a buffering of need for forest products from shortfalls in availability. First, these countries have the wealth to purchase wood products outside the temperate zone. Today, temperate countries consume 80% of the total value of world imports of forest products but supply only 50% of the value of its exports. Second, temperate countries have access to technology that allows product substitution when local availability is inadequate and interzonal trade is too expensive. Pressed fiberboard replaced some weak plywood supplies during the 1970s in the United States (Rose *et al.*, 1987), for example, and currently, increasingly expensive lumber is being replaced in some residential structures with steel, concrete-filled plastic foam, or similar non-forest products.

15.4.2. *Availability of Temperate Forest Products*

Harvests from temperate-zone forests of all types are used mainly for industrial purposes (Table 15-8), although there are great differences between the two Asian regions in Table 15-8 and the other regions. In Europe, the United States, and the temperate Southern Hemisphere, the industrial wood portion of the total is about 80%, whereas in Asian temperate regions it is only 8.6% (tropical) and 38.0% (temperate) (Table 15-8). Overall, temperate-zone use of forest products focuses on industrial wood.

The scenario analysis above defined no significant climate or land-use related declines in future forest availability. Forest survey measurements are consonant with this analysis. Considering that carbon storage from net ecosystem production in European forests increased about 30% between the early 1970s and the late 1980s and is further increasing, the wood resource is seen as plentiful for the foreseeable future, if no unexpected catastrophic events occur (Kauppi *et al.*, 1992). The remarkable net ecosystem production (NEP) increment in the last two decades may relate less to intrinsic productivity of forests than to increased forest area generated as European agriculture decreased while imports of less-expensive foreign lumber increased (more than one-third of global industrial roundwood imports in 1990; approximately 10% less than Japan imported, and six times the imports by North America; FAO, 1993a). If so, change in land-use policy or in costs of imported roundwood would have a great impact on European NEP and forest availability.

Climate effects may be indirect. In Europe, migration of the Mediterranean tree species to the north may be hampered because most of them are not adapted to the prevailing acidic soil conditions in the northern areas (Ulrich and Puhe, 1993). In the worst case, this may result in losses of some species, with negative effects on biodiversity and wood availability.

Frequent extreme events affecting wide regions—like storms or insect infestations—leading to great amounts of wood that must be harvested, may have a great influence on annual cut and the economic situation of forestry. For example, the price index for timber in the Federal Republic of Germany (FRG) declined from 116% in 1990 to 79% in 1991 as a result of hurricane Wiebke, which caused large windfalls in many parts of

Table 15-8: *Current production and consumption, and projected need for industrial roundwood and fuelwood in 10^6 m^3 (FAO, 1993a).*

	Production 1991		Need 1991 and 2010			
	Industrial Roundwood	Fuelwood and Charcoal	Industrial Roundwood		Fuelwood and Charcoal	
Region			1991	2010	1991	2010
West Europe[1]	138	28	144	207	29	30
East Europe	338	160	323	494	160	102
Temperate/Tropical South Asia	28	299	29	40	299	413
Temperate East Asia	118	193	176	345	193	208
North America[2]	410	86	382	582	86	130
Temperate Southern Hemisphere	42	10	28	44	1	11
Total	1074	776	1082	1712	768	894

[1]Excludes Finland, Norway, and Sweden.
[2]Excludes Canada.

western Europe (Stat. Bundesamt, 1992). Pests can largely dictate where and how many trees must be harvested. If climate-induced changes cause extensive sanitary fellings, this may reduce revenue per unit of wood and hence reduce incentives for intensive management and investment (Pollard, 1993).

One of the most important anthropogenic effects on forest product availability in temperate zones in the past has been intensive land use. Nevertheless, until now in Europe, stable food demand, substantial producer subsidies, and high productivity increases have generated enormous surpluses of agricultural products. As a consequence, the use of arable land decreased substantially in these regions. The situation is similar in the United States and Japan. In the European Community (EC) up to 44 Mha could go out of agriculture without substantial decreases in productivity (Eisenkrämer, 1987; Delorme, 1987). Therefore, in western Europe the common agricultural policy of the EC will be a more important driving force for future changes in land use than climate-induced ecosystem changes (Kitamura and Parry, 1993). This phenomenon is abstracted in IMAGE model projections (Table 15-2) and is responsible for the simulated increase in temperate forest area in Europe (Zuidema *et al.*, 1994).

IMAGE projections suggest a 2% decrease in total area of temperate forests between 1990 and 2050 (Table 15-2). However, if only the temperate deciduous forests are considered, the forested area increases by 60.5 Mha (89%) from 1990 to 2050 (Zuidema, 1994). In contrast, temperate forest area projected by BIOME under four different climate scenarios increases between 25 and 52% by the time the climate resulting from a doubled CO_2 concentration occurs (Table 15-1). If either the BIOME projections for all temperate forests or the IMAGE projections for temperate deciduous forests becomes reality, a wood availability increase of one-tenth to one-half will result.

15.4.3. Need for Temperate Forest Products

Current production and consumption of roundwood in the temperate zone are fairly balanced (Table 15-8). Nevertheless, there are also countries where consumption greatly exceeds production (e.g., Japan, China, Austria, Italy). Projections for 2010 (FAO, 1993a) indicate that the need for industrial roundwood will increase between 38% (temperate South Asia) and 96% (temperate East Asia). It is likely that need will increase everywhere for particular wood types (softwood logs and pulpwood), whereas in some regions (Japan and western Europe) need for all kinds of wood products will increase. As a consequence, future increases in consumption must be met partly by increases of imports. A great portion of these may come from other temperate forested countries, such as Canada, New Zealand, and Chile, but also from plantations in the tropical zone.

Fuelwood consumption in temperate zones is not as important as it is in tropical and subtropical countries. The only exception to this may be China, where 32.5% of the wood production in 1988 was consumed for fuelwood (Xu, 1994). Nevertheless, in temperate South Asia and North America, significant increases (38% and 51% respectively) in fuelwood consumption by 2010 are expected (Table 15-8).

In the developed countries of the temperate zone there is a high and growing need for assets that support a high quality of life. This has produced a change from the wood production point of view to a multiple-use perspective (FAO, 1993c). These needs are not considered in the scenario analysis of Section 15.2 but will generate considerable change in wood availability (much of it being removed from accessibility) and need. The non-wood functions (soil protection, recreation, biodiversity, and cultural uses) and goods and services (fruits, honey, water supply, and so on) are of very high importance. Table 15-9 gives an overview of the importance of main forest functions in some temperate regions.

Table 15-9 shows that in Europe and the United States, other functions than wood production have high importance in relevant areas. For most of the developed temperate-zone countries, it is the explicit policy to emphasize non-wood functions of their forests, especially functions of water protection and recreation (FAO, 1993c). The economic evaluation of these benefits is much more complex than that of wood production because, for most of these values drawn from the forests, supply and demand generally are not regulated by market mechanisms. There are only a few non-timber products that have a direct economic importance for individual countries—for example, cork in Portugal and Spain, chestnuts in Italy, or Christmas trees in Denmark—but they have immediate effects on local people and communities.

Table 15-9: *Importance of forest functions by area as a percentage of total forest land (FAO, 1993c).*

	Europe			USA			Former USSR		
Function	High	Medium	Low	High	Medium	Low	High	Medium	Low
Wood Production	54	24	22	36	41	23	0	18	82
Protection	11	17	72	36	30	34	9	15	76
Water	9	17	74	16	79	5	7	17	76
Hunting	27	55	18	9	45	46	-	-	-
Nature Conservation	4	37	59	8	42	50	0	19	81
Recreation	12	39	49	19	33	48	2	11	87

15.5. Evaluation of Boreal Wood Availability and Consumption

The scenario analysis of Section 15.2 presents a dichotomy in expectations for wood availability in the boreal zone. The climate-only scenarios (Table 15-1) assumed that agriculture occupies 50% of the land permitted by its climatic potential, boreal forest displaces nonforested tundra, and temperate vegetation replaces much of the current lower-latitude range of boreal forests. This scenario suggests that boreal forest areas will shrink between 20 and 50%, depending on the climate change scenario used, by the time a doubling of GHGs occurs sometime in the next century. The scenario driven primarily by land use (Table 15-2) included agricultural land area that was linked to a declining population and demand for food, and allowed little climate-induced change in forest geography, except in the few areas that shifted out of agricultural production. That scenario suggested that boreal forests would increase in area by 10 or 11% by the year 2050.

At the same time, the population-based need estimates indicated a relatively constant need of 0.5% of availability (Tables 15-3 and 15-4)—considerably less than the sustainable harvest to be expected of available supplies, even under the most deleterious climate-only scenario. These are the suppositions to be examined in Sections 15.5.1 through 15.5.3.

15.5.1. Critical Considerations

More than any others, the boreal forests are subject to periodic damage from large-scale disturbances such as fire, long-term drought, windstorm, and insect infestations. Even chronic and uniform climate warming is likely to cause increasing frequencies of irregular, large-scale, and widespread catastrophic disturbance events in which large areas of forest are destroyed in a single growth season. Recovery from these events may take centuries (Payette *et al.*, 1989), and the resulting availability of forest products as sanitation and salvage fellings will thus be very irregular. Therefore, the shortcomings of the static vegetation models described in Box 15-1 are very relevant to boreal forests.

15.5.2. Availability of Boreal Forest Products

Growth increments in natural forests accrue only about 1.5% each year, but active management of the boreal forests yields much higher increment and growing stocks (Kuusela, 1990). In Sweden, active management has raised the average growing stock from 72 m^3/ha in 1925 to 97 m^3/ha in 1985, and the stock is estimated to reach 125 m^3/ha in the year 2050.

The long-term sustainable timber supply from a biological point of view has been estimated with different degrees of sophistication in the boreal countries. The sustainable harvest level is often called the annual allowable cut (AAC). This comprises 910–930 x 10^6 m^3/yr for the next 50–100 years [Runyon (1991), OMNR (1992), and Booth (1993) for Canada; Nilsson *et al.* (1992a) and Hägglund (1994) for Nordic countries; Isaev (1991), Nilsson *et al.* (1992b), and Backman (1994) for the former Soviet Union]. The long-term economic wood supply takes the economic conditions into account and is lower than the AAC (580–630 x 10^6 m^3/yr; *ibid*). Comparison of these values, or of the approximately 100 x 10^9 m^3 of growing stock in boreal forests (90 x 10^9 m^3 tabulated in Table 15-3), to the annual harvests of 750 x 10^6 m^3, indicates that long-term sustainable biological availability substantially exceeds the prospective need for wood in the boreal zone.

Arnold (1992) found a number of broad trends in the long-term future supply of forest products (50-year time horizon) based on analyses of existing studies:

- There will continue to be a major shift from old-growth supply to planted and second-growth supply.
- There will be large resources in boreal forests to support expanded production if need requires.

The following constitutes a broad summary of global forest product availability based on a number of studies (Cardellichio *et al.*, 1988; Kallio *et al.*, 1987; Sedjo and Lyon, 1990; Arnold, 1992; Nilsson *et al.*, 1992a; Thunberg, 1993; Perez-Garcia, 1993; OMNR, 1992; Backman, 1994):

- The availability of coniferous wood (softwood) from North America is expected to decrease due to younger age class structure and tightening environmental regulation.
- Russia will be dealing with a restructuring of its entire society for a long time and will be hard-pressed to sustain timber production at current levels.
- Europe will probably need more than it supplies.

The overall conclusion from these analyses is that the major supply in the near to medium term will come from the traditional wood supply regions, but within 50 years an increase of production through plantation forests may be required (some 150 million ha).

Chapter 1 and Section 15.2 both discuss expected changes in climate and responses by natural forest ecosystems. In a warmer and drier boreal zone, it is likely that geographic boundaries of boreal forest ecosystems will shift (Emanuel *et al.*, 1985a, 1985b; Solomon, 1992; Smith and Shugart, 1993). While the forest ecosystems adapt to climate changes, ecosystems will be in disequilibrium as existing species are replaced by new species more adapted to the environment. Soil conditions that lack the requirements of invading species in many areas will exacerbate this condition. The area of forest affected will greatly depend on the magnitude and rate of the climate change. A likely result of any future climate change is that during the next 50 years the wood availability in the boreal zone will increase. However, it should be pointed out that forest management and protection may have to be intensified substantially during this period, which will be costly (Nilsson and Pitt, 1991; Apps *et al.*, 1993).

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As illustrated earlier (Table 15-2), future changes in land use driven by economic factors could increase forest land in the boreal zone in the future (Waggoner, 1994; Nilsson *et al.*, 1992a; Zuidema *et al.*, 1994). Air pollutants are thought to be a problem in the boreal zone today (Nilsson *et al.*, 1992a, 1992b; de Steiguer, 1993); if so, they would affect wood availability as well as the availability of non-wood products in the boreal zone in the mid-term.

In the long run (>50 years), effects of climate change on wood availability could be significant as the availability of wood from existing species runs out and new species are insufficiently developed to provide a new source of supply. Yet in terms of the sustainable use of forests (i.e., of need, discussed in Section 15.5.3), the scenario estimates of availability until 2050 and those that would result from quantification of climate change effects both suggest an excess of availability over need. However, it is also important to emphasize that a significant portion of harvested supply in the future could evolve from irregular, widespread, and catastrophic mortality events that cannot be simulated or predicted by current modeling methods.

15.5.3. Need for Boreal Forest Products

The consumption of forest products by the sparse population of boreal regions can hardly affect boreal forest stocks. Future population estimates suggest little change in population under current immigration policies (e.g., Alcamo *et al.*, 1994). Instead, assessment of needs from boreal regions must focus on trade in forest products and on the resulting economic forces that will continue to define the need for boreal forest products.

Need for forest industry products is determined by changes in population, income, and price and by technological change. Past consumption can only be disaggregated to relevant end uses (preferences) in the more developed countries, and useful predictions can only be made for short periods in the future. Forest products are international commodities, and need and availability in one region depend on developments elsewhere on the globe.

The boreal forests have played an important role as suppliers of raw material for forest industrial products globally and of so-called non-wood benefits. The production of industrial roundwood from the boreal forests in 1991 corresponds to some 33% of world production. The consumption figures presented by FAO for the year 2010 are regarded as strong overestimates among industrial experts; those presented in Table 15-10, calculated as described in Section 15.2.4, may be more realistic.

The most crucial role of boreal forest products is probably the balance of payments. The boreal countries are major net exporters of forest products. More than 20% of the world's forest industry product value stems from the boreal forests. Table 15-11 indicates that for Canada and the Nordic countries (especially Norway and Finland), a very significant portion of their trade involves forest products. It seems likely that wood exports eventually will increase to even greater importance in the former Soviet Union (FSU).

Table 15-10: *Industrial roundwood consumption projected to 2020 in boreal regions, in 10^6 m^3, based on analyses in Table 15-5.*

	Year		
	1991	2010	2020
Coniferous (Softwoods)	452	434–588	496–611
Deciduous (Hardwoods)	60	123–145	141–181
Total Boreal Demand	512	557–733	637–792
Global Need	1602	2145–2674	2551–3156

Arnold (1992) examined long-term trends in need for forest products. Among the most important conclusions relating to boreal wood consumption are the following:

- Global need for industrial wood has been projected to grow by 35 to 75% over the next 50 years.
- Consumption will continue to be concentrated in the developed world, but a substantial part of the increase in consumption will occur in the developing countries.
- Need for roundwood will grow more slowly than need for finished wood products due to technological development.
- Use of nonconiferous (hardwood) species will grow faster than for coniferous (softwood) species.

As in temperate regions, boreal-region forests no longer are viewed as simply a provider of raw materials for industry and a stimulus in the general economy of a country (Westoby, 1962). Today, the nonmarket forest production properties (climate change, biodiversity, global tourism, non-wood products, erosion, water supply) are among the most prominent issues in world forestry (Hyde *et al.*, 1991). The boreal forests promote a large variety of global as well as local and regional non-wood products. However, the extent and value of these services are

Table 15-11: *Economic importance of the forest sector in boreal countries in million U.S.$ (FAO, 1993a).*

	Prod.	Consum.	Import	Export	% of Trade	% of GDP
Canada	30482	15931	1840	16931	13	5
Nordics[1]	22115	4876	2388	19628	4–36	2–7
FSU[2]	38485	36639	927	2773	4	2
Total	91082	57446	5155	39332		

[1]Norway, Sweden, Finland, and Denmark.
[2]Former Soviet Union.

uncertain because most of them are not connected by any market mechanism. The boreal countries also have stated that future boreal forest policies will place emphasis on non-wood functions.

Economic analyses of the current impact of the non-wood functions on the macro-economy in the boreal countries are limited in scope and uncertain. Hultkrantz (1992) and Solberg and Svendsrud (1992) estimated the value of the non-wood products at 35–75% of the industrial forest sector value (adjusted GDP-calculation) for Sweden and Norway, respectively. Based on the earlier discussion, we conclude that this value will increase in the future in the boreal zone. In the long run, forest management for non-wood products may well become a more valuable activity than logging.

In the future, increased conflicts in the boreal forests are expected between traditional forestry and requirements for wilderness areas, between timber production and biodiversity, and between applied forest technology and landscape development. There will be increased public concern regarding the health and survival of the forests. The forecast reconstruction of the structure of the forest industry will generate regional unemployment and social strain in the boreal countries. There are approximately one million aboriginal people living in the boreal zone. The cultures and economies of these people are intricately adapted to the natural environment, and they depend upon it for self-perpetuation.

The forest industry has restructured extremely quickly during the last 20 years in the boreal countries due to economic development, technological development, market conditions, and internationalization. This kind of structural change is expected to continue in the future. Technological development is also very rapid in the forest sector, especially in the forest industry. Most of the lumber grades known today in the forest industry were not known 20 years ago. This development is also expected to continue in the future.

Many of the changes taking place in the forest sector of the boreal countries are based on the changed end-use preferences. Preference changes, based on shifts in knowledge, values, consumption, and so forth, have happened within a few years (e.g., bleached to unbleached paper, clearcuts to landscape planning), and they influence the whole forest sector. Preference shifts will continue to permeate the future societies of the boreal zone.

What, then, will be the constitution of overall forces on the forest industry? Most obviously, forces other than climate will probably overshadow the impact of ecosystem responses to climate early on (the next 50 years). A major question involves the impact on economic considerations of non-wood functions like biodiversity, landscape conservation, soil carbon capacity, and sustainable watershed development, which could significantly reduce available timber supplies. Unfortunately, we lack benchmarks for measuring the impact of climate change on these functions. In the long run (>50 years), and based on today's knowledge, the situation could be reversed; ecosystem changes induced by shifting climate might overshadow the impact of the other driving forces in the boreal forests.

In summary, the conclusions from scenario analysis about boreal timber availability and need that begin Section 15.5 appear to be very unrealistic. First, timber availability may be more strongly affected by environmental changes in boreal regions than in other zones: increased mortality and slowed forest succession from rapidly warming climate and large-scale disturbances; and enhanced growth from warmer growing season temperatures and increased atmospheric CO_2. These variables are not simulated by the models that produced the scenarios in Section 15.2. Second, boreal forest timber need is controlled by trade in forest products outside the zone. Hence, economic considerations drive need and its subsequent implementation—that is, harvest of timber. The models underlying the scenarios in Section 15.2 contain no consideration of forest economic or trade processes or implications, and therefore are not capable of realistic analysis of boreal forest product need in the future. The economics of wood consumption and the analysis of temperate and tropical zone timber needs, discussed in Sections 15.3 and 15.4, suggest that serious shortfalls of boreal industrial roundwood could occur during the twenty-first century. This would result if future temperate and tropical zone consumption of boreal softwoods expands beyond available wood capacities.

15.6. Adaptation and Coping Options

In the short term, timber supplies from all zones can be readily assured in intensively managed forests. The use of forest plantations to mitigate increasing atmospheric CO_2 and to generate fuels from biomass is a subject of Chapter 24. Unfortunately, past intensive management, especially fire suppression and tree selection at species and intra-specific levels, has created forests that now may be more vulnerable to fire, pests, and pathogens (Schowalter and Filip, 1993), although others dispute that conclusion. Given the current degree of uncertainty over future climates and the subsequent response of forest ecosystems, adaptation strategies (those enacted to minimize forest damage from changing environment) entail greater degrees of risk than do mitigation measures (those enacted to reduce the rate or magnitude of the environmental changes). Emerging principles of risk assessment and management should guide the choice and implementation of "no-regrets," "proactive," and "reactive" options for adaptation (Gucinski and McKelvey, 1992).

15.6.1. Harvest Options

Certain standard harvest options appropriate for ameliorating effects of climate change are suggested:

- **Sanitation Harvests**—Increased timber losses are expected from pests, diseases, and fire because the trees themselves may be stressed by warmer conditions and the greater moisture deficits expected to accompany warming (see Chapter 1), and land clearance for tropical agriculture. Extensive sanitary felling can produce large volumes of timber, reducing revenue per unit of wood and reducing incentives for intensive management, while disrupting future timber availability.

- **Changing Harvesting Method**—Harvesting and even site preparation may be quite dependent on cold winters in northern regions where forests occur on predominantly swamp lands that can only be accessed when frozen (Pollard, 1987). Use of ecosystem protection approaches (e.g., Franklin, 1989; Clark and Stankey, 1991) can be particularly useful in light of multiple-use needs in temperate and boreal regions and the need for mixes of species and ages in all zones to prepare for several different outcomes of environmental change.
- **Shortening Rotations**—Reduction of rotation age is a simple tactic for reducing exposure of maturing timber stocks to deteriorating conditions, as well as increasing opportunities for modifying the genetic makeup of the forest. Gains may be offset by diminished timber quality, a lower mean annual increment, and impacts on other values such as certain game species and aesthetic qualities. Short-rotation plantations in tropical regions are an important option in meeting local fuelwood needs, coincidentally relieving pressure to harvest more pristine forests.
- **Increased Thinning**—The stimulation of tree vigor following stand thinning has special application under increasing moisture deficits. The modification of forest microclimate by thinning offers considerable potential for the management of pests (Amman, 1989; Filip *et al.*, 1992; Paine and Baker, 1993).

15.6.2. Establishment Options

Establishment options that can be quite effective in reducing effects of climate change are selected from common silvicultural practices:

- **Choice of Species in Anticipatory Planting**—Mixed species for current planting should be considered wherever possible, as a means to increase diversity and flexibility in adaptive management. Critical non-timber values such as snow retention, soil stability, water quality, and carbon storage should be taken into account.
- **Vulnerability of Young Stands in Anticipatory Planting**—The planting of species and varieties better adapted to future conditions may well increase vulnerability of the resulting stands during their early establishment. Selection of provenance offers an important tactic to reduce the vulnerability.
- **Assisting Natural Migrations in Protected Areas**—Protected areas are the richest sources of genetic materials and warrant expansion into comprehensive systems. To be effective they must function in landscapes where ecological integrity is sufficient to permit the movement of living organisms; there must be a comprehensive approach to both commodity and reserved lands (Franklin *et al.*, 1990).
- **Assisting Natural Migrations by Transplanting Species**—Large numbers of seedlings raised in nurseries many hundreds of kilometers from planting sites can be planted in the millions per day (Farnum, 1992). Optimism must be tempered by experience, however: Forest managers have been attempting to reforest Iceland for the past 50 years without much apparent success (Loftsson, 1993).
- **Gene Pool Conservation**—Specialist species (indicated by restricted geographic ranges) will be most at risk, and their only chance of surviving may be through conservation in forest reserves, arboreta, and conventional seed banks and cryogenic storage.

15.7. Research Needs

New research products needed to conduct an accurate assessment of socioeconomic impacts of forest responses to climate change have become obvious from the foregoing analysis. The assessments are, and will be, based on quantitative scenarios of changing availability of and need for forest products and amenities. Validity of scenarios is critical if they are to function as descriptions of the implications of current knowledge for future conditions. In all regions, scenarios were inadequate because the effects of increasing CO_2 and forest dieback could not be quantified. In tropical regions, the scenarios were deemed inadequate because they probably underestimated the regional and local importance of land use on timber availability. In temperate regions, the scenarios were incapable of quantifying the buffering effects on timber needs, offered by shifting technology aimed at product substitution and on availability by intense mechanical management of forests. In boreal regions, the scenarios excluded transient responses of timber availability to environmental change and extraregional responses of timber needs by economic processes, which replace local forest product demand there. All regions probably will undergo changes that could not be expected only from the variables considered in this assessment. Thus, research required for an adequate assessment includes both environmental monitoring and data collection, and development of models to project future impacts.

15.7.1. Data Monitoring and Collection

All countries need to produce accurate national forest inventories. Some countries maintain such inventories, but they often use different periods and research designs. For example, in Europe, information from repeated surveys is available only from one-third of the forest area (Kauppi *et al.*, 1992). In addition, existing inventories do not consider regeneration properties, such as frequency of flowering, seed production, or seedling establishment. With regard to climate change, these factors are very important because early life stages are most sensitive to variation in temperature and moisture conditions.

An obvious need involves the collection and analysis of data regarding the beneficial effects of atmospheric CO_2 concentrations. As Chapter 1 points out, information from a single season of monitoring tree seedlings in greenhouse pots is inadequate to document the decadal-scale responses by mixed assemblages of growing and mature trees in ecosystems. Our analysis in Section 15.2 highlights the uncertainties regarding the impacts of these effects, which preclude confidence in estimates we generated of future forest product supplies.

15.7.2. Global Modeling

The analyses generated for this assessment repeatedly demonstrated the absolute necessity for development of models describing transient responses of forests to rapid environmental change. Indeed, as Box 15-1 indicates, the problem to be assessed involves impacts of rapidly changing climate during the next century, not stable climate, and involves variously lagged forest response variables, not responses in lock-step with climate change. We lack models of vegetation response to climate that incorporate the real drivers of future vegetation dynamics: Transient processes involving differential rates of mortality, establishment, and growth; climate control of forest establishment and succession; absence and slow introduction of seeds of trees from provenances, varieties, and species appropriate for the available climate; and so on. For this "transient" assessment, the static model estimates of forest growth over the next 50 to 75 years are woefully inadequate.

A second kind of critically absent model is a forest economics simulation capability that is linked to environmental change. The global trade model developed at the International Institute for Applied Systems Analysis (e.g., Dykstra and Kallio, 1987) is an example of the integrated supply and demand model needed; however, it does not project climate-controlled or land-use-constrained wood availability. Instead, a forest trade model embedded in a global integrated assessment model like IMAGE may be the most appropriate vehicle for calculation of the impacts of climate-ecological-economic relationships.

A third form of model conspicuously absent is a climate model that could provide *regional* estimates of the climatic change implied by increasing GHG concentrations. The existing climate models are not able to generate reliable estimates on regional temperature, precipitation, and hydrology. Yet much of the forest response that is relevant to socioeconomic assessment varies significantly from one locale or region to another. In addition, in order to assess the quantitative implications of ecophysiological processes under chronic climatic change, climate models must describe the regional and seasonal changes of temperature and precipitation.

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