Climate change impacts on forestry

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Changing temperature and precipitation pattern and increasing concentrations of atmospheric CO_2 are likely to drive significant modifications in natural and modified forests. Our review is focused on recent publications that discuss the changes in commercial forestry, excluding the ecosystem functions of forests and nontimber forest products. We concentrate on potential direct and indirect impacts of climate change on forest industry, the projections of future trends in commercial forestry, the possible role of biofuels, and changes in supply and demand.

CO_2 | economics | industrial forestry | biofuels

Globally, forests cover ≈4 billion hectares (ha) of land, or 30% of the Earth's land surface (1). In 2005, 3.5 billion m^3 of wood of 434 billion m^3 of growing stock were removed from the forests (Fig. 1); ≈60% of this amount was industrial roundwood and the rest was fuel wood (1). The majority of the forest land is covered with primary (36%) or modified (53%) natural forests. The primary forest area has been slowly decreasing by ≈6 million ha annually since the 1990s, and this rate is especially high in Brazil and Indonesia; these two countries are responsible for the loss of 4.9 million ha of forests annually. Forest loss tends to occur in low-income countries, largely in the tropics, whereas higher-income countries have reversed their earlier forest losses and are already experiencing forest expansion (2).

Only 3% of the forest land is covered with productive forest plantations; however, this area had been growing rapidly by 2 million ha annually in the 1990s and by 2.8 million ha through this decade. Plantations are being established largely in the tropics and subtropics, e.g., Brazil and Indonesia, but also in high-productivity temperate regions, e.g., Chile and China. Despite their relatively small area, forest plantations provide more than a third of industrial roundwood, and the shift of production from natural forests to the plantations is projected to accelerate to >40% in the 2030s (3, 4) and 75% in the 2050s (5).

Approximately half of the total wood harvest is reported by the countries to the Food and Agriculture Organization (FAO) as fuels. This estimate must, however, be increased up to as much as 60–65% (making fuel the single most important product of the sector), as ≈15% of the industrial roundwood is eventually used for energy by the forest industry (6). The role of wood for fuel is especially high in developing countries, which use it as a source of 15% of their primary energy consumption and effectively produce >90% of global wood fuels. Whereas in developing countries the wood fuels are typically consumed in a form of wood or charcoal, in the developed countries more than half of wood fuels are recovered from the burning of black liquor, which is a byproduct of the papermaking industry (6).

Aside from timber and fuel production, the wide range of services supplied by the forests includes nontimber forest products, such as berries and mushrooms, providing wildlife habitats, soil and water protection, biodiversity conservation, tourism and recreation opportunities, medicinal plants, etc. These services are especially important for 1.2 billion forest-dependent people, living in extreme poverty (4). In many rural sub-Saharan Africa communities, nontimber forest products may contribute >50% of a farmer's cash income, provide the health needs for >80% of the population (4), and supply ⅔ of annual meat consumption (8). An increasingly important service of the forests is carbon sink and preservation, although there are new doubts on the effectiveness of afforestation in the boreal and midlatitude zones to curb the temperature increase caused by lower albedo of forest land cover as compared with grasslands or crops (9, 10).

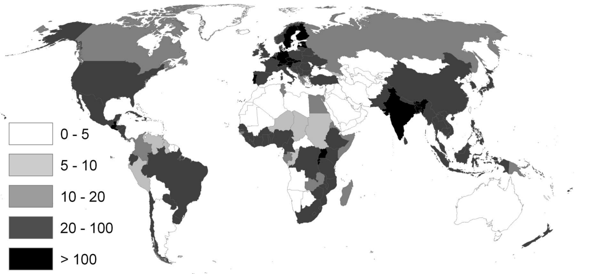

Fig. 1. Global wood harvest (including wood fuel) computed on a per-country base, m^3/km^2 (7). White areas correspond to low harvest or no data.

Climate Change Impact on Forests

Effects of Temperature, Precipitation, and CO_2 Concentration Change.

It is likely that changing temperature and precipitation pattern will produce a strong direct impact on both natural and modified forests. A number of biogeographical models demonstrate a polarward shift of potential vegetation for the $2\times CO_2$ climate by 500 km or more for boreal zones (11–13). The equilibrium models and some dynamic vegetation models project that this vegetation shift toward newly available areas with favorable climate conditions will eventually result in forest expansion and replacement of up to 50% of current tundra area. There is, however, a concern that the lagged forest migration (compare the tree species migration rates after the last glacial period of few kilometers per decade or less to projected future climate zones shift rate of 50 km per decade) may lead to massive loss of natural forests with increased deforestation at the southern boundary of the boreal forests and a correspondent large carbon pulse (13–15). At the same time, some researchers maintain that tree species migration rates can be much more rapid (16). For timber production, which relies on managed forests with migration facilitated by human actions, this negative effect of lagged migration might be of lesser importance than for natural forests.

Increasing concentrations of the atmospheric CO_2, aside from modifying the temperature and precipitation pattern, may also increase the production through the "carbon fertilization effect." Earlier experiments in closed or open-top chambers demonstrated very high potential for CO_2-induced growth enhancement, such as an 80% increase in wood production for

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Abbreviations: ha, hectares; FAO, Food and Agriculture Organization; FACE, free-air CO_2 enrichment.

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orange trees (17). It is, however, unknown how this response would be modified in the field without the size limitations of the chamber. The free-air CO_2 enrichment (FACE) experiments demonstrated a smaller effect of increased CO_2 concentration on tree growth. Long-term FACE studies suggest an average net primary production (NPP) increase of 23% in response to doubling CO_2 concentration in young tree stands with the range 0–35% (18, 19). Further, in the only FACE study of the mature 100-year-old tree stand little long-term increase in stem growth was found (19), which might be partially explained by the difficulties in controlling for constant CO_2 concentration in a large-scale experiment. Further, the initial CO_2-induced growth enhancement is both limited with and modifies the effects of competition, disturbance, air pollutants such as troposphere ozone, and nutrient limitations (20). As a contrast, models often presume high fertilization effects (e.g., ref. 21 used in their projections a 35% NPP increase under the $2\times CO_2$ scenario). The lack of long-term experimental data for mature tree stands prevents better estimation of CO_2-induced growth enhancement in model coefficients.

Regardless of the contradictory effects of variations in CO_2 concentration, insolation, nutrients availability, temperature, and precipitation, the forest growth rate have been increasing since the middle of the 20th century. Of the 49 papers of forest productivity reviewed in ref. 22, only five reported production decrease, whereas production increase was reported in 37, and others did not show a constant trend. Some of this growth enhancement may be caused by the trend in land-use change (23) and the carbon fertilization effect (22), but generally it is attributed to warmer climate conditions and extended growing season. Simulated by the yield models growth enhancement seems to be consistent with these historical changes.

Fires, Insects, Pathogens, and Extreme Events. For forestry, the climate change-induced modifications of frequency and intensity of forest wildfires, outbreaks of insects and pathogens, and extreme events such as high winds, may be more important than the direct impact of higher temperatures and elevated CO_2. At the same time, very few forest production models include these effects, which severely limits the reliability of the model results. Forest fire may be an exclusion here. The last two decades demonstrated increasing burned areas in Canada, the western United States, and Russia, because of both climatic conditions and other factors such as fuel conditions, ignition sources, land-use change, and variations in fire protection (24–26). Other regions demonstrated both increasing and decreasing fire activity (27–30). In warmer climates of this century, prolonged snow-free period and increasing frequency and intensity of droughts are expected to elevate the frequency of forest fires in many regions (31–33). In Canada, the burned area might double by the end of the century under the $3\times CO_2$ scenario such as the IS92a Intergovernmental Panel on Climate Change "business as usual" scenario (31). The potential losses of the timber, pulp, and paper production, as well as the damage to health and nontimber forest products caused by elevated fire activity, are quite uncertain as much of the fire damage is expected to occur in less-accessible regions.

For many forest types, forest health questions are of great concern with pest and disease outbreaks as major sources of natural disturbance. The effects vary from defoliation and growth loss, to timber damage, to massive forest diebacks. For example, in 1998–2002, 5 million ha of forest (1.7% of the forest area) was adversely affected by insects in the United States, and 14 million ha was affected in Canada (4.5%); the area annually damaged by insects in North America is 2.9% of the total forest area (1). It is very likely that these natural disturbances will be altered by climate change and have an impact on forestry (34). There is evidence that warmer temperatures have already shifted the habitats of some forest insects, e.g., the mountain pine beetle (35). Other important forest insects, such as the gypsy moth, are more responsive to precipitation change. Climate change can dramatically shift the current boundaries of insects and pathogens and modify tree physiology and tree defense mechanisms. A growing concern is that at the new habitats the insects may damage the tree species that presently cannot tolerate insect outbreaks, e.g., under a very moderate 2°C warming the mountain pine beetle is likely to seriously threaten the Rocky Mountain whitebark pines, which provide food for many wildlife species (36).

Even without fires or insect damage, the change in frequency of extreme events, such as strong winds, winter storms, droughts, etc. can bring massive loss to commercial forestry. These effects of climate extremes on commercial forestry are region-specific and include reduced access to forestland, increased costs for road and facility maintenance, direct damage to trees by wind, snow, frosts, or ice, effects of wetter winters and early thaws on logging, etc. High wind events can damage trees through branch breaking, crown loss, trunk breakage, or complete stand destruction, especially caused by faster build-up of growing stocks in a warmer climate. For example, in January 2005 Hurricane Gudrun with maximum gusts of 43 m/s damaged >60 million m^3 of timber in Sweden. The salvaged timber doubled the harvest level of southern Sweden (37). In a warmer climate, the frequency of some extreme events such as heat waves and severe droughts will increase, although many uncertainties still exist.

The damage from the extreme events such as a severe drought can be further aggravated by increased damage from insect outbreaks and wildfires (38, 39). For example, the 2003 Europe heat wave led to an extreme forest fire season. In Portugal, 0.4 million ha of forests (5.6% of the total forest area in the country) was destroyed. At a larger scale, a positive feedback between deforestation, forest fragmentation, wildfire, and increased frequency of droughts appear to exist in the Amazon basin, so that a warmer and drier regional climate may trigger massive deforestation (40). The model simulations (41) show that during the 2001 El Niño Southern Oscillation period ≈⅓ of Amazon forests had already become susceptible to fire. Further, a widely used Lund–Potsdam–Jena dynamic vegetation model points at a possibility of eventual loss of Amazonian rainforests under a very significant, yet plausible, warming signal corresponding to IS92a's more than triple concentration of CO_2 by the end of the century (42).

Forest fires, insect outbreaks, wind damage, and other extreme events result in substantial economic damage to forest sector, e.g., in the United States, the 2003 forest fires resulted in a $337 million loss in wood. Other adverse effects included reductions in biodiversity and nontimber forest products, negative impacts on erosion and hydrology, and loss of aesthetic and recreational values (43). In a changing climate, higher direct and indirect risks caused by more frequent extreme events will affect timber supplies, market prices, and cost of insurance (44), although the costs are highly uncertain.

Impact of Climate Change on Forest Sector

Change in Supply. Yield models demonstrate that climate change can increase global timber production through location changes of forests, i.e., through a polarward shift of the most important for forestry species. Climate change can also accelerate vegetation growth caused by a warmer climate, longer growth seasons, and elevated atmospheric CO_2 concentrations (refs. 5, 21, 34, 45, and 46 and Table 1). Changing timber supply will affect the market, generally lowering prices. It will also impact supply for other uses, e.g., enhancing the potential of using various types of wood biomass energy.

Table 1. Examples of simulated climate change impacts on forestry

Study area (ref.)	Scenario, general circulation model (GCM)	Production impact	Economic impact
Global (21)	UIUC and Hamburg T-106 for CO_2 topping 550 ppm in 2060	2045: production up by 29–38%; reductions in North America, Russia; increase in South America and Oceania; 2145: production up by 30%, increase in North America, South America, Russia	2045: price reduced, high latitudes' loss, low latitudes' gain; 2145: price increase up to 80% (no climate change), 50% (with climate change), high latitudes' gain, low latitudes' loss; benefits go to consumers.
Global (58)	TEM and CGTM MIT GCM, MIT EPPA emissions	Harvest increase in the American West (2–11%), New Zealand (10–12%), South America (10–13%);harvest decrease in Canada	Demand satisfied; price drop with an increase in welfare to producers and consumers
Global (62)	ECHAM-3 ($2\times CO_2$ in 2060), TSM 2000, BIOME	2080s, no climate change: increase of the industrial timber harvest by 65% (normal demand) or 150% (high demand); emerging regions triple their production; with climate change: increase of the industrial timber harvest by 25% (normal demand) or 56% (high demand), Eastern Siberia and American South dominate production	No climate change: pulpwood price increases 44%; solid wood increase 21%; With climate change: pulpwood price decrease 25%; solid wood decrease 34%; global welfare 4.8% higher than in no climate change scenario.
Europe (38)	HadCM2 under IS92a	18% climate-related increase in stemwood growth by 2030, slowing down on a longer term	Decrease or increase in prices is possible
Europe (46)	Baseline, 20–40%, increase in forest growth by 2020	Increased production in Western Europe, decreased production in Eastern Europe.	Price drop with an increase in welfare to producers and consumers; increased profits of forest industry and forest owners.
Europe (63)	IPCC A1f, A2, B1, B2 up to 2100; Several options of management	Increased forest growth (especially in Northern Europe) and stocks, except for A1f; 60–80% of stock change is caused by management, climate explains 10–30%, and the rest is caused by land-use change.	In the A1f and A2 scenarios, wood demand exceeded potential felling, particularly in the second half of the 21st century; in the B1 and B2 scenarios future wood demand can be satisfied
United States (34, 64)	Combinations of two GCMs and two vegetation models under IS92a	Increase in timber inventory by 12% (midterm); 24% (long term) and small increase in harvest; major shift in species and increase in burnt area by 25–50%; generally, high elevation and northern forests decline, southern forests expand.	Reduction in log prices; producer welfare reduced comparing to no climate change scenario; lower prices; consumers will gain and forest owners will lose
United States (61)	Combinations of two GCMs, three biogeographical and three biogeochemical models	Depending on the models used, productivity gains or losses are predicted; major shift or loss of species distribution.	Small, yet usually generally positive, impact on welfare economic market for all scenarios considered in the model with losses in productivity dampened in economic model

UIUC, University of Illinois at Urbana–Champaign; TEM, Terrestrial Ecosystem Model; CGTM, Center for International Trade in Forest Products Global Trade Model; MIT, Massachusetts Institute of Technology; EPPA, Emissions Prediction and Policy Analysis; ECHAM-3, European Center Hambury Model, version 3; TSM 2000, Timber Supply Model; BIOME 3, Global Biome Model, version 3; HadCM2, Hadley Centre Coupled Model, version 2; IPCC, Intergovernmental Panel on Climate Change.

Change in Demand. Contrary to earlier FAO predictions of fast-growing demand for industrial timber to 2.1 billion m^3 by 2015 and 2.7 billion m^3 by 2030 (3, 47–49), actual demand growth has been much slower. Current demand for 1.6 billion m^3 is just slightly above the demand for 1.5 billion m^3 in the early 1980s (1). Recent projections of the FAO and models of the global forest sector (21, 50, 52)§ often assume a more modest demand growth to 1.8 billion to 1.9 billion m^3 by 2010–2015. Similarly to this correction of earlier projections for industrial timber, global fuel wood use has already peaked at 1.9 billion m^3 and is stable or declining (26), with the share of charcoal continuing to increase as fuel wood is converted to charcoal (53). However, the use of wood for fuel and biomass energy could dramatically escalate in the face of rising energy prices and new technologies, particularly if incentives are created to shift away from carbon-emitting fossil fuels and toward biofuels, which are viewed as recycling the emitted carbon.

Some model-based estimates project an increase in biofuel demand during the next 50 years by as much as a factor of 10 (54). In some countries, biofuels, particularly ethanol from grains and other plant materials, e.g., sugarcane, have already become an important source of nonconventional transport energy. Biofuels derived from cellulosic biomass (fibrous and wood portions of trees and plants) offer an even more attractive opportunity as an alternative to conventional energy sources (55). Also, wood cellulose can be used in gasification processes, e.g., integrated

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§Häggblom R, World Bank Seminar: Business Opportunities in Forestry Sector, May 7, 2004, Helsinki, Finland.

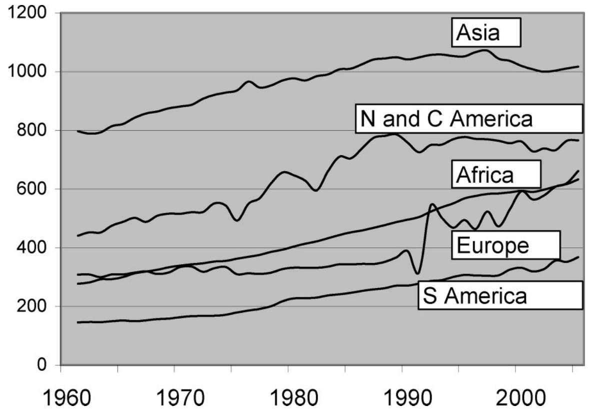

Fig. 2. The trends in global timber production, billion m^3 (7).

gasification combined cycle process, to produce synthetic gases, including hydrogen. These gases can be further used to produce energy directly or as feedstock to produce a variety of energy products, including not only ethanol but also biocrude, using processes such as Fisher-Tropsch. Wood-fired gasification plants can be constructed as stand-alone projects, as is now under consideration in some locations. An intriguing possibility is that new gasification biorefineries replace aging traditional boilers in existing pulp mills (56). Pulp mills have large energy requirements and are designed to facilitate the flow of large amounts of wood.

Should wood biofuels become common the forest industry would face the same types of challenges that the American grain industry has faced since ethanol came into larger-scale production: associated with the expansion of land under corn cultivation are ever-increasing pressures on the land resource, as reflected in the dramatic increases in corn prices and the doubling of corn land rents in much of the corn-belt region. Currently these concerns seem to be premature as the cost of cellulosic ethanol (\$0.8 to \$1 per liter compared with $\approx$\$0.6 per liter of corn ethanol in the United States) precludes its commercial use (57). However, with rapid evolution of the technology, the prices for renewable wood-based fuels are decreasing, even though it is still impossible to estimate the extent to which wood-based fuels will become competitive with petroleum or other biofuels. Hence, the actual demand for forest products could be higher than FAO projections, affecting viability of simulation studies, discussed in the next section. Additionally, there are many other products and services that depend on forest resources for which, again, there are no satisfactory estimates of global future demand.

Timber Production. Driven by changing supply and demand, total roundwood production, including both industrial wood and fuel wood, has been growing steadily from 2.5 billion m^3 in 1960s to 3.2 billion m^3 in 1990s. In 2005 production was at a peak 3.5 billion m^3 because of a long trend of increasing production in Europe, Africa, and South America, whereas Asia and North America remained constant or declined (Fig. 2). Modeling studies generally predict further increase of global industrial roundwood production, with increases or decreases in prices in the future in the order of $\pm 20\%$ (5, 21, 34, 38, 44, 45, 58), and with benefits of higher production mainly going to consumers. The future trend of fuel wood is more problematic depending in large part on the use to which wood is put to substitute for high-priced carbon-emitting fossil fuels. At the same time, a global shift in the industrial wood supply between the temperate and tropical zones and between the Northern and Southern Hemispheres is possible. The current trend is toward high productivity south and away from temperate and boreal forests (59). However, warming could shift some of the activities back toward the north. These changes could increase international trade in forest products to balance the regional imbalances in demand and supply (3). For the United States, the net impact of climate change on the forestry sector may be small because of the large stock of existing forests, technological change in the timber industry, and the ability to adapt fast (34, 60). The results of simulation studies are summarized in Table 1.

Conclusions

Supporting the major conclusions of an Intergovernmental Panel on Climate Change report (65), recent modeling experiments project that moderate temperature growth as expected under doubling atmospheric CO_2 climate change simulations will positively impact global forest sector, increasing timber supply and reducing or conserving the prices. However, it is not clear how well these models simulate forest responses. The effects of elevated CO_2 measured in experimental settings and implemented in models may overestimate actual field responses, because of many limiting factors such as pests, weeds, competition for resources, soil water, air quality, etc., which are neither well understood at large scales, nor well implemented in leading models (20, 66, 67). Further, the carbon fertilization effects were measured for young tree stands and as so may exceed those for the mature trees (20). The models generally assume a large impact of elevated CO_2 level in the atmosphere on production, which might have to be reduced when better results of FACE-type experiments are available.

There are also inconsistencies between the models used by ecologists to estimate the effects of climate change on forest production and composition and the models used by foresters to predict forest yield. Future development of the dynamic vegetation models (11, 68–72) that integrate both the net primary production and forestry yield approaches will significantly improve predictions by simulating the composition of deciduous/evergreen trees, forest biomass, production, water and nutrient cycling, the effects of fires, insect outbreaks, and extreme events, and climate feedbacks.

Although models suggest that global timber productivity will likely increase with climate change, regional production will exhibit large variability, as illustrated in Table 1. In boreal regions natural forests would migrate to the higher latitudes. Countries affected would likely include Russia and Canada. Warming could be accompanied by increased forest management in northern parts of some of these countries, particularly the Nordic countries, as increased tree growth rates are experienced. Climate change will also substantially impact other services, such as seed availability, nuts, berries, hunting, resins, and plants used in pharmaceutical and botanical medicine and the cosmetics industry, and these impacts will also be highly diverse and regionalized.

Another factor to consider is the effects of impacts other than climate change such as land-use change and tree plantation establishment. In many regions, these effects may be more important than the direct impact of climate. Indeed, over the past half-century industrial wood production has been increasingly shifting from native forests to planted forests. Whereas also no industrial wood came from planted forests 50 years ago, >⅓ of current harvests are from planted forests (73, 74). New planted forests are typically developed on sites that have rapid growth and access to processing and markets; hence, very large areas of new forest plantations have been established in tropical and subtropical countries, particularly Latin America and parts of Asia, with China and India being the leading world countries in planted forests.

Recent studies on likely impact of climate change on forestry support those mentioned in a previous Intergovernmental Panel on Climate Change report (65), which includes conclusions about increasing global timber supply and slow increase in demand for forest production, followed by falling prices. However, if indeed wood-based ethanol becomes competitive with other biofuels, these earlier estimates are likely to be corrected toward growing demand and higher prices.

The response of forestry to global warming is likely to be multifaceted. On some sites, species more appropriate to the climate will replace the earlier species that is no longer suited to the climate. Also, planted forests can be relocated to more regions with more suitable climates. In general, we would expect planting and associated forestry operations to tend more toward higher latitudes, especially from some tropical sites, should they warm substantially. Plantations would likely shift toward more subtropical regions from tropical ones. In the United States, we might expect to see planted forest moving northward, with more spilling over into Canada. In Latin America forest plantations may shift toward southern Brazil and Argentina. In some cases the same sites will be used but the choice of species will change to those more suitable to the new climate.

Climate change impacts on forestry and a shift in production preferences (e.g., toward a wider use of biofuels) will translate into social and economic impacts through the relocation of forest economic activity. Distributional effects will involve businesses, landowners, workers, consumers, governments, and tourism. Net benefits will accrue to regions experiencing increased forest production, whereas regions with declining activity will likely face net losses. Although forest-based communities in developing countries are likely to have a modest impact on global wood production, they may be especially vulnerable because of limited adaptability in rural, resource-dependent communities to respond to risk in a proactive manner (51, 75).

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