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# Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change

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ABSTRACT

The Global Forest Products Model (GFPM) was modified to link the forest sector to two scenarios of the Intergovernmental Panel on Climate Change (IPCC), and to represent the utilization of fuelwood and industrial roundwood to produce biofuels. The scenarios examined were a subset of the "story lines" prepared by the IPCC. Each scenario has projections of population and gross domestic product. These projections were used as input in the GFPM simulations. The IPCC also makes projections of forest area, which were integrated in the timber supply sub-model of the GFPM. The IPCC scenarios also predict bioenergy production. These projections were used in the GFPM to determine forest area, forest stock, and the demand, supply, prices, and trade of forest products up to 2060. The main finding concerns the important impact of the high demand for biofuels implied in some of the IPCC scenarios. In particular, scenario A1B would induce a nearly 6-fold increase in the world demand for fuelwood by 2060. As a result, the real price of fuelwood would rise and converge towards the price of industrial roundwood by about 2025. At that point, industrial roundwood, which was used in the past to manufacture sawnwood, panels, and pulp, would begin to be used for energy production. The price of all wood would then continue to rise steadily up to 2060, and the price of manufactured product would increase in concert. The high fuelwood harvest would imply ecologically stressed forests in several countries, even under scenario A2 with a nearly 3-fold increase in fuelwood production by 2060.



## 1. Introduction

Although separated by great, but diminishing, geographical and cultural distances, the forest sectors of different countries are linked through international trade and global environmental policies. To a large extent, the future of any country, even a large country such as the United States, depends on world markets. It is therefore critical to understand how these markets work, and how they are affected by economic, demographic, and biological change, and by deliberate policy.

During the last three decades, international trade of forest products has expanded rapidly, attracting more attention and driving much of the forest policy debate. As a case in point, China's rapid economic growth is having profound effects on the forest economy of the Asia Pacific, including the United States, through demand for raw materials and exports of processed wood products (Katsigris et al., 2005).

As a result, in the United States, the decision was made for the 2010 Forest Assessment mandated by the Resources Planning Act (RPA), to firmly anchor the national assessment within a comprehensive international context. Specifically, the imports and exports of the United States, and the consequent domestic production and prices should be consistent with developments in the global forest sector. The concept is to develop global scenarios with the Global Forest Products Model (GFPM, Buongiorno et al., 2003), and consistent but more detailed national projections with a United States Forest Products Model (USFPM, Kramp, 2008) with the same structure as the GFPM but finer regional and product description.

Besides trade, much attention has been given to the critical issue of climate change and what policies and programs may be developed to address it. Consequently, it was decided to link the 2010 RPA Forest Assessment directly to the scenarios described by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al., 2000). The IPCC is a scientific intergovernmental body with the mission to "assess the latest scientific, technical, and socio-economic literature relevant to understanding the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation" (IPCC, 2008).

The IPCC scenarios contain long-term projections of global and regional economic activity, population, land uses, and greenhouse gases. A notable component of each scenario is a projection of biofuel production, which could have major implications for forests and forest industries.

Kirilenko and Sedjo (2007) review past estimates of the impact of climate change on the forest sector. Although they differ in methods, the studies commonly use the projections of atmospheric and biological

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climate change models as input in economic forest sector models, for countries (McCarl et al., 2000), regions (Solberg et al., 2003), or the world (Perez-Garcia et al., 2002; Sohngen and Sedjo, 2005).

Some past studies assume higher growth and a migration of forests towards the poles due to elevated $CO_2$ concentrations, higher temperatures and longer growing seasons (Nabuurs et al., 2002). This in turn leads to increased timber inventories and supply, particularly in South America and Oceania, and hence lower timber prices (Sohngen and Mendelsohn, 1998; Perez-Garcia et al., 2002; Solberg et al., 2003; Sohngen and Sedjo, 2005). This response may, however, be over-estimated due to limiting factors such as forest pests, weeds, etc. (Kirilenko and Sedjo, 2007), which were taken into account by Sohngen and Sedjo (2005).

On the demand side, biomass energy consumption may increase by as much as a factor of five to seven by 2050, due to rising energy prices and new technologies (Alcamo et al., 2005). Kirilenko and Sedjo (2007) note that past estimates of the impact of climate change (e.g., IPPC, 2001; Perez-Garcia et al., 2002; Sohngen and Mendelsohn, 1998) have not taken into account this potentially large demand.

This paper assesses some of the consequences for the world forest sector of the scenarios developed by the Intergovernmental Panel on Climate Change, which imply very large increases in biofuel production. The first part of this paper describes how the GFPM was used in translating the IPCC scenarios into projections specific to the forest sector. The results, consisting of projections to 2060 are then presented for the production, trade, and prices, of fuelwood and industrial roundwood. The projections are global, for the main regions, and for selected individual countries. The paper concludes with a critique of the method and the potential for further developments.

## 2. Methods

### 2.1. Model structure and parameters

The Global Forest Products Model is a spatial dynamic economic model of the forest sector. The model is dynamic as it is essentially a system of difference equations: the equilibrium in a particular year is a function of the equilibrium in the previous year. The GFPM and several applications are described in detail in Buongiorno et al. (2003), and the most recent version, together with the software and its documentation is available at: http://fwe.wisc.edu/facstaff/buongiorno/. The model simulates the evolution of competitive world markets for forest products. It recognizes 180 individual countries and their interaction through imports and exports. In each country the model simulates the changes in forest area and forest stock. It also calculates the consumption, production, and trade of up to 14 commodity groups (Fig. 1). In each projected year, prices are computed that clear world markets for all products.

Fig. 1 symbolizes the flow and transformation of forest products in each country, from the supply of raw materials such as industrial

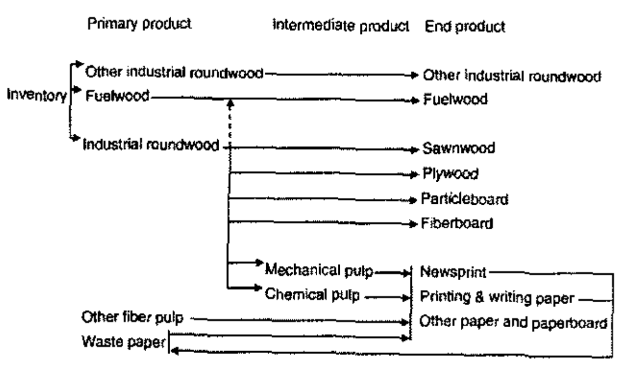


**Fig. 1.** Products transformation within a country of the GFPM.

roundwood and fuelwood, which depend directly on inventory, to the demand for final products: sawnwood, wood-based panels, and paper and paperboard. The intermediate products such as mechanical and chemical pulp depend on the production of paper products, and induce a demand for industrial roundwood. Additional sources of raw materials consist of non-wood fiber pulp, and of the waste paper recovered after consumption of paper and paperboard. In this particular application, part of what used to be industrial roundwood may be diverted to fuelwood if and when, due to high biofuel demand, the price of fuelwood approaches that of industrial roundwood (dashed arrow in Fig. 1).

The GFPM has a static element that describes the world spatial market equilibrium in a particular year, and a dynamic part that simulates the changes from year to year. Computation of the spatial equilibrium in any given year relies on Samuelson's (1952) demonstration that this equilibrium results from maximization of "social surplus", which in the GFPM is the sum of the producer and consumer surplus. Equivalently, this is the value to consumers of all end products in all countries minus the cost of supplying the raw materials, the cost of transforming them in end products, and the cost of transportation:

$$\max Z = \sum_i \sum_k \int_0^{D_{ik}} P_{ik}(D_{ik})dD_{ik} - \sum_i \sum_k \int_0^{Y_{ik}} m_{ik}(Y_{ik})dY_{ik} - \sum_i \sum_j \sum_k c_{ijk}T_{ijk} \quad (1)$$

where the subscripts $i$ and $j$ refer to countries and $k$ to a product. $P$ is price, $D$ is the end-product demand, $Y$ is production, and $T$ is quantity transported. For raw materials such as industrial roundwood or waste paper, $m(Y)$ is the marginal cost of production. For manufactured products such as sawnwood it is the marginal cost of the exogenous inputs: labor, capital and energy. The freight cost, $c$, includes tariffs and taxes.

In Eq. (1) the sum of the integrals of the inverse demand $P(D)$ is the value of end products to consumers. The sum of the integrals of the supply functions $m(Y)$ is the total production cost for raw materials, or the exogenous cost of production (capital, labor, energy) for products manufactured from raw materials. The last summation refers to the exogenous total transportation cost between all countries for all products.

The essential constraints that describe the equilibrium are the material balance constraints that ensure that for each country and product the total supply is equal to the total demand:

$$\sum_j T_{jik} + Y_{ik} = D_{ik} + \sum_n a_{ikn}Y_{in} + \sum_j T_{ijk} \quad \forall i, k \quad (2)$$

The left-hand-side of the equation refers to the total imports of a country plus its domestic production. The right-hand-side expresses how much of the particular product is consumed as an end product, or used as input in the production of another product, or exported. The coefficient $a_{ikn}$ indicates how much of product $k$ is used to make product $n$ in country $i$. These coefficients vary over time to indicate technical change, for example in the use of waste paper to manufacture paper and paperboard.

In the GFPM the final demand and the raw materials supply are represented by econometric equations. The intermediate demand and supply are represented by the input–output coefficients, $a_{ikn}$, and the corresponding output-dependent manufacturing cost, $m(Y)$, which covers labor, energy, and capital. With local linearization of the demand, supply, and manufacturing cost equations the problem described by Eqs. (1) and (2) has a quadratic objective function and linear constraints.

The dual solution of this quadratic program gives a shadow price for each constraint (Eq. (2)), which is the market-clearing equilibrium price for each product and country in the particular year considered. Given Eqs. (1) and (2), in the absence of constraints to limit the trade, the export price is the same for all exporting countries, while the price in importing countries is equal to the export price plus the transport cost. Price distortions may occur in individual countries due to trade inertia constraints used in the GFPM to express the incomplete adjustment of trade to changes in economic conditions (Buongiorno et al., 2003, p. 43).

The dynamic part of the GFPM describes endogenous and exogenous changes in the conditions of the equilibrium expressed by Eqs. (1) and (2). For example, one type of exogenous change refers to the yearly shift of the demand for the end products due to economic growth:

$$D = D_{-1}(1 + \alpha_y g_y) \tag{3}$$

where $D$ is the demand for a particular product in a country in the current year, at last-year's price, $D_{-1}$ is last-year"s demand, $g_y$ is the rate of GDP growth, and $\alpha_y$ is the elasticity of demand with respect to GDP. The demand equations were estimated with panel data of countries observed from 1961 to 2005 (Simangunsong and Buongiorno, 2001). The elasticity with respect to GDP was used in Eq. (3) while the elasticity with respect to price, determined the first term of Eq. (1), the area under the demand curves.

The wood supply model for industrial roundwood and fuelwood is a neoclassical model of supply linking harvest to price and forest stock (Turner et al., 2006). Forest stock changes as result of forest area change, harvest, and growth of stock on the remaining forest. The change in forest area in the GFPM depends on the level of GDP per capita according to the equation (Turner et al., 2006):

$$g_{aa} = \alpha_0 + \alpha_1 y' + \alpha_2 y'^2 \tag{4}$$

In this "environmental Kuznet's curve" $g_{aa}$ is the annual rate of forest area change, $y'$ is GDP per capita, the coefficient $\alpha_1$ is positive, and $\alpha_2$ is negative. The GFPM parameters imply that forest area decreases at a decreasing rate up to a GDP per capita of about $9000 per person. Then, forest area increases at an increasing rate up to a GDP per capita of about $20,000 per person. Beyond that forest area increases at a decreasing rate up to about $33,000 per person, at which point forest area stabilizes.

The endogenous rate of growth of forest stock, without harvest, $g_{ua}$ is described by a negative relationship between growth and forest density, the ratio of forest volume, $I$, to forest area, $A$ (Turner et al., 2006):

$$g_{ua} = \gamma_0 \left(\frac{I}{A}\right)^{\sigma} \tag{5}$$

With $\sigma = -0.81$ a doubling of forest stock per unit area decreases forest growth by about 80%, other things being equal. Both $\sigma$ and $\gamma_0$ were estimated from cross-sectional data. In the main countries $\gamma_0$ was calibrated so that the curve of Eq. (5) would go through the observation for that country.

Buongiorno et al. (2001), updated in Zhu et al. (2007) explain the calibration methods used to estimate the input–output parameters and the corresponding manufacturing cost in Eqs. (1) and (2). The main databases are the FAOSTAT (FAO, 2008a) and the World Bank Development Indicators Data Base (World Bank, 2008). The calibration is done by optimization. Using data from 1992 to 2006 it estimates input–output coefficients that minimize the deviation of calculated from observed production for all products, given a-priori bounds on the input–output coefficients. Manufacturing costs are estimated as the difference between the price of a product and the cost of wood and fiber that go into it, under the assumption of equilibrium and thus zero net profit (beyond a normal return to capital).

### 2.2. IPCC scenarios

Three scenarios of the Intergovernmental Panel on Climate Change (IPCC), labeled A1B, A2, and B2 have been selected to set the basic assumptions for the 2010 RPA Forest Assessment (USDA Forest Service, 2008). Each scenario results from a separate IPCC "storyline" about the direction of global social, economic, technical and policy developments. The storylines also reflect different directions possible for the interaction between developing and industrialized countries. As the implications of scenario B2 tend to be between those of scenarios A1B and A2, and to save space, only the effects of scenarios A1B and A2 are presented here.

Scenario A1B, which assumes continuing globalization, would lead to high income growth and low population growth, and thus the highest income per capita by the year 2060. Another important feature for the 2010 Forest Assessment is that scenario A1B assumes a very rapid growth of biofuel production. From 2006 to 2060 the global production of biofuels would increase 5.5 times.

Scenario A2 assumes a slowdown of globalization, and the rise of more regional interests. This would lead to a lower income growth than scenario A1B, and higher population growth, and thus lower income per capita. Biofuel production would grow more slowly than in A1B, but still be substantial. By 2060 the global production of biofuels would be 2.7 times that of 2006.

For the GFPM simulations, the three main exogenous variables taken from these scenarios were the growth of GDP and population, the change in forest area, and the growth of biofuel production. The historical and the IPCC predicted growth rates of these variables are summarized in Table 1.

GDP growth from the IPCC was available only by region. National GDP growth was deducted from the regional growth in such a way

**Table 1**
Observed and predicted annual rates of growth (%) of IPCC projections used as exogenous variables in the GFPM simulations.

| Region | Observed 1992–2006 | Predicted 2006–2060 | |
|---|---|---|---|
| | | Scenario A1B | Scenario A2 |
| *Population* | | | |
| ALM[a] | 2.29 | 1.05 | 1.62 |
| Asia[b] | 1.25 | 0.29 | 1.00 |
| OECD90[c] | 0.58 | 0.26 | 0.43 |
| REF[d] | 0.13 | −0.07 | 0.46 |
| World | 1.33 | 0.50 | 1.09 |
| *Gross domestic product* | | | |
| ALM | 4.93 | 5.41 | 3.69 |
| Asia | 6.83 | 5.70 | 3.59 |
| OECD90 | 2.21 | 1.90 | 1.50 |
| REF | 1.15 | 4.85 | 3.10 |
| World | 2.95 | 3.71 | 2.35 |
| *Forest area* | | | |
| ALM | −0.16 | −0.02 | −0.01 |
| Asia | −0.22 | 0.10 | 0.10 |
| OECD90 | 0.01 | 0.01 | 0.11 |
| REF | −0.24 | −0.04 | −0.01 |
| World | −0.14 | 0.00 | 0.03 |
| *Biofuel production* | | | |
| ALM | 1.68 | 3.84 | 2.45 |
| Asia | −1.89 | 1.94 | 1.04 |
| OECD90 | −5.52 | 5.56 | 2.71 |
| REF | 2.54 | 1.99 | 1.76 |
| World | −1.26 | 3.36 | 1.83 |

[a] Africa, Latin America, Middle East.
[b] Except Middle East.
[c] OECD countries in year 1990.
[d] Central and Eastern Europe and Newly Independent States of the former Soviet Union.

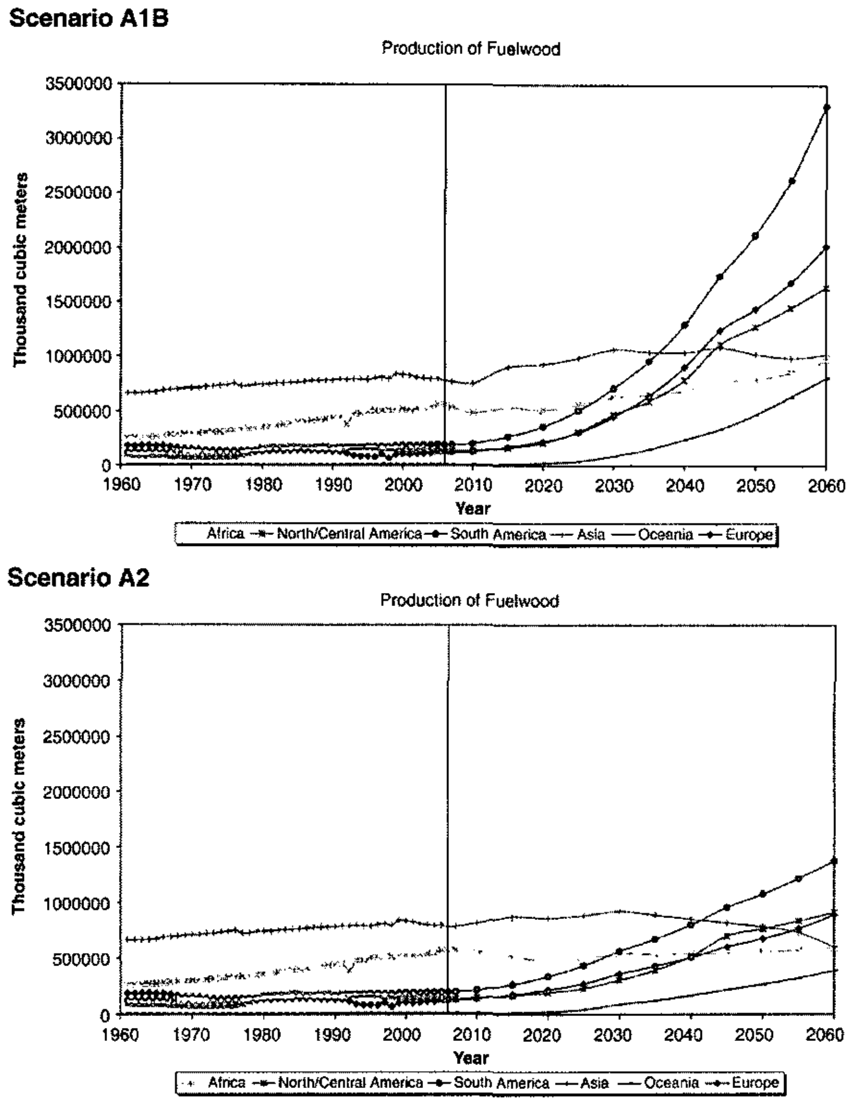


**Fig. 2.** Regional projections of fuelwood production.

that the regional growth remained the same as in the IPCC and the growth of individual countries converged towards this average regional growth rate.

The national growth rates of forest area predicted from the environmental Kuznet's curve (Eq. (4)) were adjusted proportionally so that the regional area change would match that of the IPCC regional projections for each scenario (Table 1). In all scenarios, the growth of forest stock was predicted with Eq. (5), as the IPCC data do not allow a determination of the effect of climate change on forest growth.

The demand for fuelwood was assumed to shift in the GFPM simulations at rates that led to the same rate of growth of world fuelwood production as the growth of world biofuel production in the IPCC scenarios (Table 1). The assumed rate of growth of fuelwood demand in individual countries took into account the availability of forest resources.

Given these assumptions, the quantity–price equilibrium in each country, and the corresponding trade, were computed endogenously by the GFPM. The model structure allowed transformation of part of the industrial roundwood (i.e. wood used in the past to manufacture wood products) into fuelwood, when the price of fuelwood rose to the level of the price of industrial roundwood.

## 3. Results

### 3.1. Fuelwood production

Fig. 2 shows the growth of fuelwood production, by main production region, from 2006 to 2060, according to scenarios A1B and A2. In accord with FAO's definition, fuelwood includes wood used for heating, cooking, and power production (FAO, 2008b), in the GFPM simulations the power production includes that coming from biofuels extracted from wood.

In agreement with the IPCC scenarios, the world production of fuelwood under scenario A1B increased by a factor of 5.4 from 2006 to 2060, and by a factor of 2.6 under scenario A2 to meet the assumed growth in biofuel demand. In both scenarios, fuelwood production would grow fastest in North America, South America, and Europe. Although Asia and Africa produced a large part of the world share of fuelwood production in 2006, production would grow at a slower rate in Asia and Africa than in the other regions.

Table 2 shows the historical rates of growth of fuelwood production and the predicted rates up to 2060 for selected countries and the group of developed and developing countries. The reversal of

**Table 2**
Annual growth rate of fuelwood production for selected countries (%).

| | Observed 1992–2006 | Predicted 2006–2060 | |
|---|---|---|---|
| | | Scenario A1B | Scenario A2 |
| Canada | −5.3 | 10.8 | 8.3 |
| USA | −4.9 | 5.4 | 4.8 |
| Brazil | 0.9 | 5.2 | 3.1 |
| Indonesia | −3.5 | 0.2 | 0.3 |
| Japan | −3.0 | 12.9 | 8.6 |
| Finland | 4.4 | 5.1 | 3.9 |
| Russian Fed. | −2.3 | 6.2 | 3.7 |
| Sweden | 3.2 | 5.0 | 3.9 |
| Developed | −0.4 | 6.0 | 4.5 |
| Developing | 0.3 | 2.3 | 1.0 |

historical and predicted trends in developed countries is striking. For example, although fuelwood production decreased at about 5 % per year in the United States and Canada from 1992 to 2006, it would increase at 5 to 11% per year under scenario A1B and 5 to 8% per year under scenario A2. In Japan, fuelwood production could grow as fast as 13% per year under scenario A1B, and at 9% per year under scenario A2. In Finland and Sweden, fuelwood production would accelerate under scenario A1B, but slow down or stay the same under scenario A2, compared to historical growth. In developing countries, fuelwood production increased at an average rate of 0.3% per year from 1992 to 2006 while it would grow at 1% to 2% from 2006 to 2060 depending on the scenario. In Indonesia where the availability of fuel oil induced a decrease in fuelwood production from 1992 to 2006, fuelwood production would stabilize under either scenario.

### 3.2. Fuelwood trade

Although Asia would not see the fastest rise of production, it would experience a sharp increase in imports. Under scenario A1B (Fig. 3) Asia's net imports would accelerate after 2025, and reach nearly 125 million $m^3$ per year by 2060. From 2030 to 2060, Oceania would be a major exporter, together with Europe and North America. Under scenario A2, the net imports of Asia would similarly increase 160 million $m^3$ per year by 2060. The net exporters would be South America, Europe, and Oceania.

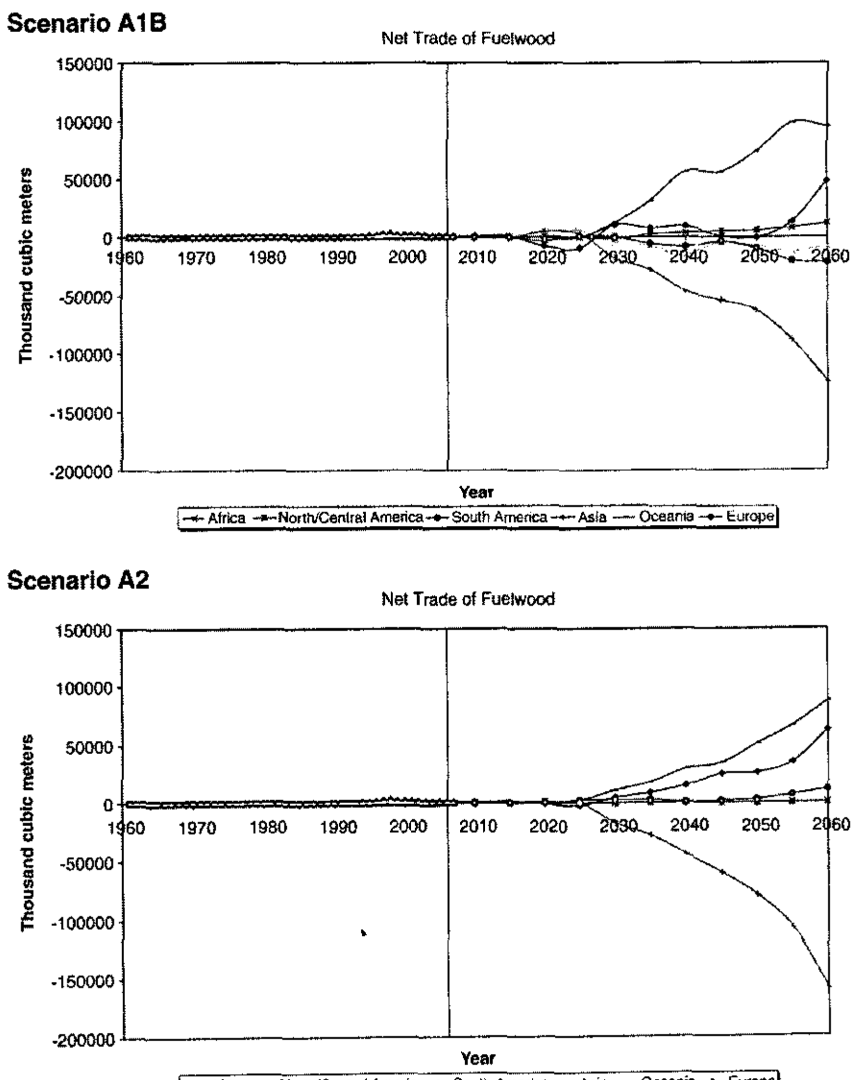


**Fig. 3.** Regional projections of net trade of fuelwood (exports minus imports).

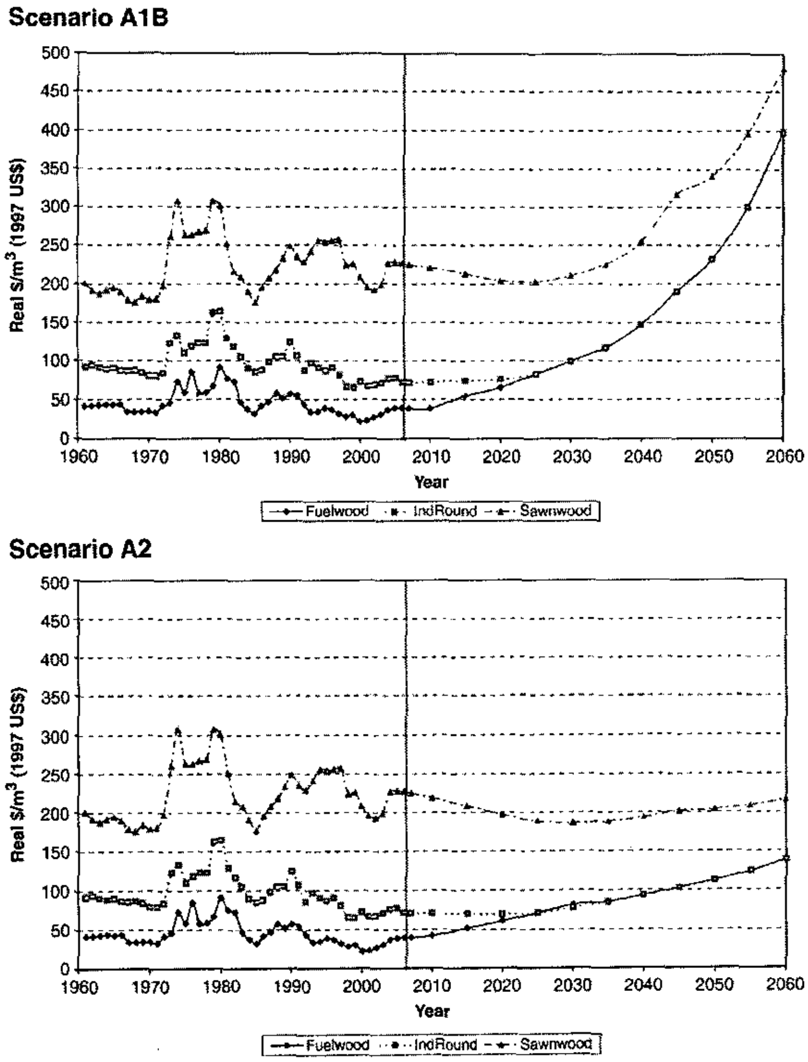


**Fig. 4.** Predicted world price of fuelwood, industrial roundwood, and sawnwood.

### *3.3. Prices of fuelwood and industrial roundwood*

The sharp increase in the world demand for fuelwood under scenario A1B was linked to the evolution of the prices of fuelwood and industrial roundwood. Fig. 4 shows the GFPM projections of the world prices of fuelwood, industrial roundwood and sawnwood, for scenarios A1B and A2. Prices in U.S. dollar per $m^3$ were expressed in real terms, with the purchasing power of 1997. Under both scenarios, from 2006 to 2030 the real price of industrial roundwood (wood used in making sawnwood, pulp, and panels) would remain roughly constant. Meanwhile, due to the strong growth in the demand for biofuels, the price of fuelwood would rise. With scenario A1B the prices of fuelwood and of industrial roundwood would converge towards \$83 per $m^3$ by about 2025. Subsequently the price of the two types of wood would rise steadily to nearly \$400 per $m^3$ by 2060. Meanwhile, the price of sawnwood would approximately follow the trend of the price of industrial roundwood, as it has in the past, reflecting the contribution of roundwood to the cost of sawnwood.

Under scenario A2, the world demand for fuelwood would be much lower (Fig. 2) than under scenario A1B. Nevertheless, the price of fuelwood and that of industrial roundwood would still converge in 2025, but at the somewhat lower price of \$71 per $m^3$ than with scenario A1B. The price of industrial roundwood would rise steadily in real terms, and so would the price of sawnwood, but much more slowly than under scenario A1B (Fig. 4). By 2060 the real price of industrial roundwood and sawnwood would be about the same as industrial roundwood was around 1980.

In both scenarios, the predicted prices of panels, and wood pulp, not shown here, followed the trends of the price of industrial roundwood, though at a slower rate than sawnwood due to the lower share of wood cost in their production. The price of pulp would be affected even less by the rise of wood prices due to the substitution of cheap recycled paper for wood pulp.

### *3.4. Industries production*

The growth of all forest industries, except biofuel production, would be affected negatively by the rise of the demand for fuelwood that would push up the price of industrial roundwood. For example, the top panel of Fig. 5 shows the predicted production of wood pulp in the main regions, according to scenario A1B. Only in Asia would wood pulp output be higher in 2060 than in 2006. Recall that this is the only region where fuelwood production would rise moderately (Fig. 2). Wood pulp production would stagnate in Africa, Oceania, and South

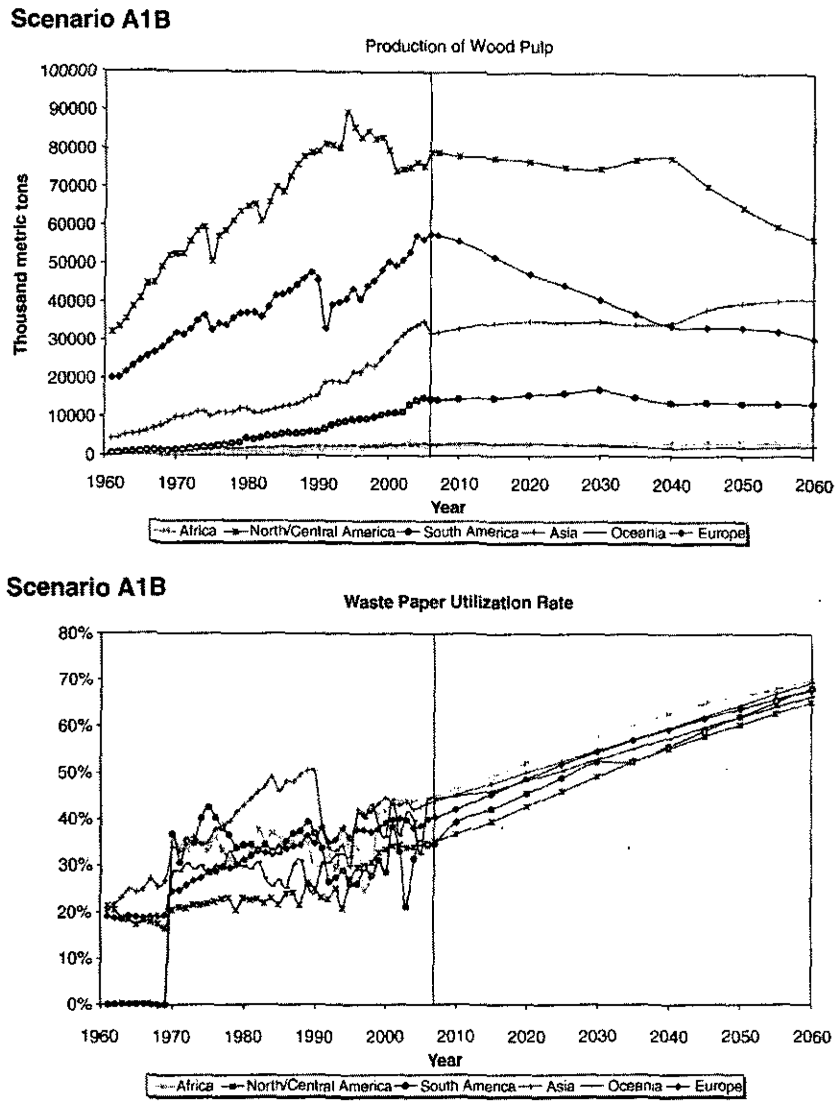


**Fig. 5.** Regional projections of wood pulp production and waste paper utilization rates.

America. In North America, wood pulp output would stay approximately constant up to 2040 and then decline rapidly. In Europe, it would decline rapidly until 2040 and end up producing less than Asia by 2060. Globally, the production of wood pulp would be 22% lower in 2060 than in 2006 under scenario A1B.

However, it must be noted that this decrease in wood pulp production would be due only in part to the rise of the price of industrial roundwood in conjunction with the increased demand for fuelwood. At least as important would be the increase in the substitution of wood pulp by recycled paper in the production of paper and paperboard. As shown in the lower panel of Fig. 5, the exogenous assumptions regarding the change in waste paper utilization rate, the share of waste paper in the total fiber used in the manufacture of paper and paperboard, implied a rise from a world average of 40% in 2006 to 68% in 2060.

### 3.5. Forest area and forest stock

In this application, the projections of forest area were exogenous, based on the regional IPCC projections of forest area. They differed little by scenario, and suggested little change (Fig. 6). Forest stock was predicted endogenously with the GFPM and thus it reflected the harvest rates implied by each scenario due to the demand for products, driving the demand for industrial roundwood and fuelwood, and the IPCC forest area change assumptions (Table 1).

Fig. 6 shows the projections under scenario A1B. Forest stock was predicted to be lower by 2060 in North America, Asia, and Africa, but it would be higher in South America, Europe, and Oceania. Table 3 shows the annual rates of change of forest stock from 2006 to 2060, for the main countries. Under scenario A1B global forest stock was predicted to remain about constant from 2006 to 2060, in developed and developing countries. With scenario A2, the lower demand for biofuel would let the global growing stock increase at 0.2% per year in developing countries and at 0.4% per year in developed countries, from 2006 to 2060. For both scenarios there would be substantial differences between countries. Some of the fastest rates of decline in forest stock would occur in Indonesia, Sweden, Finland, and the United States. This would be compensated by an increase in the growth rate of forest stock in the Russian Federation, a continuing increase, but at a slower than the past rate in Japan, and a reversal of the historical decline in forest stock in Brazil to a positive growth rate from 2006 to 2060.

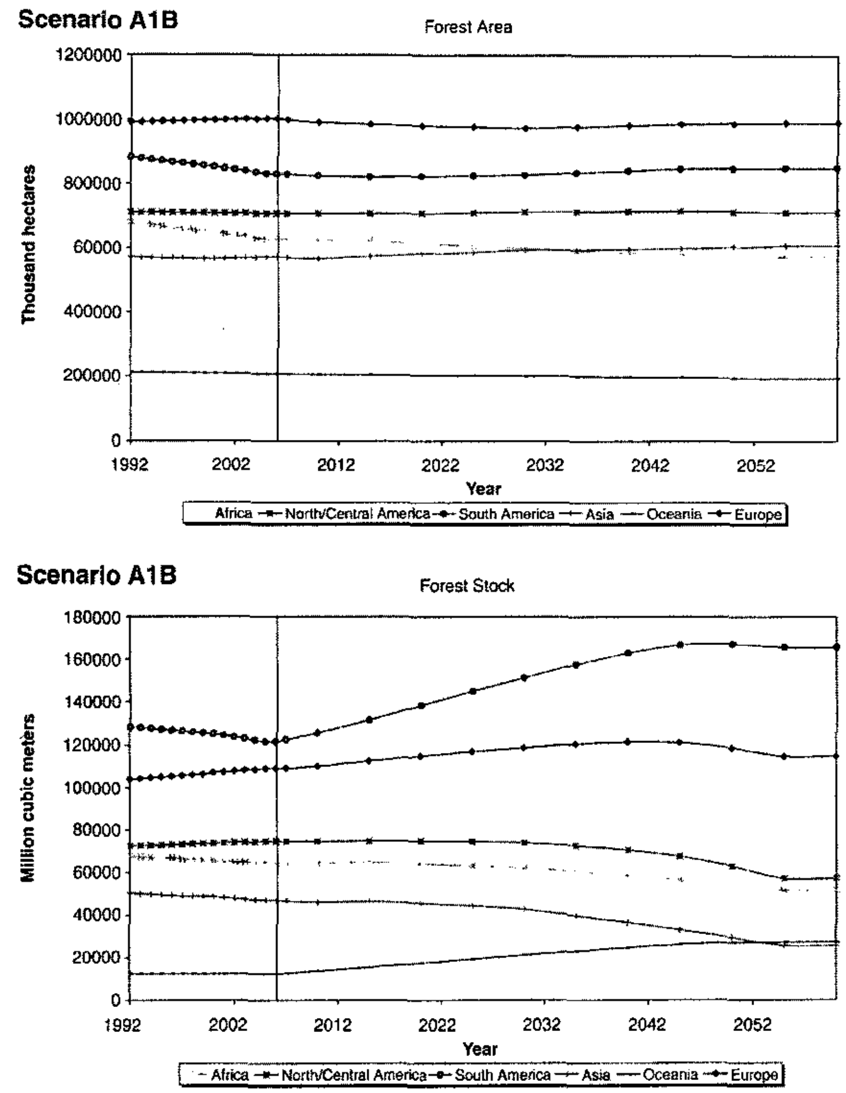


**Fig. 6.** Regional projections of forest area and forest stock.

## 4. Summary and discussion

This study sought to identify some of the consequences for the world forest sector of the scenarios developed by the Intergovernmental Panel on Climate Change. The IPCC scenarios include projections of economic growth, demographic growth, forest area, and demand for biofuel.

The implications of two scenarios were incorporated in the Global Forest Products Model to predict the effects on the global demand and supply of forest products, their international trade and their prices, up to 2060. These implications were assessed in an internally consistent framework taking into account the complex interaction among countries, through trade, and forest sectors, through manufacturing.

The main finding concerns the important impact of the high demand for biofuels implied in some of the IPCC scenarios. In particular, scenario A1B which projects a nearly 6-fold increase in the world demand for biofuels by 2060, would increase considerably the demand for fuelwood. As a result, the real price of fuelwood would increase substantially and converge towards the price of industrial roundwood by about 2035. At that point, industrial roundwood, which was used in the past to manufacture sawnwood, panels, and pulp, would begin to be used for energy production. The price of all wood would then continue to rise steadily up to 2060, and the price of manufactured product would increase in concert. This results in more roundwood being diverted into fuelwood for the rapidly growing economies of Asia

**Table 3**
Annual growth rate of forest stock in selected countries (%).

| Countries | Observed 1992–2006 | Predicted 2006–2060 | |
|---|---|---|---|
| | | Scenario A1B | Scenario A2 |
| Canada | 0.0 | −0.1 | 0.2 |
| USA | 0.7 | −0.7 | −0.4 |
| Brazil | −0.5 | 0.2 | 0.3 |
| Indonesia | −6.3 | −2.8 | −1.8 |
| Japan | 1.9 | 0.7 | 1.0 |
| Finland | 0.8 | −1.4 | −0.5 |
| Russian Fed. | 0.0 | 0.4 | 0.5 |
| Sweden | 0.8 | −1.9 | −0.8 |
| Developed | 0.4 | 0.1 | 0.4 |
| Developing | −0.4 | 0.0 | 0.2 |

and in response more roundwood harvested from the highly productive forests of South America and Oceania.

According to our projections, the large increase in fuelwood demand induced by biofuel production would not lead globally to a lower growing stock by 2060, even under scenario A1B. This finding agrees with Smeets and Faaij (2007) estimate that the potential annual world production of roundwood, fuelwood and forest bioenergy would be about 12.5 billion $m^3$ in 2050, similar to the scenario A1B projection of 12.0 billion $m^3$ of world consumption of total roundwood. But the A1B projection would imply ecologically stressed forests, according to Smeets and Faaij who suggest that the potential would be only 7.1 billion $m^3$ if the ecological integrity of the world's forests were protected, and in fact our A1B projections indicate decreases in growing stock in many countries. The A2 projection of 6.3 billion $m^3$ global consumption would instead seem possible without excessively damaging forest ecology, although according to our projections the volume of growing stock would decrease in some countries even under scenario A2.

A similar study (EEA, 2007) has been done for Europe, up to the year 2030. It used the EFI-GTM model (Kallio et al., 2004) to estimate the change in the mix of potential sources of biomass for bioenergy (industrial and harvest residues, imports, competition with other uses) at different prices, taking into consideration available biomass resources and competing demands for wood. Like the present study, EEA (2007) predicted that at high bioenergy prices, wood would be reallocated from competing uses, particularly chemical pulp, to bioenergy. As Europe's wood imports would also rise to meet bioenergy demand this would increase the possibility of illegal logging and unsustainable forest management in some supplying countries.

The validity of the projections presented here depends on three sources of uncertainty. One is the theoretical GFPM structure and its parameters, such as the demand elasticities, input–output coefficients, and forest growth equation parameters. Another is the base-year data describing the current state of the world. The third stems from the exogenous predictions: population and GDP growth rates, regional forest area change, biofuel demand growth from the IPCC scenarios, and other exogenous changes.

The GFPM is calibrated in such a way that its base-year solution, here for 2006, reproduces exactly the observed data. Earlier dynamic tests of prediction errors from 1980 to 2000 show that the model replicates the observed trends, if not the year to year detail. As expected, projections of consumption and production are more accurate than those of trade; and regional projections are more accurate than those for individual countries (Buongiorno et al., 2003; Turner, 2004).

The base-year data used in the GFPM (FAO, 2008a; World Bank, 2008) are inaccurate, but the only internationally comparable data. The goal programming approach of the calibration procedure does correct some of the errors in the forestry production data of the FAOSTAT (Buongiorno et al., 2001; Zhu et al., 2007). Some strong assumptions have been made in the projections. In particular, technical change is reflected only by the increasing use of waste paper in paper and paperboard manufacture, and the possibility of increasing the use of harvest residues has not been considered explicitly. It is also possible that future carbon pricing policies may have effects on forests and forest industries that are not taken into account in the IPCC scenarios or the model.

Perhaps the main source of uncertainty rests in the future world situation stylized by the IPCC scenarios. Scenarios A1B and A2 vary considerably in terms of future population, economic growth, regional forest area change, and biofuel production. Given the current state of knowledge, no definite probability may be assigned to each scenario. Yet they are both plausible outcomes. The results presented here, supplemented by due caution and wisdom should prove useful as a consistent first approximation of the implications of this future worldview for forestry.

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