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Consequences of increasing bioenergy demand on wood and forests: An application of the Global Forest Products Model

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The Global Forest Products Model (GFPM) was applied to project the consequences for the global forest sector of doubling the rate of growth of bioenergy demand relative to a base scenario, other drivers being maintained constant. The results showed that this would lead to the convergence of the price of fuelwood and industrial roundwood, raising the price of industrial roundwood by nearly 30% in 2030. The price of sawnwood and panels would be 15% higher. The price of paper would be 3% higher. Concurrently, the demand for all manufactured wood products would be lower in all countries, but the production would rise in countries with competitive advantage. The global value added in wood processing industries would be 1% lower in 2030. The forest stock would be 2% lower for the world and 4% lower for Asia. These effects varied substantially by country.

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Introduction

This study was part of the 2010 Forest Assessment of the USDA Forest Service, mandated by the Resources Planning Act (RPA). One goal is to fit the national assessment in its global context. Thus, the trade of the United States, and the related demand, supply and prices should be consistent with global developments.

Two of the tools used for the Forest Assessment are the Global Forest Products Model (GFPM, Buongiorno et al., 2003), and the United States Forest Products Module (USFPM, Kramp and Ince, 2010) which has the same structure as the GFPM but a finer description of products and regions within the United States.

The 2010 RPA Forest Assessment uses scenarios of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al., 2000). The IPCC scenarios project global and regional economic activity, population, land uses, and greenhouse gases. Each scenario also projects biofuel demand, which could have serious implications for forests and related industries.

Biomass energy consumption may increase by as much as five to seven times by 2050 (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 tended to ignore this potentially large demand.

Raunikar et al. (2010) did recognize the effects of bioenergy demand on forests in comparing the IPCC scenarios A1B and A2, but since other assumptions are not the same in the two scenarios (in particular, economic and demographic growth are quite different in A1B and A2), one cannot identify the partial effect of bioenergy demand from that study. Other previous studies that have dealt quantitatively with the economics of wood bioenergy supply and demand, and its implications for forests have concerned more national or regional issues. In particular, Stennes et al. (2010) have studied the implications of expanding bioenergy production from wood in British Columbia with a regional wood fiber allocation model, while Bright et al. (2010) made an environmental assessment of wood-based biofuel production and consumption scenarios in Norway, with their implications for the trade of paper products.

This paper attempts to determine, other things being equal, the consequences for the world forest sector and specific countries of a fast acceleration of bioenergy demand. The next part of the paper describes how the GFPM was used for this purpose. The results, consisting of projections to 2030 are then presented for the production, consumption, and prices, of various products, globally and for the main countries. The paper concludes with a discussion of the method and the potential for further developments.

Methods

The GFPM model

The Global Forest Products Model is a spatial dynamic economic model of the forest sector (see Appendix A). The model is dynamic: the equilibrium in a particular year is a function of the equilibrium in the previous year. It assumes that markets work optimally in the short-run (one year) to maximize consumer and producer surplus for all products in all countries (Samuelson, 1952). It further assumes that imperfect foresight prevails over longer time periods so that there is no inter temporal optimization but a recursive dependency of the current equilibrium on the past, along the principles originally proposed by Day (1973), and implemented in the dynamic part of the GFPM as shown in Appendix A. Validation with historical data suggests that this is a plausible approach to model the global forest sector (Buongiorno et al., 2003, pp. 75–88).

The GFPM and several applications are described in detail in Buongiorno et al. (2003). The current version of the model, together with the software, data, and documentation are available at: http://fwe.wisc.edu/facstaff/buongiorno/.

The GFPM 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, trade, and prices, of 14 commodity groups covering fuelwood, industrial roundwood, sawnwood, wood-based panels, pulp, paper and paperboard. For each year the model also predicts the value added by manufacturing wood in all industries.

The estimation of the demand elasticity parameters followed Simangunsong and Buongiorno (2001), and the timber supply parameters were based on Turner et al. (2006), updated with more recent data. Buongiorno et al. (2001), updated and supplemented by Zhu et al. (2009) explain the estimation of the input–output parameters and the corresponding manufacturing cost. The main databases were the FAOSTAT (FAO, 2008a) for production, trade, and price statistics, the FAO global forest resource assessment (FAO, 2006) for forest area, and forest stock, and the World Bank Development Indicators Data Base (World Bank, 2008).

Scenarios

The consequences of increased bioenergy demand were determined by comparing two scenarios that differed only by the future demand for bioenergy. The *high* scenario was the scenario A1B of the IPCC. Scenario A1B is one of the three scenarios selected for the 2010 RPA Forest Assessment (USDA Forest Service, 2008). It reflects a particular "storyline" about the direction of global social, economic, technical and policy developments, and interaction between developing and industrialized countries. We used scenario A1B because it assumes a high level of future bioenergy demand, and thus could reveal the effect of such a strong policy compared to a more moderate level of future demand.

The scenario A1B assumes continuing globalization, with high income growth and low population growth. Furthermore, scenario A1B projects a very rapid growth of bioenergy demand. From 2006 to 2030 the global consumption of biofuel would increase by approximately 80%.

In contrast, the alternative *low* scenario assumed that the global demand of biofuel would rise approximately 20% from 2006 to 2030. Meanwhile, the same assumptions were made as for the *high* scenario concerning the other drivers. Thus, comparison of the *low* and *high* scenario showed the partial effect of increased bioenergy demand, other things being equal.

For the GFPM simulations, the three same exogenous variables for both scenarios were the growth of GDP and population, change in forest area, and the growth of fuelwood demand. National GDP growth was deducted from the regional growth so that the regional growth was the same as in the IPCC scenario A1B and the growth of individual countries converged towards this average regional growth rate.

The national growth rates of forest area projected from the environmental Kuznet's curve (Eq. (15) in Appendix A) were adjusted so that the regional area change would match that of the IPCC regional projections for scenario, as shown in Appendix A.

For the *high* scenario, the demand for fuelwood was shifted at national rates that led to the same global growth as that of world bioenergy demand in the A1B scenario, an 80% increase from 2006 to 2030, while assuming that the ratio of fuelwood consumption to GDP would converge over time. For the *low* scenario, the demand for fuelwood shifted in all countries at half the annual rate of the growth in the *high* scenario, leading to a 20% increase in fuelwood demand from 2006 to 2030.

Given these assumptions, the quantity-price equilibrium in each country, and the corresponding trade, were computed by the GFPM. As formulated, the model allowed transformation of part of the industrial roundwood (i.e. wood used in the past to make sawnwood, panels, and pulp) into fuelwood, when the price of fuelwood reached the price of industrial roundwood.

Results

Projected fuelwood consumption

Fig. 1 shows the growth of fuelwood consumption, by main world region, from 2006 to 2030, according to the *low* and *high* fuelwood demand. In accord with FAO's definition, fuelwood includes wood used for heating, cooking, and power production (FAO, 2008b). In the *low* projections, while the global fuelwood consumption would increase by approximately 20% from 2006 to 2030, it would increase by almost 60% in Europe and North America, 30% in Asia, and 20% in South America. The projected slight decline of fuelwood consumption in Africa was due to the assumption of fast economic

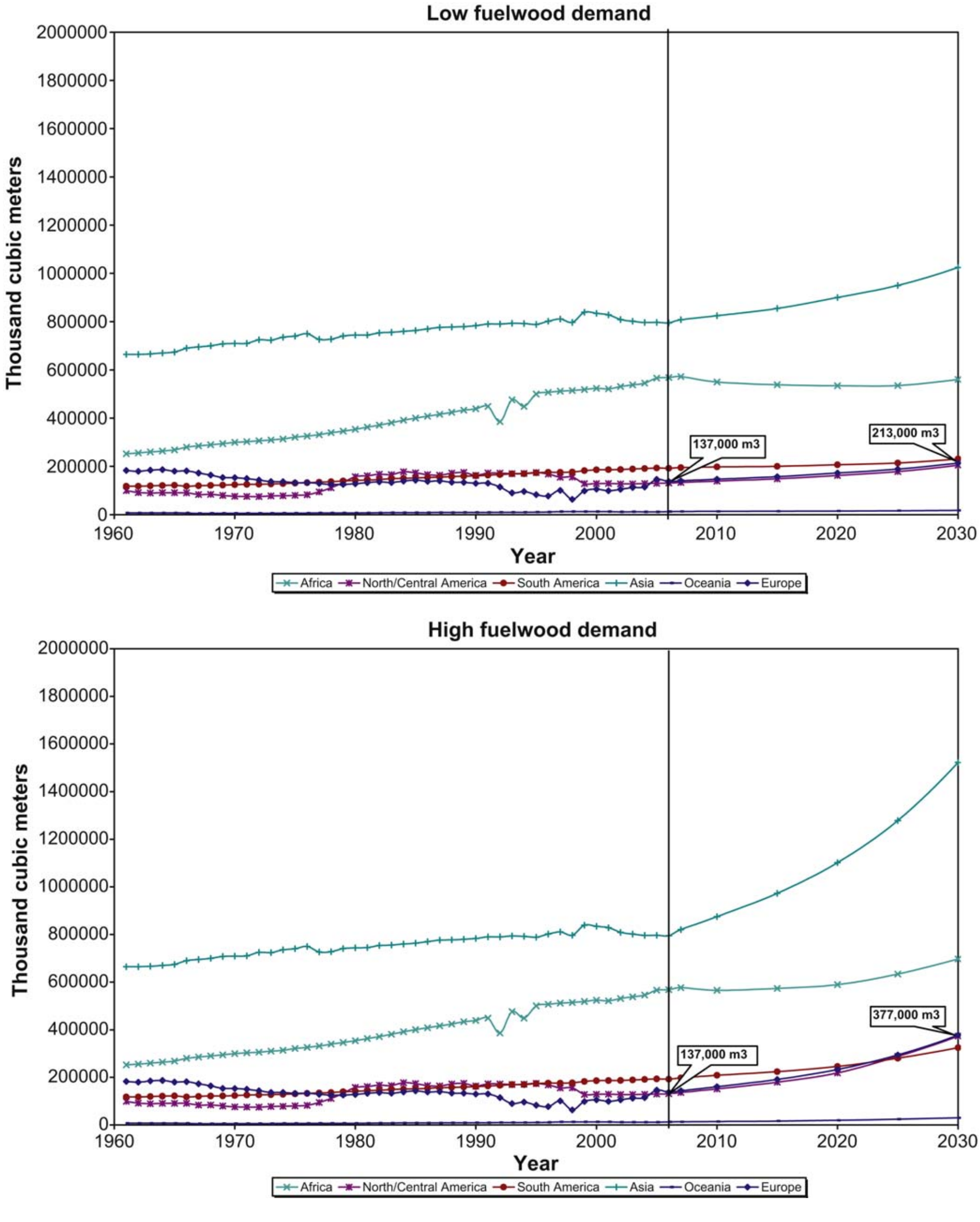

Fig. 1. Projected fuelwood demand with low and high scenario.

growth and moderate demographic growth embedded in IPCC scenario A1B, which led to substitution of fuelwood by other fuels especially in household usage.

The trends were quite different with the *high* fuelwood demand scenario. While, in agreement with the IPCC scenario A1B, the world fuelwood consumption would increase by 80% from 2006 to 2030, there would be an even stronger increase of fuelwood consumption in Europe and North America, approximately 180% from 2006 to 2030. In South America fuelwood consumption would rise by approximately 70% during the same period, and in Africa by 20%.

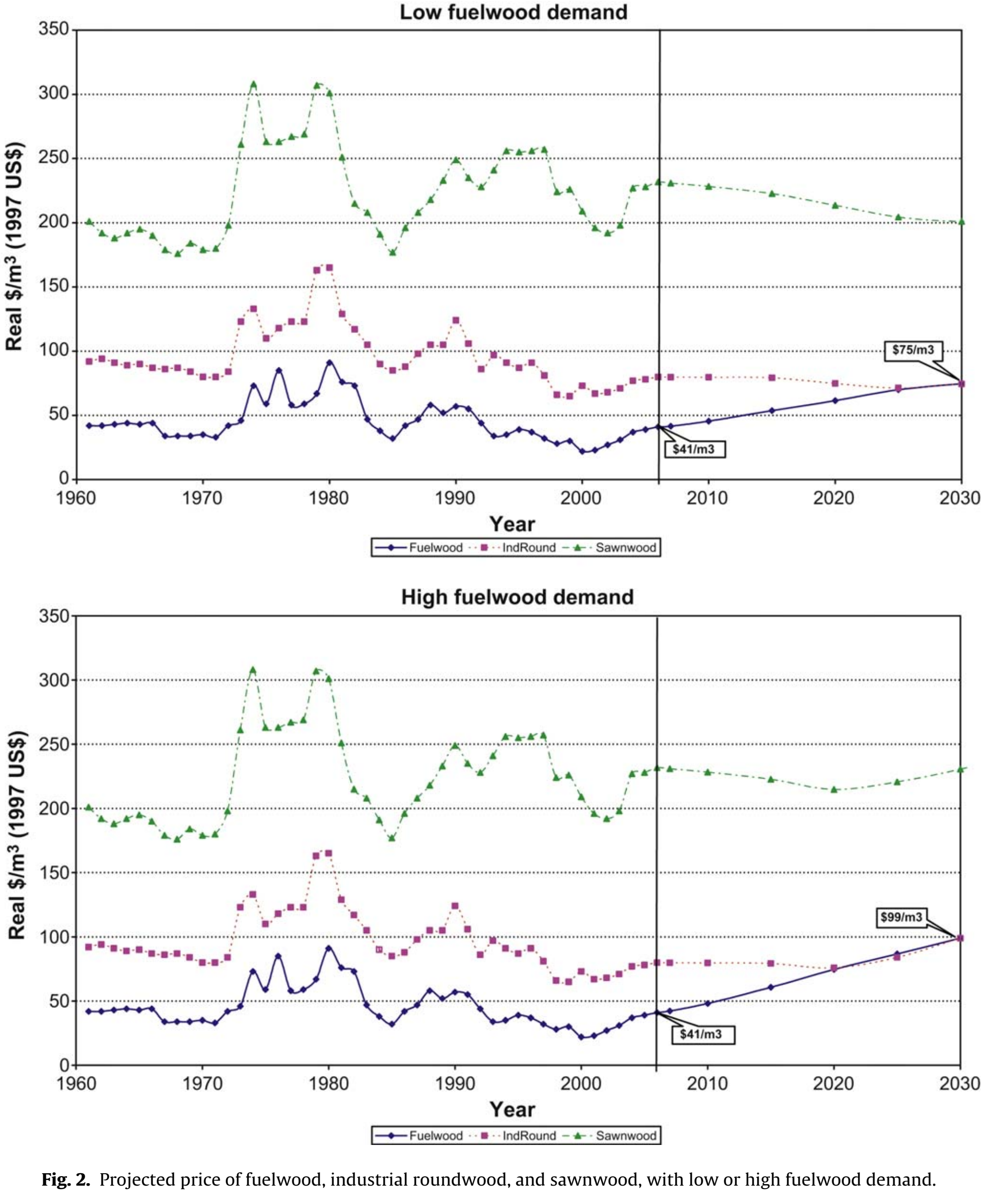

Fig. 2. Projected price of fuelwood, industrial roundwood, and sawnwood, with low or high fuelwood demand.

Projected wood prices

Assuming a *low* future fuelwood demand from 2006 to 2030 the world price of industrial roundwood (wood used in making sawnwood, pulp, and panels) would remain roughly constant (Fig. 2). Meanwhile, in concert with the 20% increase of fuelwood demand, the price of fuelwood would nearly double, approaching the price of industrial roundwood by 2025.

Under the *high* fuelwood demand scenario the price of fuelwood would converge with the price of industrial roundwood, at 75 US$/$m^3$ (in US$ of 1997 purchasing power) by about 2025. Subsequently the price of fuelwood and industrial roundwood would rise in concert to approximately \$100/m^3

by 2030. The price of sawnwood would approximately follow the trend of the price of industrial roundwood, as it has in the past since roundwood is the main cost of sawnwood production.

The remainder of the paper focuses on the consequences of a rise in fuelwood demand, other things being equal. Thus, the following results present the effects of the change in fuelwood demand between the *low* and the *high* scenario, i.e. a doubling of the rate of growth of demand, with all the other driving variables changing as in the A1B scenario.

Consequences for wood raw material

In Table 1 and the following tables, the price and production effects of doubling the rate of growth of fuelwood demand are shown in absolute value and in percent. Caution must be exerted in interpreting the percentage changes of production as the very large differences in production make relative changes ineffective for comparing some countries. The selected countries had the largest economies, measured by gross domestic product, in each region.

Table 1
Consequences for roundwood price and production in 2030 by region and selected countries.

	Effects on							
	Fuelwood				Industrial roundwood[a]			
	Price $/m³		Production Million m³		Price $/m³		Production Million m³	
Africa			108.1	24%			−4.7	−10%
Egypt	24	29%	0.0	0%	25	27%	0.0	3%
Nigeria	24	29%	−2.5	−8%	30	22%	−0.5	−11%
South Africa	24	29%	2.1	15%	11	11%	−0.2	−1%
North/Central America			286.3	92%			−28.4	−5%
Canada	19	23%	19.0	329%	18	23%	20.4	12%
Mexico	29	39%	18.8	31%	25	26%	1.0	19%
United States of America	24	33%	236.6	121%	24	33%	−50.0	−13%
South America			191.7	43%			11.0	5%
Argentina	24	33%	10.0	85%	24	32%	−2.6	−21%
Brazil	24	33%	123.9	38%	23	31%	18.7	14%
Chile	24	33%	33.5	78%	24	33%	−5.8	−11%
Asia			146.4	21%			17.8	8%
China	31	36%	80.3	27%	21	23%	10.2	11%
India	24	29%	−21.1	−29%	24	27%	−0.9	−30%
Indonesia	24	29%	15.3	19%	21	22%	3.0	15%
Japan	18	23%	4.9	681%	19	23%	4.6	11%
Korea, Republic of	24	33%	4.8	30%	24	27%	2.7	23%
Malaysia	24	33%	13.0	51%	24	32%	−0.7	−5%
Oceania			25.4	113%			−7.1	−17%
Australia	24	33%	11.3	108%	24	33%	−1.2	−6%
New Zealand	24	33%	8.2	364%	20	29%	−3.7	−21%
Europe			315.0	95%			−39.7	−6%
EU-25			216.6	122%			119.0	26%
Austria	24	33%	2.6	31%	23	29%	4.4	28%
Finland	24	33%	3.3	32%	18	22%	11.6	21%
France	24	33%	34.1	57%	24	33%	−7.7	−20%
Germany	24	33%	55.5	334%	25	34%	−26.4	−34%
Italy	33	45%	6.6	43%	24	28%	1.3	22%
Russian Federation	24	33%	49.1	57%	20	27%	16.9	13%
Spain	24	33%	4.1	64%	19	24%	2.4	12%
Sweden	24	33%	3.4	32%	17	19%	15.2	18%
United Kingdom	33	45%	1.6	193%	25	31%	2.3	19%
Developed, all			599	107%			−71	−5%
Developing, all			474	28%			20	5%
World	24	33%	1073	48%	24	33%	−51	−3%

[a] Excluding energy wood.

According to Table 1, doubling the rate of growth of fuelwood demand would raise the world price of fuelwood by 24 \$/m^3, or 33% by 2030, and by 23–45% depending on the country. Fuelwood production would increase the most in absolute value in the United States, Brazil, and China. World fuelwood production would increase by about 1 billion m^3, or nearly 50%, with 60% of this growth taking place in developed countries.

Doubling the rate of growth of fuelwood demand would also increase the world price of industrial roundwood by 33% in 2030, and by 11–30% for the selected countries in Table 1. The global production of industrial roundwood, excluding the energy wood which is counted in the fuelwood category, would decrease by about 51 million m^3, or 3%, reflecting the reallocation of some industrial roundwood to energy production. In contrast with fuelwood, 75% of the increase in industrial roundwood production would be in developed countries. The decrease would occur mostly in the group of developed countries, while industrial roundwood production would be 5% higher in developing countries.

Consequences for sawnwood

Doubling the rate of growth of fuelwood demand from 2006 to 2030 resulted in an increase of 15% of the world price of sawnwood (an aggregate of coniferous and non-coniferous sawnwood) in 2030. The price increase would vary from 8% to 26% for the selected countries in Table 2.

Meanwhile, global production and consumption were almost 6 million m^3 lower in 2030, 1% lower than the level obtained with the *low* scenario. Approximately 2/3 of the decrease in consumption was in developed countries. Due to the higher price of sawnwood, consumption would be lower in all countries. In contrast, while production would be lower in some countries, such as the United States and the Russian Federation, it would be higher in others, in particular Canada and China, revealing a competitive advantage in sawmilling.

In the United States, sawnwood production would decrease much more than consumption, indicating a decrease in net trade. Meanwhile the Canadian production would rise by nearly 10 million m^3 per year, while consumption would hardly change, suggesting an improvement in net trade, presumably due to increased exports to the United States. In a few countries, such as Brazil, India, France, and Germany, the trade balance would remain unchanged, as the decrease in production would match the decrease in consumption.

Consequences for wood-based panels

The GFPM recognizes explicitly three groups of wood-based panels: Veneer and plywood, fiberboard, and particleboard. For example, Table 3 shows the impact on particleboard markets of doubling the rate of growth of fuelwood demand from 2006 to 2030.

The result was a 14% increase in the world price of particleboard in 2030, ranging from 8% to 17% for the countries in Table 3. The corresponding world production and consumption were 5 million m^3, or 3%, lower in 2030. Most of the decline in production was in developed countries.

Due to the higher price, particleboard consumption decreased in all countries. But a competitive advantage was apparent in a few countries. For example, in Canada, the Republic of Korea and Italy production increased, while domestic consumption decreased, indicating an improvement in net trade. In the United States instead, the decrease in production was approximately four times the decrease in consumption, indicating a serious degradation of the trade balance. For China, Russia, Germany, Brazil, and France, there was no effect on net trade as the decrease in production matched the decrease in consumption.

Consequences for pulp and paper

The pulp and paper industry and its market are described in the GFPM with two intermediate products manufactured from industrial roundwood: mechanical pulp, and chemical pulp; three end products made with this pulp: newsprint, printing and writing paper, and paper and paperboard; one recycled product: post-consumer waste paper; and one other-fiber pulp.

Table 2
Consequences for sawnwood by region and selected countries.

	Effects on					
	Price $/m^3$		Production 1000 m^3		Consumption 1000 m^3	
Africa			−1029	−7%	−269	−2%
Egypt	50	26%	−47	−3%	−47	−2%
Nigeria	56	25%	−62	−2%	−62	−2%
South Africa	25	10%	−42	−2%	−31	−1%
North/Central America			−15,761	−9%	−2161	−1%
Canada	26	13%	9518	26%	−267	−1%
Mexico	35	15%	−1282	−40%	−108	−1%
United States of America	31	14%	−23,973	−19%	−1749	−1%
South America			−623	−2%	−587	−2%
Argentina	36	17%	−29	−2%	−29	−2%
Brazil	37	17%	−404	−2%	−404	−2%
Chile	37	18%	−107	−1%	−104	−2%
Asia			7909	8%	−1240	−1%
China	26	11%	7048	28%	−388	−1%
India	32	12%	−231	−1%	−231	−1%
Indonesia	24	10%	−37	−1%	−37	−1%
Japan	19	8%	300	2%	−165	−1%
Korea, Republic of	25	10%	92	2%	−61	−1%
Malaysia	24	11%	−45	−1%	−45	−1%
Oceania			−265	−3%	−128	−1%
Australia	41	18%	−223	−4%	−91	−2%
New Zealand	24	12%	−29	−1%	−29	−1%
Europe			3806	2%	−1577	−1%
EU-25			4383	4%	−1270	−1%
Austria	25	12%	1115	16%	−59	−1%
Finland	24	11%	1779	24%	−58	−1%
France	26	12%	−138	−1%	−138	−1%
Germany	24	12%	−213	−1%	−213	−1%
Italy	30	13%	1052	95%	−111	−1%
Russian Federation	40	19%	−1964	−12%	−168	−2%
Spain	18	8%	699	16%	−54	−1%
Sweden	30	15%	−1804	−4%	−83	−1%
United Kingdom	29	13%	2246	56%	−133	−1%
Developed, all			−10,705	−3%	−3942	−1%
Developing, all			4743	3%	−2020	−1%
World	30	15%	−5962	−1%	−5962	−1%

As expected, the magnitude of the effects of higher fuelwood demand diminished with increased levels of processing. An example of this, for printing and writing paper, is in Table 4. Doubling the rate of growth of fuelwood demand from 2006 to 2030 raised the world price of printing and writing paper by 3% in 2030, and the price in individual countries by 2–6%. This was much less than the 33% increase of the world price of industrial roundwood (see Table 1), and still less than the 12% increase of the world price of wood pulp.

The higher price of printing and writing paper led to a decrease in consumption in all countries (Table 4), and a decrease of about 2 million metric tonnes (1%) in world consumption, 80% of it occurring in developed countries. The changes in production and consumption for individual countries revealed strong differences in comparative advantage. While the decline in production in the United States, China, Japan, France, and Brazil matched that of consumption, leaving net trade unchanged, the production in Sweden and Germany would decrease much more than domestic consumption, with a deterioration of the trade balance. Meanwhile Canada and Finland increased production, added to their small decrease in domestic consumption meant a large increase in net trade of printing and writing paper.

Table 3
Consequences for particleboard by region and selected countries.

	Effects on					
	Price		Production		Consumption	
	$/m³		1000 m³	Dif%	1000 m³	
Africa			−46	−3%	−67	−3%
Egypt	48	17%	−2	−5%	−2	−5%
Nigeria	56	17%	−5	−5%	−5	−5%
South Africa	24	8%	−19	−3%	−19	−2%
North/Central America			−3708	−8%	−1711	−4%
Canada	26	12%	2837	23%	−115	−3%
Mexico	32	13%	−12	−46%	−15	−3%
United States of America	36	16%	−6529	−18%	−1573	−4%
South America			−326	−5%	−275	−4%
Argentina	34	15%	−27	−4%	−27	−4%
Brazil	36	15%	−158	−4%	−158	−4%
Chile	39	18%	−84	−9%	−35	−5%
Asia			21	0%	−841	−3%
China	24	9%	−436	−3%	−437	−3%
India	29	10%	−7	−3%	−6	−3%
Indonesia	23	9%	−14	−3%	−13	−3%
Japan	17	7%	133	11%	−35	−2%
Korea, Republic of	32	13%	393	68%	−96	−3%
Malaysia	24	11%	−12	−5%	−1	−4%
Oceania			−83	−6%	−73	−5%
Australia	45	20%	−78	−6%	−67	−5%
New Zealand	24	11%	−5	−2%	−5	−3%
Europe			−897	−2%	−2072	−3%
EU-25			−449	−1%	−1588	−4%
Austria	24	11%	241	16%	−29	−3%
Finland	24	11%	41	12%	−8	−3%
France	32	14%	−142	−3%	−142	−4%
Germany	24	11%	−285	−3%	−285	−3%
Italy	27	11%	780	27%	−118	−3%
Russian Federation	35	14%	−303	−4%	−303	−4%
Spain	19	8%	−110	−3%	−85	−2%
Sweden	29	12%	−26	−3%	−26	−3%
United Kingdom	29	12%	253	8%	−131	−3%
Developed, all			−4593	−4%	−3952	−4%
Developing, all			−445	−1%	−1087	−3%
World	30	14%	−5038	−3%	−5039	−3%

Consequences for value added

A standard output of the GFPM is the value added by manufacturing. This is the value of all the output minus the cost of the input. In the sawnwood, panels, and pulp sectors it is the value of sawnwood and panels minus the cost of the industrial roundwood used in making them. In the paper sector, the value added is the value of newsprint, printing and writing paper, and other paper and paperboard, minus the cost of wood pulp, recycled paper, and other fiber input.

In this application, no transformation of the fuelwood, harvested in the forest or obtained from industry residues, was considered. Therefore, the change in value added was only the change occurring in traditional forest industries (sawnwood, panels, pulp, and paper and paperboard).

Table 5 shows that, was the rate of growth of fuelwood demand to double from 2006 to 2030, the global value added in traditional industries would decrease by some $3.7 billion, or about 1%, in constant $US of 1997 purchasing power. Most of the decrease would be in developed countries. The largest absolute decrease of value added would occur in the United States, Brazil, and Sweden. However, other countries would gain, in particular Canada, Finland, China, and the Republic of Korea. In several countries the increase in fuelwood demand would have relatively little effect on value added.

Table 4
Consequences for printing and writing paper by region and selected countries.

	Effects on					
	Price $/m³		Production 1000 tonnes		Consumption 1000 tonnes	
Africa			−46	−3%	−35	−1%
Egypt	28	3%	−21	−20%	−8	−1%
Nigeria	28	3%	−2	−60%	−4	−1%
South Africa	15	2%	−7	−1%	−7	−1%
North/Central America			−246	−1%	−636	−2%
Canada	25	3%	329	4%	−50	−1%
Mexico	23	3%	−33	−3%	−33	−1%
United States of America	41	5%	−546	−2%	−546	−2%
South America			−113	−2%	−112	−2%
Argentina	33	4%	−17	−1%	−17	−1%
Brazil	42	6%	−71	−2%	−71	−2%
Chile	25	3%	0		−3	−1%
Asia			−407	−1%	−627	−1%
China	19	2%	−324	−1%	−324	−1%
India	21	2%	148	4%	−35	−1%
Indonesia	33	4%	−20	−1%	−19	−2%
Japan	15	2%	−94	−1%	−94	−1%
Korea, Republic of	28	4%	−27	−1%	−28	−1%
Malaysia	25	3%	−30	−12%	−32	−1%
Oceania			−43	−2%	−47	−2%
Australia	44	6%	−43	−2%	−43	−2%
New Zealand	25	3%	0		−4	−1%
Europe			−1182	−2%	−580	−1%
EU-25			−1287	−2%	−515	−1%
Austria	25	3%	8	0%	−7	−1%
Finland	25	3%	333	2%	−7	−1%
France	31	4%	−88	−1%	−88	−1%
Germany	25	3%	−220	−2%	−110	−1%
Italy	23	3%	−50	−1%	−50	−1%
Russian Federation	38	5%	−24	−2%	−24	−2%
Spain	23	3%	−32	−1%	−33	−1%
Sweden	25	3%	−641	−15%	−1	−1%
United Kingdom	25	3%	−117	−3%	−79	−1%
Developed, all			−1552	−1%	−1333	−1%
Developing, all			−486	−1%	−704	−1%
World	25	3%	−2037	−1%	−2037	−1%

Consequences for forest stock

As the GFPM predicts changes in forest area based on income per capita, according to a Kuznet's curve, the predictions of forest area were the same in the *low* and *high* fuelwood demand scenarios. However, forest stock did change due to the different harvest rates and the growth response implied by the two scenarios.

As expected, doubling the rate of growth of fuelwood demand from 2006 to 2030 relative to the *low* scenario would have a negative impact on forest stock in all countries (Table 5). Globally, forest stock would be 7.6 billion m^3 (2%) lower in 2030. 70% of the impact would be on forests in developing countries. The forest stock reduction would be especially large in absolute value in Brazil, China, and the United States. In relative terms, the effect would be the highest in Nigeria and India, and it would also be substantial in Indonesia and in South Africa.

Summary and discussion

The Global Forest Products Model was applied to project the consequences for the global forest sector of a large increase in the demand for wood energy. Two scenarios were compared according

Table 5
Consequences for value added and forest stock by region and selected countries.

	Consequences for			
	Value added Million $		Forest stock Million m^3	
Africa	−128	−2%	−1319	−2%
Egypt	8	2%	0	
Nigeria	−25	−20%	−129	−35%
South Africa	−12	−1%	−56	−14%
North/Central America	−4208	−4%	−1157	−1%
Canada	1792	7%	−110	0%
Mexico	−262	−5%	−175	−6%
United States of America	−5763	−7%	−721	−2%
South America	−1543	−8%	−1228	−1%
Argentina	−126	−5%	−38	−2%
Brazil	−1254	−10%	−864	−1%
Chile	−167	−6%	−132	−4%
Asia	2532	2%	−2531	−6%
China	480	1%	−1059	−9%
India	67	1%	−477	−50%
Indonesia	−52	−1%	−282	−10%
Japan	1001	4%	−27	0%
Korea, Republic of	548	7%	−34	−2%
Malaysia	−21	−1%	−41	−1%
Oceania	−136	−3%	−88	−1%
Australia	−159	−5%	−42	0%
New Zealand	24	1%	−17	−2%
Europe	−252	0%	−1279	−1%
EU-25	−202	0%	−755	−3%
Austria	285	7%	−26	−2%
Finland	229	2%	−45	−2%
France	−140	−1%	−203	−6%
Germany	715	4%	−112	−3%
Italy	341	5%	−50	−2%
Russian Federation	−300	−3%	−334	0%
Spain	154	2%	−23	−2%
Sweden	−1697	−17%	−87	−2%
United Kingdom	364	5%	−11	−2%
Developed, all	−3374	−1%	−2257	−1%
Developing, all	−362	0%	−5345	−2%
World	−3735	−1%	−7601	−2%

to which a *high* scenario doubled the annual growth rate of demand of fuelwood relative to the *low* scenario. Other shifters, such as income and population were kept the same in the two scenarios.

The partial effect of doubling the growth rate of fuelwood demand was to cause the world price of fuelwood and industrial roundwood to converge. The price of industrial roundwood would be approximately 30% higher in 2030. The price of sawnwood and panels increased by nearly 15%, and the price of paper increased by 3%. The global value added in wood processing industries was 1% lower. The global forest stock decreased by 2%. The projected effects varied substantially by country. While consumption of end products would decrease in all countries, production could rise in some countries.

These findings agree with the EEA (2007), which found with the EFI-GTM model (Kallio et al., 2004) that at high bioenergy prices, wood would be reallocated from other uses, especially chemical pulp, to energy.

The projections presented here depend critically on the theoretical GFPM structure and on its parameters. The influence of errors in the exogenous drivers, such as GDP and population projections was minimized by keeping them the same in the two scenarios and concentrating on the changes between the *low* and *high* scenarios.

Potential improvements of the model include, by order of importance, first recognition of the effect of rising wood prices on investments in forestry and land allocation. Second, the development of a theory and empirical representation of trade to replace the trade inertia constraints which currently limit periodic variations in trade to be similar to those observed historically (Eqs. (6) and (24)). Third, distinguish between hardwoods and softwoods, and between logs and pulpwood. However, in planning such improvements, one should keep in mind the limitation of the data and that simplicity is generally preferable for model use, transparency, and application to illusive precision.

Furthermore, although the model projected the consequence of a rise in fuelwood demand on the forestry stock it did not, and cannot yet, describe the structure of this stock, i.e. the size, species, and age of the trees that make it up. Yet, history tells of drastic changes during the industrial revolution when the demand for fuel and charcoal for salt and iron production led to extensive coppice forests (Badré, 1992; Degron, 1995). A similar expansion of mono-specific short-rotation plantations must be expected if the highest fuelwood demand considered here were realized. This would have serious consequences for the ecological and aesthetic values of forests, which must be considered in addition to the data presented here, in any serious policy debate on the future role of forests as fonts of bioenergy.

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Appendix A.

The GFPM calculates every year a global equilibrium across countries and products, linked dynamically to past equilibriums.

Spatial global equilibrium

Objective function

The consumer and producer surplus in a given year, for all countries and products (Samuelson, 1952):

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

where i,j = country, k = product, P = price in US dollars of constant value, D = final product demand, S = raw material supply, Y = quantity manufactured, m = manufacturing cost, T = quantity transported, and c = cost of transportation, including tariff. All variables refer to a specific year. In making predictions, the period between successive equilibria may be multiple years.

End product demand

$$D_{ik} = D_{ik}^{*} \left(\frac{P_{ik}}{P_{ik,-1}} \right)^{\delta_{ik}} \quad (2)$$

where D^* = current demand at last period's price, P_{-1} = last period's price, and δ = price elasticity of demand.

As shown in the section on market dynamics, below, D^* depends on last period's demand, and the growth of GDP in the country. In the base year, D^* is equal to the observed base-year consumption, and P_{-1} is equal to the observed base-year price.

Eqs. (2), (3) and (7) below are approximated by the tangent at the at the point of coordinates D^* and P_{-1}. Thus, Eq. (1) is of second degree and the entire equilibrium problem has a quadratic objective function and linear constraints.

Primary product supply

$$S_{ik} = S^*_{ik}\left(\frac{P_{ik}}{P_{ik,-1}}\right)^{\lambda_{ik}} \tag{3}$$

where S^* = current supply at last period's price and λ = price elasticity of supply. As shown in the section on market dynamics, below, S^* depends on the last period's supply and on exogenous or endogenous supply shifters. In the base year, S^* is equal to the base-year supply, and P_{-1} is equal to the observed base year price.

Total wood supply

$$S_i = S_{i,r} + S_{in} + \theta_i S_{if} \tag{4}$$

r = industrial roundwood, n = other industrial roundwood, f = fuelwood, θ = fraction of fuelwood that comes from the forest.

$$S_i \le I_i$$

I_i = forest stock.

Material balance

$$\sum_j T_{jik} + S_{ik} + Y_{ik} - D_{ik} - \sum_n a_{ikn} Y_{in} - \sum_j T_{ijk} \quad = 0 \quad \forall i, k \tag{5}$$

where a_{ikn} = input of product k per unit of product n.

In addition, by-products, which result from the production of a manufactured commodity satisfy the constraint:

$$Y_{il} - b_{ikl} Y_{ik} = 0 \quad \forall i, k, l$$

where b_{ikl} is the amount of by-product l that can be recovered per unit of production of manufactured commodity k.

Trade inertia

$$T^L_{ijk} \le T_{ijk} \le T^U_{ijk} \tag{6}$$

where the superscripts L and U refer to a lower bound, and upper bound, respectively.

Prices

The shadow prices of the material balance constraints (5) give the market-clearing prices for each commodity and country.

Manufacturing cost

Manufacturing is represented by activity analysis, with input–output coefficients and a manufacturing cost. The manufacturing cost is the marginal cost of the inputs not recognized explicitly by the model (labor, energy, capital, etc.);

$$m = m^*_{ik}\left(\frac{Y_{ik}}{Y_{ik,-1}}\right)^{s_{ik}} \tag{7}$$

where m^* = current manufacturing cost, at last period's output and s = elasticity of manufacturing cost with respect to output.

As shown in the next section, m^* depends on the last period's quantity manufactured and on the exogenous rate of change of manufacturing cost. In the base year, m^* is equal to the observed base-year manufacturing cost and $Y_{ik,-1}$ is equal to the observed base-year quantity manufactured.

Transport cost

The transport cost for commodity k from country i to country j in any given year is:

$$c_{ijk} = f_{ijk} + t^{I}_{jk}(f_{ijk} + P_{ik,-1}) \tag{8}$$

where c = international transport cost,[1] per unit of volume, f = freight cost, per unit of volume, t^I = import ad-valorem tariff, and P_{-1} = last period's equilibrium export price computed endogenously by the model. In the base year, P_{-1} is equal to the observed base-year price.

Market dynamics[2]

All periodic exponential rates of change, r_p, are defined by the annual exponential rate of change, r_a, as:

$$r_p = (1 + r_a)^p - 1 \tag{9}$$

where p is the length of a period, in years.

All periodic linear changes, Δv_p are defined by the corresponding annual linear change, Δv_a, as:

$$\Delta v_p = p \Delta v_a \tag{10}$$

Shifts of demand

$$D^* = D_{-1}(1 + \alpha_y g_y) \tag{11}$$

g_y = GDP periodic growth rate, α = elasticity.

Shifts of supply

For industrial roundwood and fuelwood:

$$S^* = S_{-1}(1 + \beta_I g_I + \beta_{y'} g_{y'}) \quad \text{for}\, k = r, n, f \tag{12}$$

where g_I = periodic rate of change of forest stock (endogenous, see below), $g_{y'}$ = periodic rate of change of GDP per capita, and β = elasticity.

For waste paper and other fiber pulp:

$$S^* = S_{-1}(1 + \beta_y g_y) \tag{13}$$

Changes in forest area and forest stock

$$A = (1 + g_a)A_{-1} \tag{14}$$

where A = forest area, and g_a = periodic rate of forest area change based on the period length, p, Eq. (9) and the annual rate of forest area change, g_{aa}, defined by an environmental Kuznet's curve (Turner et al., 2006):

$$g_{aa} = \alpha_0 + \alpha_1 y' + \alpha_2 y'^2 \qquad \text{for}\, y' \Leftarrow y'^*, \quad \text{else}\, g_{aa} = 0 \tag{15}$$

where for each country, α_0 is calibrated so that in the base year the observed g_{aa} is equal to the g_{aa} projected with (15) given the income per capita y'.

y' = income per capita, projected from:

$$y' = (1 + g_{y'})y'_{-1} \tag{16}$$

y'^* is defined by

$$g_{aa} = \alpha_0 + \alpha_1 y'^* + \alpha_2 y'^{*2} = 0 \quad \text{and} \quad y'^* > \frac{-\alpha_1}{2\alpha_2} \tag{17}$$

[1] Domestic transport cost is reflected by the supply Eq. (3) and the manufacturing cost (7).

[2] Unless otherwise indicated, variables refer to one country, one commodity, and one year. Rates of change refer to a multi-year period.

Forest stock evolves over time according to a growth-drain equation:

$$I = I_{-1} + G_{-1} - pS_{-1} \tag{18}$$

where $G = (g_a + g_u + g_u^*)I$ is the periodic change of forest stock without harvest, g_u = periodic rate of forest growth on a given area, without harvest, and $g_u{}^*$ = adjustment of periodic rate of forest growth on a given area, without harvest. The last is exogenous, for example to represent the effect of invasive species, or of climate change.

The periodic rate of forest growth, g_u, is based on the annual rate of forest growth, g_{ua}, defined by:

$$g_{ua} = \gamma_0 \left(\frac{I}{A}\right)^{\sigma} \tag{19}$$

where σ is negative, so that g_{ua} decreases with stock per unit area. For each country, γ_0 is calibrated so that in the base year the observed g_{ua} is equal to the g_{ua} predicted by (19) given the stock per unit area, I/A.

The periodic rate of change of forest stock net of harvest, used in Eq. (12) is then:

$$g_I = \frac{I - I_{-1}}{I_{-1}} \tag{20}$$

Changes in manufacturing coefficients and costs

The input–output coefficients a in Eq. (5), may change exogenously over time, for example to reflect increasing use of recycled paper in paper manufacturing:

$$a = a_{-1} + \Delta a \tag{21}$$

where Δa = periodic change in input–output coefficient.

The manufacturing cost function shifts exogenously over time:

$$m^* = m_{-1}(1 + g_m) \tag{22}$$

where g_m = the exogenous rate of periodic change in manufacturing cost.

Changes in freight cost and tariff

The freight cost and the import tariffs in Eq. (8) may change exogenously over time:

$$f = f_{-1} + \Delta f, \quad t = t_{-1} + \Delta t \tag{23}$$

where Δf and Δt are periodic changes in freight cost and tariff, respectively.

Changes in trade inertia bounds

$$\begin{aligned} T^L &= T_{-1}(1 - \varepsilon)^p \\ T^U &= T_{-1}(1 - \varepsilon)^p \end{aligned} \tag{24}$$

ε = absolute value of maximum annual relative change in trade flow (exogenous, based on historical data).

Linear approximation of demand, supply, manufacturing cost

For example, consider a demand equation such as (2). Omitting the subscripts for region and product, the inverse demand equation in any given year is:

$$P = P_{-1}\left(\frac{D}{D^*}\right)^{1/\sigma}$$

The linear approximation is:

$$P = a + bD \quad \text{with} \quad a = P_{-1} - bD^* \quad \text{and} \quad b = \frac{P_{-1}}{\sigma D^*} \qquad \text{for } D^* > 1, \quad \text{else } b = \frac{P_{-1}}{\sigma} \tag{25}$$

$b = 0$ if $\sigma = 0$. The same method is used for the supply, and the manufacturing cost equations.

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