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Modeling some long-term implications of CO_2 fertilization for global forests and forest industries

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Abstract

Background: This paper explored the long-term, ceteris-paribus effects of potential CO_2 fertilization on the global forest sector. Based on the findings of Norby et al. (PNAS 2005, 102(50)) about forest response to elevated [CO_2].

Methods: Forest productivity was increased in the Global Forest Products Model (GFPM) in proportion to the rising [CO_2] projected in the IPCC scenario A1B, A2, and B2.
Projections of the forest area and forest stock and of the production, consumption, prices, and trade of products ranging from fuelwood to paper and paperboard were obtained with the GFPM for each scenario, with and without CO_2 fertilization beginning in 2011 and up to 2065.

Results: CO2 fertilization increased wood supply, leading to lower wood prices which in turn induced modest lower prices of end products and higher global consumption. However, production and value added in industries decreased in some regions due to the relative competitive advantages and to the varying regional effects of CO_2 fertilization.

Conclusion: The main effect of CO_2 fertilization was to raise the level of the world forest stock in 2065 by 9 to 10 % for scenarios A2 and B2 and by 20 % for scenario A1B. The rise in forest stock induced by fertilization was in part counteracted by its stimulation of the wood supply which resulted in lower wood prices and increased harvests.

Keywords: CO_2 fertilization, Climate change, Prices, Supply, Demand, International trade

Background

The CO_2 content of the atmosphere has been rising steadily, from a global average of approximately 340 ppm (parts per million) in 1980 to 400 ppm in 2013 (NOAA-ESRL 2015). The [CO_2] is expected to increase faster in the next century. According to the International Panel on Climate Change, atmospheric [CO_2] could reach 600 to 900 ppm in 2100, depending on varying scenarios concerning economic and demographic growth, and mitigation policies (IPCC 2013). This rise in [CO_2] has consequences for climate change as it influences directly global temperature levels (IPCC 2012, Zickfeld et al. 2012). In this context, forests are a potential source of CO_2 emissions especially due to deforestation (Woodwell et al. 1983).

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On the other hand, forests also act as carbon sinks accumulating carbon in trees through photosynthesis. This later role means that forests can be part of a negative feedback working against atmospheric CO_2 accumulation. In this process, net primary productivity (NPP) can be stimulated by the increase in atmospheric CO_2. This phenomenon, referred to as "CO_2 fertilization", has been incorporated into vegetation models to predict its consequences for climate change and carbon dynamics (Thompson et al. 2004). Another consequence of CO_2 fertilization is its impact on forest stock and thus on wood supply and forest industries which is addressed in this study.

The general issue of climate change and forestry has received wide attention (see Kirilenko and Sedjo 2007 for a review). Several studies have used projections of biological consequences of climate change 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 studies assume higher growth of forests due to elevated CO_2 concentrations, higher temperatures and longer growing seasons (Nabuurs et al. 2002). Faster growth in turn leads to increased timber inventories and supply, and hence lower timber prices (Sohngen and Mendelsohn 1998, Perez-Garcia et al. 2002, Solberg et al. 2003, Sohngen and Sedjo 2005); although this may be limited by the propagation of pests, diseases, and invasive species (Sohngen and Sedjo 2005).

In view of the difficulty of determining the effect of multi-factor climate change on forests this study concentrated on the partial, ceteris-paribus, effect of CO_2 fertilization alone. Specifically, it used the findings of Norby et al. (2005) to predict their long-term consequences for the forest sector, other things being held constant including other parameters of climate change such as temperature and precipitation. Special attention was given to the possibility that the impact could vary considerably depending on the context; that is on different scenarios concerning world economic, demographic growth, and policy.

The next section of the paper describes the theory, models, and data used to in the study. This is followed by the results for the main countries and regions, by product group, consumption, production and prices, forest stock, and value added in forest industries. The conclusion summarizes the main results, and their limitations and potential improvements.

Methods

Theory

The market equilibrium principles that underlie the analysis are illustrated in Fig. 1. It describes the demand, supply, trade, and prices for one commodity, wood, with and without CO_2 fertilization of forests, in a world divided in two regions, at a particular point in time. Without CO_2 fertilization Region 1, with demand schedule D1 and supply schedule S1, is a net exporter and Region 2, with demand schedule D2 and supply schedule S2 is a net importer. In Fig. 1, the transport cost is ignored, and as a result the price, *P*, is the same in Region 1 and Region 2. In the exporting Region 1 the price *P* is higher than the autarky price at the intersection of D1 and S1 that would prevail without trade, while in the importing Region 2 it is lower. With CO_2 fertilization the forest stock increases in both regions and as a result the supply schedules shift to the right to S_1' and S_2'. Consequently, the price decreases from *P* to *P*'. Other things being equal, the demand is unchanged by the CO_2 fertilization. However, in accord with the lower price, the quantities consumed increase from C_1 to C_1' in region 1 and from C_2 to C_2' in region 1. The lower price also induces lower production but with the assumption of Fig. 1 this is more than compensated by the supply shifts so that the quantity produced also increases from Q_1 to Q_1' in region 1 and Q_2 to Q_2' in region 2. For trade, in this Figure, the result of the CO_2 fertilization is a slight decrease in exports from region 1 and correspondingly lower imports in region 2.

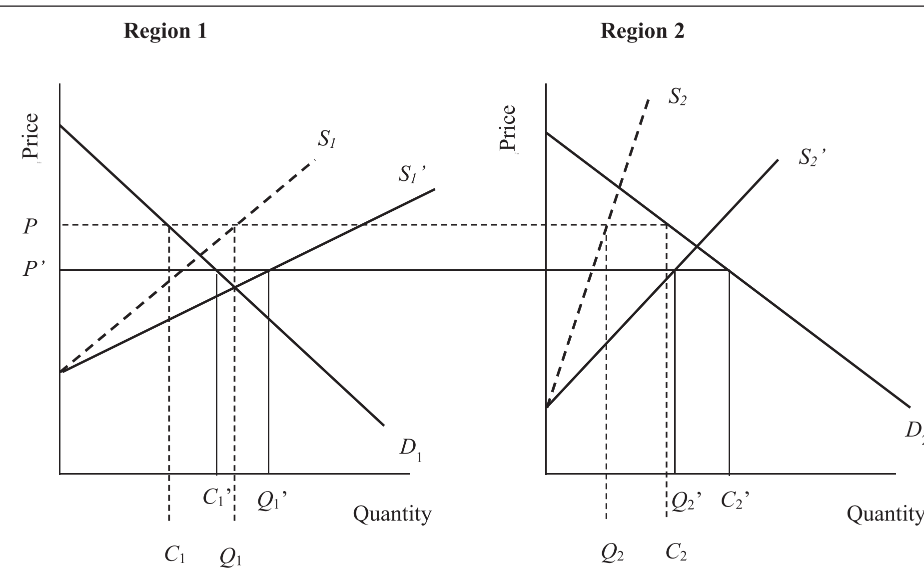

Fig. 1 Theoretical effects of supply shifts induced by CO_2 fertilization of forest stock on the production, consumption, trade, and price of wood in two trading regions. Dotted lines refer to the situation without CO_2 fertilization and the solid lines with CO_2 fertilization

However, the magnitude and even the direction of change may differ depending on the demand and supply curves and on the magnitude of the shifts. For example, in response to CO_2 fertilization, production may decrease in a region if the price effect (movement along the supply curve) exceeds the effect of the supply shift. Also, net trade may increase if the differential in CO_2 fertilization change the comparative advantage of a region relative to the other. Thus, in a multi-region, multi-products situation, the adjustment of the global equilibrium due to CO_2 fertilization is hard to predict from purely theoretical considerations, and requires a more elaborate model of the forest sector.

Global forest products model (GFPM)

The GFPM adapted for this study calculates every year a global equilibrium across countries and products, linked dynamically to past equilibria. The static phase refers to the calculation of the equilibrium in a given year. The dynamic phase simulates the change in equilibrium conditions from year to year. More details concerning the formulation and the computer implementation are available in Buongiorno and Zhu (2014a). The current model deals with 180 countries, forest area and stock, and 14 wood products.

In the static phase, the spatial global economic equilibrium in a given year is obtained by solving a quadratic programming problem in which the objective function is the social surplus in the global forest sector in a given year, which competitive markets maximize (Samuelson 1952, Takayama and Judge 1971). This surplus is equal to the value of the products to consumers (area under all the demand curves), minus the cost of supplying the raw materials (area under their supply curves), minus the transformation cost from raw materials, such as industrial roundwood to sawnwood, and minus the transport cost between countries including trade taxes. The main constraints define the material balance for each country and product: The quantity imported plus the domestic supply and the manufactured quantity must equal the domestic demand plus the quantity used in manufacturing other products and exports. Upon solution of this quadratic problem the shadow prices of the material balance constraints give the market-clearing prices for each commodity and country.

The dynamic phase of the GFPM describes the changes in the condition of the global equilibrium from one period to the next. The demand equations shift over time as a function of the GDP periodic growth rate, and the lagged consumption growth rate, in accord with adaptive expectations or imperfect foresight (Johnston, 1984 p. 348). The shifts of roundwood supply are determined by the rate of change of forest stock (endogenous, see below). There is one equation of this type for industrial roundwood (logs and pulpwood), fuelwood, and other industrial roundwood. The supply shifts of waste paper and other fiber pulp depend on GDP growth.

The changes in national forest area depend on the level of income per capita, according to a Kuznet's curve (Koop and Tole 1999, Buongiorno 2014). For each country, the curve is calibrated so that in the base year the observed rate of forest area change is equal to the predicted, given the income per capita. The national forest stock evolves over time according to a growth-drain equation:

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

where I is the forest stock at the beginning of the current period, S_{-1} is the harvest during the previous period and G_{-1} is the change of forest stock, without harvest, during the previous period, such that:

$$G_{-1} = \left(g_a + g_u\left(1 + g_u^*\right)\right) I_{-1} \tag{2}$$

Where g_a is the forest area growth rate, and g_u is the periodic rate of forest growth on a given area without harvest. In this application g_u* is the relative change of the periodic rate of forest growth due to CO_2 fertilization. The periodic rate of forest growth, g_u, is inversely related to the stock per unit area (Buongiorno 2014). For each country this relationship is calibrated so that in the base year the observed g_u is equal to the predicted given the stock per unit area. Equation (1) then gives the periodic rate of change of forest stock net of harvest, which determines the shift of the wood supply curves.

Other dynamic elements include the changes in the input–output coefficients, for example to reflect increasing use of recycled paper in paper manufacturing, and the changes in manufacturing cost (Buongiorno and Zhu, 2014b).

Model calibration

The input–output (I-O) coefficients and manufacturing costs of the GFPM used in this study were determined simultaneously by a calibration procedure based on FAOSTAT data from 2010 to 2012 (Buongiorno and Zhu 2014b). Each I-O coefficient in a year and country is the ratio of the amount of input used in making a product to the amount of output. The GFPM calibration procedure estimates the I-O coefficients while adjusting the production of the input or output if needed based on prior knowledge of manufacturing processes. Together with data on local prices the procedure also gives estimates of the manufacturing costs. With input–output coefficients and manufacturing costs determined in this way for all other countries, and the end-product demand and wood supply equations positioned with the price and quantity in each country, the solution of the global equilibrium closely replicates the base-year input data, in terms of production, consumption, net trade (exports minus imports), and prices.

The parameters of the dynamic demand equations leading to the elasticities were estimated with panel country-year data from 1992 to 2012, using the fixed-effects method (Wooldridge 2002, p. 265), with the results shown in Table 1. The environmental Kuznets curve for forest area change, and the equation of the growth rate of forest stock were both estimated with data from FAO(2010) as in Buongiorno (2014). The elasticities of fuelwood and industrial roundwood supply with price and growing stock were from Turner et al. (2006). The freight cost between countries was estimated as the difference between unit value of imports and exports. Data on import tariff duties came from the World Trade Organization data base (WTO 2013).

The solution for each year equilibrium is computed with an interior point solver (BPMPD, Mészáros 1999). The GFPM input and output for calibration and simulation is facilitated by Excel spreadsheets and graphics. A recent version of the complete software, its documentation, and a pre-calibrated data set are available freely for academic research (Buongiorno and Zhu, 2014a).

Table 1 Parameters of demand equations for end products

	Variable		
	$\ln(C_{-1})$	$\ln(Y)$	$\ln(P)$
Fuelwood	0.78	0.10	−0.10[a]
	(0.03)	(0.03)	
Other industrial roundwood	0.78	−0.05	−0.10[a]
	(0.02)	(0.02)	
Sawnwood	0.56	0.14	−0.10
	(0.02)	(0.02)	(0.02)
Plywood & veneer	0.56	0.24	−0.20
	(0.02)	(0.02)	(0.02)
Particleboard	0.60	0.22	−0.28
	(0.02)	(0.03)	(0.03)
Fiberboard	0.54	0.55	−0.26
	(0.02)	(0.04)	(0.03)
Newsprint	0.53	0.11	−0.17
	(0.02)	(0.02)	(0.02)
Printing and writing paper	0.52	0.31	−0.26
	(0.02)	(0.02)	(0.03)
Other paper and paperboard	0.60	0.23	−0.09
	(0.02)	(0.02)	(0.02)

Notes: C_{-1} = annual consumption lagged one year, Y = Gross domestic product, P = price
Standard errors in parentheses. [a]Elasticity constrained to −0.10

IPCC scenarios

Three global scenarios, A1B, A2, and B2 were used in the projections from 2011 to 2065. The scenarios are based on the IPPC scenarios (Nakicenovic et al., 2000), extended and modified for the purpose of the United States Forest Service 2010 RPA Assessment (USDA Forest Service 2012). Each scenario results from a separate IPCC "storyline" about future global social, economic, technical and policy developments. The storylines also reflect different interaction between developing and industrialized countries.

Scenario A1B, which assumes continuing globalization, leads to high income growth and low population growth, and thus the highest income per capita by the year 2065. Scenario A2 assumes a slowdown of globalization, and the rise of more regional interests. This leads to lower income growth than scenario A1B, and higher population growth, and thus lower income per capita. Scenario B2 has economic and demographic assumptions between scenarios A1B and A2.

For the GFPM simulations, the three main exogenous variables taken from these scenarios were the growth of GDP and population, and the growth of atmospheric [CO_2]. GDP growth from the IPCC was available only by region. National GDP growth was deducted from the regional growth in such a way that the regional growth remained the same as in the IPCC and the growth of individual countries converged towards this average regional growth rate (Buongiorno et al. 2012, p. 117). Table 2 shows the resulting annual growth rates of GDP for each scenario, for selected world regions and countries.

CO_2 fertilization and forest growth

Norby et al. (2005) find that "the response of net primary productivity (NPP) to elevated CO_2 is highly conserved across a broad range of productivity, with a median response of 23 ± 2 %. They define "elevated CO_2" as ~ 550 ppm of atmospheric [CO_2], which is approximately 180 ppm above the atmospheric [CO_2] in 2005. Thus, on average NPP increases by 0.13 % per ppm increase in atmospheric [CO_2]. Here, it was assumed that the percent increase in NPP was equal to the percent increase in the growth of forest stock in the absence of harvest.

Figure 2 shows the implication of this assumption for the growth rate of forest stock, given the predicted evolution of atmospheric [CO_2] in each IPCC scenario (Table 3). The highest impact was for scenario A2 in which the growth rate was 32 % higher in 2070 than in 2006. The lowest was for scenario B2 (19 %). The effect of scenario A1B was almost the same as that of A2 up to 2050 but somewhat lower in 2070 (29 %). Accordingly, in the GFPM the endogenous forest growth rate, g_u, in

Table 2 Projected annual percent GDP growth rate in selected world regions and countries, by scenario

	Scenario A1B		Scenario A2		Scenario B2	
	2011–2030	2030–2065	2011–2030	2030–2065	2011–2030	2011–2065
AFRICA	7.1	5.4	3.4	4.1	5.0	5.9
Egypt	7.2	5.1	3.8	4.4	4.6	5.2
Nigeria	8.9	6.1	5.0	4.7	7.0	7.0
South Africa	4.1	3.1	0.6	1.7	3.2	3.6
N/C AMERICA	2.6	2.3	1.9	1.8	1.7	1.4
Canada	2.2	1.9	1.7	1.3	1.6	0.8
Mexico	5.2	3.2	1.8	2.1	2.5	3.1
USA	2.3	2.1	1.9	1.8	1.6	1.1
SOUTH AMERICA	5.3	3.3	2.0	2.5	2.7	3.4
Argentina	4.7	2.8	1.4	1.9	2.0	2.7
Brazil	5.2	3.2	1.8	2.2	2.4	3.0
Chile	4.9	2.9	2.1	2.5	3.0	3.6
ASIA	5.5	3.8	2.5	2.4	3.7	2.8
China	7.4	3.8	3.9	3.2	5.6	2.8
India	8.8	5.1	4.2	3.2	6.8	4.0
Indonesia	8.2	4.5	3.9	2.8	5.7	2.9
Japan	1.4	1.2	0.9	0.6	0.6	0.1
Korea, Rep.	4.9	1.7	0.8	−0.1	2.9	0.3
Malaysia	6.5	2.7	2.7	1.4	4.5	1.5
OCEANIA	2.9	2.1	2.2	1.6	2.2	0.9
Australia	2.6	1.9	2.1	1.6	2.0	0.8
New Zealand	2.6	2.0	2.3	1.8	2.4	1.1
EUROPE	2.3	2.0	1.2	1.1	1.3	1.3
EU-28	1.9	1.7	1.2	1.0	1.1	0.9
Austria	1.4	1.2	0.9	0.5	0.9	0.4
Finland	1.3	1.1	0.9	0.5	0.9	0.5
France	1.9	1.6	1.4	1.0	1.1	0.6
Germany	1.5	1.3	1.0	0.7	0.8	0.3
Italy	1.3	1.2	0.8	0.5	0.6	0.2
Spain	1.7	1.6	1.3	0.9	1.1	0.6
Sweden	1.3	1.1	0.8	0.5	1.1	0.6
United Kingdom	2.0	1.7	1.5	1.1	1.3	0.8
Russian Fed.	5.7	3.2	1.1	2.9	2.9	3.0
WORLD	3.9	3.2	1.9	2.0	2.4	2.4

Source: Adapted from Buongiorno et al. (2012)

equation (2) changed over time by the relative fraction g_u* shown in Fig. 2.

Results and discussion

Price effects

Table 4 shows the world prices, defined by the unit value of imports, in 2011 and projected with the GFPM in 2065 with scenarios A1B, A2 and B2, with or without the cumulative effect of CO_2 fertilization from 2011 to 2065. In accord with theoretical expectations, the price of all products was lower with CO_2 fertilization. The fertilization effect varied substantially with the scenario. Under the A1B scenario, the price of fuelwood and industrial roundwood was 19 % lower in 2065 due to CO_2 fertilization. The price of sawwood was 9 % lower, and the price of wood-based panels was 3 % to 6 % lower. The price of mechanical and chemical pulp was 4 % and 6 % lower, respectively. The price of paper and

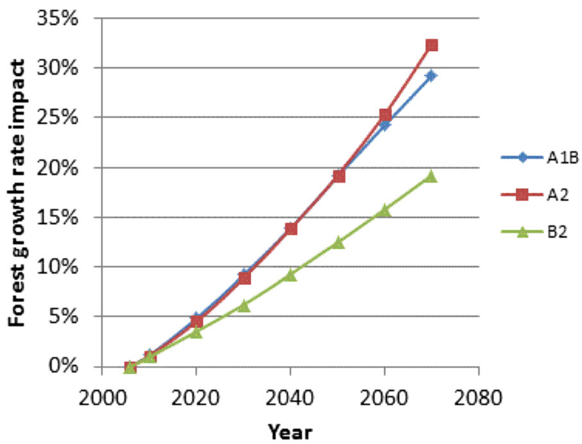

Fig. 2 Effects of CO_2 fertilization on the growth rate of forest stock, according to IPCC scenarios A1B, A2, and B2

paperboard was 3 % to 6 % lower depending on the product.

For scenario A2 the price reductions were less than for scenario A1B, and similar to the effects under scenario B2. For scenarios A2 and B2, CO_2 fertilization decreased the price of fuelwood in 2065 by 12 % to 13 % and the price of industrial roundwood by 9 % to 11 %. The price of sawnwood was 4 % to 5 % lower, and the price of wood-based panels was 1 % to 3 % lower. The price of wood pulp decreased by 2 % to 4 % with CO_2 fertilization, and the price of paper and paperboard decreased by 1 % to 3 % depending on the product.

Fuelwood consumption, production, and trade

In accord with the lower world prices induced by the CO_2 fertilization from 2011 to 2065, fuelwood consumption (production + imports-exports) was higher in 2065 in all regions than without fertilization, under all three scenarios. The largest effect of CO_2 fertilization occurred with scenario A1B, under which world consumption of fuelwood was 8 % higher in 2065, while it was 5 % to 6 % higher under scenarios A2 and B2 (Table 5). The effect on fuelwood consumption was most noticeable in developing countries, reaching 13 % in Africa under scenario A1B. The smallest relative impact was in Europe and the EU-28: 2 % with scenario A1B and 1 % with A2 and B2.

Table 3 Past and projected atmospheric CO_2 saturation (ppm), by IPCC scenario

	IPCC scenario		
Year	A1B	A2	B2
1970	325	325	325
1980	337	337	337
1990	353	353	353
2000	369	369	369
2006	382	382	380
2010	391	390	388
2020	420	417	408
2030	454	451	429
2040	491	490	453
2050	532	532	478
2060	572	580	504
2070	611	635	531

Source: IPCC(2013)

The regional effect of CO_2 fertilization on fuelwood production tended to mirror the effect on consumption, except for the EU-28 where production was somewhat lower than consumption with CO_2 fertilization under all scenarios. In that case, the movement down the supply curve due to the lower world price (Table 4) exceeded the shift of the supply curve due to CO_2 fertilization from 2011 to 2065, and resulted in lower production, which together with the higher consumption suggested a deterioration of net trade.

Industrial roundwood consumption, production, and trade

Industrial roundwood includes logs, pulpwood, and other industrial roundwood (FAO 2014, p. xx). The supply of industrial roundwood is, like that of fuelwood, directly affected by the shift due to CO_2 fertilization. However, while the demand for fuelwood, an end product, depends ultimately only on GDP and fuelwood price, the demand for industrial roundwood is more involved. Since industrial roundwood is an input in the manufacture of sawnwood, wood-based panels, and wood pulp, its demand depends on the price of these end products, and on the price of industrial roundwood, the price of other inputs and the techniques of production.

Globally, the positive supply shift of industrial roundwood due to CO_2 fertilization more than matched the movement down the supply curve due to the price reduction. Consequently, the GFPM-projected world consumption and production of industrial roundwood was 2 % to 4 % higher, depending on the scenario, with the assumption of CO_2 fertilization than without it (Table 6).

However, the complex derived demand for industrial roundwood, coupled with the shifts of industrial roundwood supply induced by the CO_2 fertilization led to varying regional effects. Consumption of industrial roundwood tended to be higher with CO_2 fertilization than without it, except in North/Central America and Asia. Under scenario A1B in particular, industrial roundwood consumption was 10 % lower in N/C America, while it was 19 % higher in South America and 10 % higher in Europe and the EU-28. With this scenario, production was 18 % higher in Asia in 2065,

Table 4 World prices of forest products in 2011 and projected in 2065 under scenarios A1B, A2 and B2, with and without CO_2 fertilization from 2011 to 2065

			2065, A1B		2065, A2		2065, B2	
Product	Unit	2011	without	with	without	with	without	with
Fuelwood	$/m3	63	61	49	48	42	51	45
Industrial roundwood	"	101	135	110	99	88	106	97
Sawnwood	"	259	324	295	277	264	287	275
Veneer & plywood	"	573	999	963	933	912	949	935
Particleboard	"	285	552	518	500	487	514	502
Fiberboard	"	433	915	883	864	850	876	865
Mechanical pulp	$/t	509	942	901	850	817	879	847
Chemical pulp	"	642	1036	978	949	924	967	946
Other fiber pulp	"	1309	3848	3812	2240	2243	2247	2242
Waste paper	"	187	563	524	417	402	499	488
Newsprint	"	632	774	731	651	635	705	687
Printing & writing paper	"	974	1128	1088	1016	1002	1063	1054
Other paper & paperboard	"	986	1586	1538	1452	1431	1512	1496

while consumption hardly changed, so that the CO_2 fertilization improved markedly Asia's trade balance of industrial roundwood. The regional pattern of the effects was similar for scenarios A2 and B2, but the magnitudes in both cases were much less than for scenario A1B.

Sawnwood and panels consumption, production, and trade

In the GFPM, sawnwood and wood-based panels (veneer and plywood, particleboard, fiberboard (FAO 2014)), are end products. Their demand depends on GDP, the product price, and lagged consumption. As indicated above,

Table 5 Projected differences in fuelwood production and consumption in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^3 m^3)	(%)	(10^3 m^3)	(%)	($10^3 m^3$t)	(%)
Production						
Africa	226040	12.5	120717	9.6	165382	9.8
N/C America	6881	2.8	2444	1.2	3299	1.5
South America	10385	2.7	2559	0.9	5076	1.6
Asia	101055	5.4	28268	2.1	46643	3.0
Oceania	626	2.9	173	1.0	170	1.0
Europe	5794	2.4	2662	1.4	2940	1.4
EU-28	286	0.2	−1596	−1.3	−1622	−1.3
World	350782	7.7	156824	4.8	223509	5.6
Consumption						
Africa	226040	12.5	120723	9.6	165382	9.8
N/C America	7017	2.8	2545	1.3	3438	1.6
South America	10385	2.7	2560	0.9	5076	1.6
Asia	101038	5.4	28249	2.1	46390	3.0
Oceania	627	2.9	173	1.0	170	1.0
Europe	5676	2.5	2574	1.4	3053	1.5
EU-28	2976	2.2	1432	1.2	1568	1.3
World	350782	7.7	156824	4.8	223509	5.6

Table 6 Projected differences in industrial roundwood production and consumption in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^3 m^3)	(%)	(10^3 m^3)	(%)	($10^3 m^3$t)	(%)
Production						
Africa	13273	15.3	4243	5.7	8616	10.9
N/C America	−65327	−7.6	−30586	−4.9	−52688	−7.7
South America	14684	5.0	1960	0.8	9435	3.7
Asia	89435	18.4	29302	7.0	33633	7.7
Oceania	−1619	−2.3	−908	−1.7	−933	−1.7
Europe	63229	6.9	35641	4.7	47494	6.0
EU-28	26916	4.3	11573	2.1	16048	2.8
World	113674	4.2	39653	1.8	45558	2.0
Consumption						
Africa	14266	19.5	4416	7.2	5790	7.8
N/C America	−58038	−10.4	−6150	−1.9	−14861	−4.3
South America	59850	19.1	3505	1.2	9556	3.0
Asia	−2504	−0.3	−3330	−0.7	−2851	−0.5
Oceania	1838	5.5	723	2.4	371	1.2
Europe	98263	10.0	40488	4.1	47553	4.8
EU-28	78223	9.6	21018	2.6	22946	2.8
World	113674	4.2	39653	1.8	45558	2.0

the price of all products in 2065 was lower with CO_2 fertilization from 2011 to 2065. Consequently, the consumption of all end products was higher (Table 7). In particular, under scenario A1B the world consumption of wood-based panels was 1.2 % higher in 2065 with CO_2 fertilization, with the highest relative changes in the range of 2 % to 2.5 % in Africa and South America. The relative increases in consumption were about half that magnitude under scenarios A2 and B2.

Meanwhile, the production of sawnwood and panels varied much more across regions. For example, under scenario A1B, while production of sawnwood and panels was 21 % to 24 % in Africa and South America with CO_2 fertilization, it was 25 % lower in N/C America. However, the regional distribution of production varied markedly between scenarios. In particular, while the production of E-28 countries was 4 % higher with CO_2 fertilization under scenario A1B and their trade balance improved as a result, their production decreased slightly with scenarios A2 and B2, implying a slight worsening of net trade.

Wood pulp consumption production and trade

The production and consumption of wood pulp (mechanical + chemical + semi-chemical pulp (FAO 2014) are determined by its demand and supply. Wood pulp is an input in the manufacture of paper and paperboard, so that its demand depends (negatively) on its own price, and (positively) on the price of paper and paperboard. Meanwhile, the supply of wood pulp is a positive function of the price of wood pulp and a negative function of the price of industrial roundwood (an input in making wood pulp). The CO_2 fertilization reduces the price of industrial roundwood, and in the process stimulates the demand for wood pulp. As shown in Table 8, under scenario A1B, the world wood pulp consumption (and the matching production) in 2065 was approximately 2 % higher with the CO_2 fertilization than without it. The effect was approximately half that much under scenarios A2 and B2.

There was a strong difference in the effect across regions. For example, under scenario A1B, the wood pulp consumption in Europe was nearly 9 % higher with CO_2 fertilization, and the production was double this amount, implying an improvement in net trade. Meanwhile, production in N/C America was about 5 % lower with CO_2 fertilization under A1B, while consumption was unchanged, so that net trade deteriorated. The direction of the effects was similar under scenarios A2 and B2, but the magnitude was smaller.

Paper and paperboard consumption production and trade

The products in the paper and paperboard group: newsprint + printing and writing paper + other paper and

Table 7 Projected differences in sawnwood and wood-based panels production and consumption in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^3 m^3)	(%)	(10^3 m^3)	(%)	($10^3 m^3$t)	(%)
Production						
Africa	5270	21.1	1063	5.9	1890	7.9
N/C America	−33242	−24.6	278	0.4	−4815	−6.9
South America	29406	23.9	1205	1.0	3836	2.9
Asia	−15345	−2.7	−6718	−2.0	−6952	−1.8
Oceania	359	3.4	332	3.6	114	1.3
Europe	30584	5.6	9805	1.9	13121	2.5
EU-28	19050	4.0	−1702	−0.4	−99	0.0
World	17033	1.2	5965	0.6	7193	0.6
Consumption						
Africa	1180	2.3	464	1.3	718	1.6
N/C America	2429	1.1	957	0.5	765	0.4
South America	1881	2.0	442	0.7	854	1.1
Asia	8014	1.1	2790	0.5	3446	0.6
Oceania	175	1.0	74	0.5	59	0.4
Europe	3355	1.2	1239	0.5	1353	0.6
EU-28	2428	1.2	970	0.6	1053	0.6
World	17033	1.2	5966	0.6	7194	0.6

Table 8 Projected differences in wood pulp production and consumption in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^3 t)	(%)	(10^3 t)	(%)	(10^3 t)	(%)
Production						
Africa	391	9.2	136	4.7	177	4.3
N/C America	−7545	−4.9	−3085	−3.5	−3928	−3.9
South America	−299	−1.7	163	1.6	240	2.0
Asia	1379	4.1	274	1.3	421	1.8
Oceania	20	0.6	31	1.1	34	1.3
Europe	11016	19.2	4016	8.0	4459	8.2
EU-28	11306	28.8	4511	11.6	4502	11.1
World	4961	1.8	1534	0.9	1401	0.7
Consumption						
Africa	231	4.8	44	1.6	17	0.4
N/C America	−15	0.0	193	0.4	30	0.1
South America	−635	−3.4	−25	−0.2	17	0.1
Asia	182	0.2	−180	−0.3	−217	−0.3
Oceania	21	0.6	2	0.1	19	0.7
Europe	5177	8.8	1500	3.4	1536	3.1
EU-28	4758	10.8	1512	4.2	1478	3.8
World	4962	1.8	1534	0.9	1401	0.7

paperboard (FAO 2014) are treated as end products in the GFPM. As for fuelwood, and sawnwood and wood-based panels the national demand is a function of GDP, price, and lagged consumption. Consequently, CO_2 fertilization influences paper and paperboard consumption through the price effect only. As the relative price reduction induced by CO_2 fertilization was smallest for paper and paper and paperboard, the effects on consumption were correspondingly small (Table 9). The largest effects, under scenario A1B implied only a 0.5 % to 0.8 % higher consumption depending on the region. Under the other two scenarios, consumption was practically the same with or without CO_2 fertilization.

There were however larger regional impacts on production due to the differences in production cost brought about by the different regional shifts of industrial roundwood supply. In particular, under scenario A1B, paper and paperboard production was nearly 4 % lower in South America with CO_2 fertilization than without it, implying a deterioration of net trade, while in Europe, production was nearly 3 % higher, with a corresponding increase of net trade.

Value added in forest industries

For the purpose of this paper, value added is defined as the value of the total output of forest industries (sawnwood, wood-based panels, wood pulp, paper and paperboard) minus the cost of the wood and fiber input used by the industries (industrial roundwood, wood pulp, other fiber pulp, and waste paper). The effects of the CO_2 fertilization from 2011 to 2065 on the input cost, value of the output and the resulting value added are summarized in Table 10 by region and scenario. The largest impacts occurred under scenario A1B according to which the CO_2 fertilization decreased the cost of the world industry inputs in 2065 by nearly \$ $94x10^9$ or 7 %. The reduction in input cost occurred in all regions, and was largest in Asia (–\$42 $x10^9$). Although the quantity of inputs, for example of industrial roundwood, increased in several regions (Table 6), their lower world prices (Table 4) still led to a reduction in total input cost.

The value of the industries outputs was also lower in several regions (Table 10) as the higher consumption of end products (e.g. sawnwood and panels) did not compensate for the reduced prices. Under scenario A1B, output value in 2065 was nearly 8 % lower in N/C America with CO_2 fertilization, and nearly 4 % lower in Asia. At world level, the reduction in output value came close to the reduction in input cost, leaving only a modest increase of value added (\$$7.6x10^9$, or less than 1 %). The effects were similar in direction for scenarios A2 and B2, but smaller in magnitude so that at world level the CO_2 fertilization had hardly an impact on value added, although the regional differences were more substantial.

Table 9 Projected differences in paper and paperboard production and consumption in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^3 t)	(%)	(10^3 t)	(%)	(10^3 t)	(%)
Production						
Africa	194	1.2	123	1.3	8	0.1
N/C America	−270	−0.1	341	0.3	60	0.0
South America	−1682	−3.8	−84	−0.3	14	0.0
Asia	3118	0.5	−536	−0.1	−985	−0.2
Oceania	42	0.5	7	0.1	30	0.5
Europe	5740	2.8	1735	1.0	2164	1.2
EU-28	5370	3.0	1826	1.2	2173	1.4
World	7143	0.7	1586	0.2	1291	0.2
Consumption						
Africa	266	0.8	46	0.2	65	0.2
N/C America	831	0.5	319	0.2	205	0.2
South America	229	0.5	43	0.1	76	0.2
Asia	4884	0.8	882	0.2	675	0.1
Oceania	49	0.6	19	0.3	12	0.2
Europe	882	0.5	277	0.2	258	0.2
EU-28	718	0.5	232	0.2	223	0.2
World	7142	0.7	1586	0.2	1291	0.2

Table 10 Projected differences in wood and fiber input cost, output value and value added in forest industries in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^6 \$)	(%)	(10^6 \$)	(%)	(10^6 \$)	(%)
Input cost						
Africa	−407	−1.8	−280	−2.3	−414	−2.3
N/C America	−29185	−12.9	−5853	−5.5	−6632	−5.1
South America	−4483	−5.6	−3476	−7.2	−2493	−4.2
Asia	−41990	−6.4	−12017	−3.8	−11212	−3.1
Oceania	−926	−8.5	−380	−5.0	−339	−4.4
Europe	−16533	−6.0	−8339	−4.4	−5037	−2.3
EU-28	−13738	−5.9	−7769	−4.8	−5394	−3.0
World	−93524	−7.3	−30343	−4.5	−26127	−3.3
Output value						
Africa	853	2.3	79	0.4	396	1.2
N/C America	−41032	−7.8	−8293	−3.0	−11767	−3.6
South America	2790	1.9	−1746	−1.7	533	0.4
Asia	−48040	−3.7	−16356	−2.1	−14277	−1.6
Oceania	−716	−3.2	−211	−1.2	−138	−0.8
Europe	243	0.0	−1690	−0.4	1469	0.3
EU-28	217	0.0	−1965	−0.5	1178	0.3
World	−85901	−3.2	−28217	−1.7	−23784	−1.3
Value added						
Africa	1260	8.8	359	4.1	809	5.7
N/C America	−11846	−4.0	−2440	−1.4	−5135	−2.6
South America	7273	10.4	1730	3.1	3026	4.9
Asia	−6050	−0.9	−4339	−0.9	−3064	−0.6
Oceania	210	1.9	169	1.7	202	2.3
Europe	16775	5.3	6649	2.5	6506	2.3
EU-28	13955	5.2	5804	2.4	6571	2.6
World	7623	0.6	2126	0.2	2344	0.2

Forest stock

CO_2 fertilization tended to increase the forest stock, but as observed above a rise in stock shifted the wood supply to the right, increasing wood harvest and thus decreasing the forest stock. These opposite tendencies were further affected by the price decrease induced by the increase in wood supply, which stimulated the demand for wood products and thus the derived demand for wood input and the attendant harvest. Table 11 summarizes the results of the GFPM simulation of these complex interactions for the forest stock in different regions and for the three scenarios.

For all scenarios and regions the growing stock was higher in 2065 with CO_2 fertilization than without it. Thus, the added growth due to CO_2 fertilization more than compensated for the cumulative effects of the increased fuelwood and industrial roundwood harvests observed above. The largest effects of the CO_2 fertilization on the level of forest stock in 2065were under scenario A1B. This was in part due to the high level of atmospheric [CO_2] and also to the rise in forest area, and thus young growing forests, induced by the higher GDP per capita growth assumed in scenario A1B. For this scenario, the forest stock was 20 % higher in 2065 with CO_2 fertilization than without it. The largest relative impacts were in Africa and Asia. Under scenarios A2 and B2 the effect of CO_2 fertilization were similar, globally (9 % to 10 %) and by region, with the largest relative impact still in Africa.

Conclusions

The objective of this paper was to explore the long-term, ceteris-paribus effects of a potential CO_2 fertilization on the global forest sector. Based on the findings of Norby et

Table 11 Projected differences in growing stock in 2065 due to CO_2 fertilization from 2011 to 2065, by region and scenario

	Scenario A1B		Scenario A2		Scenario B2	
	(10^6 m^3)	(%)	(10^6 m^3)	(%)	(10^6 m^3)	(%)
Africa	26212	34 %	13527	19 %	16089	21 %
N/C America	11414	11 %	6003	5 %	3233	3 %
South America	30998	19 %	9051	6 %	16872	10 %
Asia	20304	27 %	9977	10 %	9238	10 %
Oceania	1953	14 %	850	6 %	715	5 %
Europe	25818	19 %	15689	11 %	15537	11 %
EU-28	4972	14 %	3120	7 %	2857	7 %
World	116698	20 %	55097	9 %	61685	10 %

al. (2005) about forest response to elevated CO_2 concentration it was assumed that the effect of CO_2 fertilization on forest growth would be conserved across a broad range of productivity, with an average stimulation of 23 % for a 180 ppm increase of atmospheric [CO_2].

This increased productivity was applied to national forest growth rates in the Global Forest Products Model in proportion to the rising levels of [CO_2] projected by the International Panel for Climate Change scenarios A1B, A2, and B2. In addition to different [CO_2] levels the three scenarios projected different growth rates of gross domestic product and population, which influence the future demand for forest products, and the evolution of forest area. Projections of the forest area and forest stock, and of the production, consumption, prices, and trade of different products (ranging from fuelwood to paper and paperboard) were obtained with the GFPM for each scenario, with and without the assumption of CO_2 fertilization beginning in 2011 and up to 2065.

The results suggested that CO_2 fertilization would raise the level of the world forest stock by 9 to 10 % for scenarios A2 and B2 and by 20 % for scenario A1B. The change in forest stock was in part counteracted by the stimulation of the wood supply which resulted in lower wood prices and increased wood harvest. The lower wood prices in turn led to lower prices of end products and increased global consumption. However, production decreased in some regions due to the relative competitive advantages and to the varying regional effects of CO_2 fertilization.

These findings rely on strong assumptions; in particular that CO_2 fertilization can be summarized over very different forest types by the simple number suggested in Norby et al. (2005). Although the homogeneity of response that they observed is striking, and over a wide range of sites, they all are within the temperate zone. It is uncertain that they can be applied to other ecological zones. Hickler et al. (2008) use a dynamic vegetation model which does reproduce the data of Norby et al. (2005), and conclude that the data "might also be representative of forests globally". But, they also suggest that the NPP enhancement due to CO_2 fertilization may be much larger in tropical than boreal forests.

A review of several studies by the Center for the Study of Carbon Dioxide and Global Change (2014) does conclude that "CO_2 fertilization effects strongly increased recent Net Primary Production trends in regional totals". But, much work is still needed to quantify this effect apart from or in conjunction with changes in temperature and precipitation (Zickfeld et al. 2012). In addition, the methods used in this study require good estimates of current forest growth rates in different countries. This will mean further improvement of the global forest inventory and harvest statistics, which are currently subject to substantial errors due to infrequent and unequal sampling, and differences in definitions and classifications (FAO 2010).

Keeping these caveats in mind, the present study showed that the impact of CO_2 fertilization would depend very much on the economic and demographic context in which it occurred, but in all cases the impact on the global value added in the forest sector would be modest. On the other hand, CO_2 forest fertilization per se might have substantial effects on the long-term level of forest stock, and less on the harvest. There would thus be a net positive effect of CO_2 fertilization on the amount of carbon stored in forests, a clearly beneficial effect for overall climate change.

Competing interests
The author declares that he has no competing interests.

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