2. Global forest sector modeling: application to some impacts of climate change

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Abstract

This paper explored the potential long-term effects of a warming climate on the global wood sector, based on Way and Oren's synthesis (Tree Physiology 30,669-688) indicating positive responses of tree growth to higher temperature in boreal and temperate climates, and negative responses in the tropics. Changes in forest productivity were introduced in the Global Forest Products Model (GFPM), using Way and Oren's equations in accord with the rising temperatures projected in the IPCC scenario A1B, A2, and B2. Projections of the forest stock, production, prices, and trade of wood, and value added in industries were obtained with the GFPM for each scenario, with and without temperature changes from 2012 to 2065. In the three scenarios, the projected global growing stock of forests in 2065 was hardly changed by the rise in temperature. However, the forest stock was 2% to 6% higher in developed countries while it was 3% to 4% lower in developing countries. There were significant attendant changes in wood production, prices, trade, and value added in forest industries benefiting developed countries and harming the developing countries.

Keyword*s*: Climate change, wood, supply, demand, prices, international trade.

Introduction

The temperature of the earth has been rising steadily, and by nearly 1°C from 1950 to 2014 (NASA, 2015 and Figure 1). This trend is expected to continue. The International Panel on Climate Change projects that the earth surface temperature could increase by 1.8°C to 4.0°C over a century, depending on different scenarios concerning economic growth, demographic trends, and mitigation policies (IPCC 2007). This rise in temperature matters for global forests that are sources of wood and carbon sinks (Woodbury et al. 2007). Accordingly, past studies have addressed the effects of climate change in forest economics (see Kirilenko and Sedjo 2007 for a review), using projections of biological consequences of climate change to alter the wood supply in forest sector models (McCarl et al. 2000, Perez-Garcia et al. 2002, Solberg et al. 2003, Sohngen and Sedjo 2005).

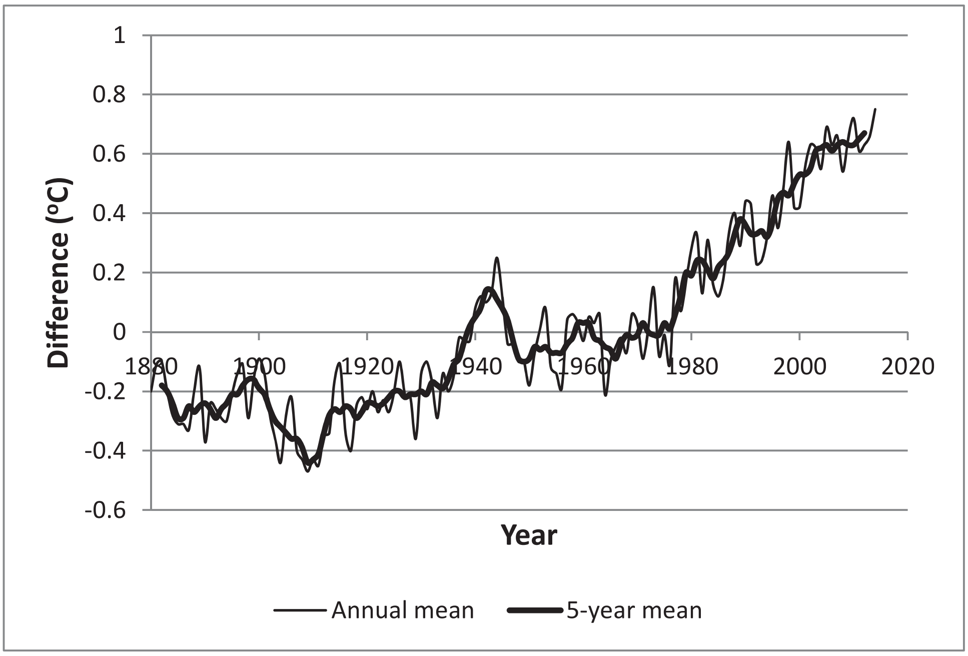

Figure 1: Difference in mean average temperature relative to the average 1951-1980 (NASA 2015).

Although some studies assume higher growth of forests due to higher temperatures and longer growing seasons (Nabuurs et al. 2002), predicting the effects of climate change on forests is extremely complex as it depends on future nutrient availability, especially water, carbon dioxide fertilization, and the adaptability of various trees to environmental changes (Boisvenue and Running, 2006). Nevertheless, Way and Oren (2010) have produced a very useful synthesis (Ryan 2010) of the effects of temperature on tree growth, in the form of equations linking changes in growth to temperature changes, differentiated for boreal, temperate, and tropical ecosystems. Accordingly, this study aimed at using the findings of Way and Oren (2010) to predict their long-term consequences for global forest stock and wood markets. Special attention was given to the possibility that the impact could vary considerably depending on the chosen scenarios concerning world economic and demographic growth, and policy, with their attendant differences in global temperatures.

The next section of the paper describes the theory, models, and data used in the study. This is followed by the projections for the main world regions of the changes due to increased temperature on forest stock, and consequently on roundwood production and trade, world wood prices, and value added in forest industries. The conclusion summarizes the main results, especially the differential impact on developed and developing countries.

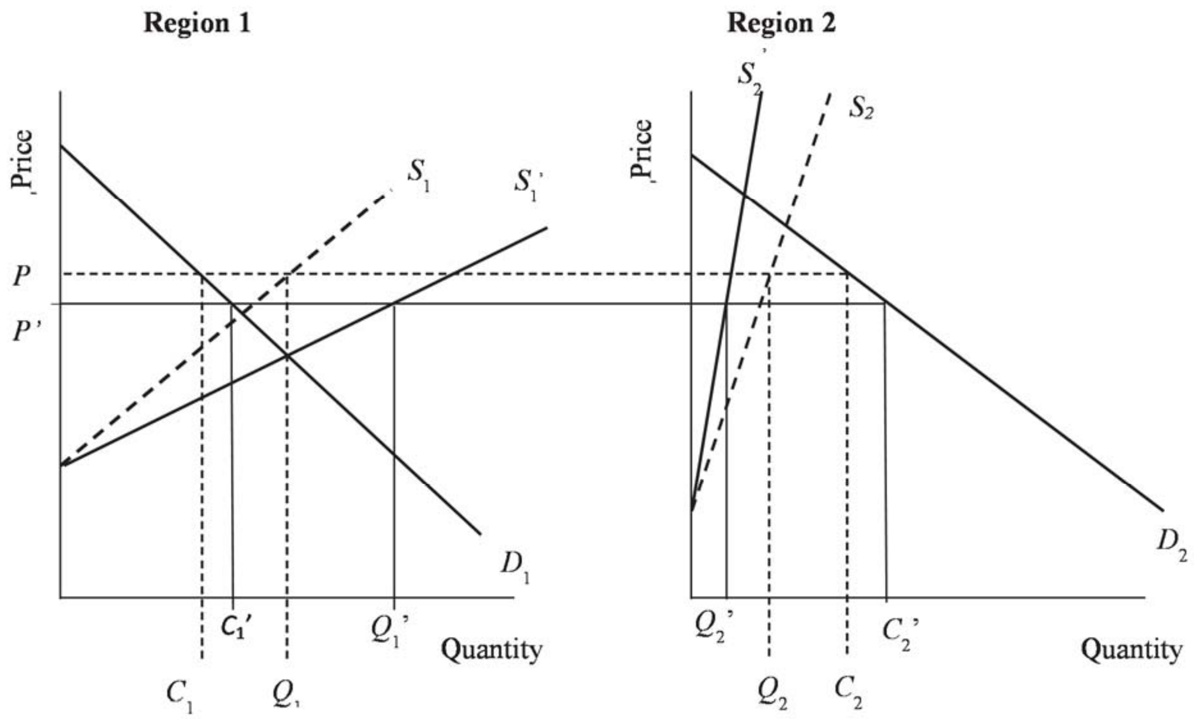

Figure 2. Theoretical impact in two trading regions of wood supply shifts induced by changes in temperature on production, consumption, net trade, and price of wood.

Methods

Theory

The general principles of the analysis are symbolized in Figure 2. The figure outlines the demand, supply, trade, and price of wood, with and without impact of temperature change on forests, in a world divided in two regions. Without temperature change Region 1, with demand schedule D1 and supply schedule S1, exports the quantity Q1-C1 and Region 2, with demand schedule D2 and supply schedule S2 exports the quantity C2-Q2=Q1-C1. Ignoring the transport cost, which is not critical for the reasoning, the price, P, is the same in Region 1 and Region 2. With the change in temperature Figure 2 assumes that forest growth is stimulated in Region 1, so that the wood supply shifts to the right to S1', while forest growth is hampered in Region 2, and accordingly the wood supply shifts to the left to S2', but by less in absolute value than the positive supply shift in Region 1. Other things being equal, the demand is unchanged by the temperature change and remains D1 in region 1 and D2 in region 2. However, the net increase in supply leads to a decrease of the equilibrium price, from P to P'. In accord with the lower price the quantity consumed increases from C1 to C1' in region 1 and from C2 to C2' in region 2. The lower price together with the negative supply shift induces lower production in region 2, from Q2 to Q2'. Meanwhile in region 1, the positive effect of the supply shift exceeds the negative effect of the price decrease, and leads to increased production from Q1 to Q1'. For trade, in this Figure, the net result of the increase in temperature is an increase of exports from region 1, and a matching increase of imports in Region 2.

Although Figure 2 is very abstract it reveals the complexity of the response to changes in temperature that may stimulate forest growth in some regions and reduce it in others. Even considering the supply side only, the direction, let alone the magnitude of changes in consumption, production, trade and price may differ considerably depending on the effect of temperature change and the elasticities of demand and supply. For example, given a positive effect of temperature increase on forest growth, production may still decrease in a region if the price effect (movement along the supply curve) exceeds the effect of the supply shift. Thus, in a multi-region, multi-products situation, the adjustment of the global equilibrium due to changes of temperature requires a more elaborate model of the forest sector.

Global Forest Products Model (GFPM)

The GFPM adapted for this study is a recursive dynamic equilibrium model of the global forest sector. The formulation and the computer software, available freely to researchers, are described in Buongiorno and Zhu (2016). The current model deals with 180 countries, forest area and stock, and 14 commodity groups, ranging from fuelwood to paper and paperboard.

For each projected year the model simulates a spatial economic equilibrium as a quadratic programming problem. The objective function is the "social surplus" in the global forest sector (Samuelson 1952, Takayama and Judge 1971). The constraints equate demand and supply for each country and product. The primal solution gives the quantities consumed, produced and traded while the dual solution gives the prices by product and country. The quadratic program is solved with the BPMPD interior point solver (Mészáros 1999).

Between years, the demand equations shift in accord with the expected gross domestic product (GDP). The shifts of roundwood supply are determined by the changes of forest stock. The changes in forest area depend on the level of income per capita, according to a Kuznet's curve (Koop and Tole 1999, Buongiorno 2014). The national forest stock changes over time according to a growth-drain equation:

$$I = I_{-1} + G_{-1} - S_{-1} \qquad (1)$$

where I and I_{-1} are respectively the level of the forest stock at the beginning of the current and previous year, S_{-1} is the harvest during the previous year and G_{-1} is the change of forest stock during the previous year, given by:

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

Where g_a is the forest area growth rate, and g_u is the rate of forest stock growth on a given area, without harvest. In this application g_u* is the relative change of the annual rate of forest stock growth due to temperature change. The forest growth rate, g_u, is an inverse function of the stock per unit area (Buongiorno 2014). Equation (1) then gives the 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 describing technologies, and the associated changes in manufacturing cost (Buongiorno and Zhu, 2015a).

The input-output (I-O) coefficients and manufacturing costs of the GFPM used in this study were calibrated for the base year 2012 with FAOSTAT data (FAO 2015) averaged from 2011 to 2013 (Buongiorno and Zhu 2015b). Together with data on local prices the calibration also gives estimates of the manufacturing costs. With input-output coefficients and manufacturing costs determined in this way, 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 replicated the base-year input data (production, consumption, net trade, and prices).

The parameters of the demand equations were estimated with panel country-year data from 1992 to 2013, using the fixed-effects method (Buongiorno 2015). 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 based on 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).

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 makes different assumptions about future global social, economic, technical and policy changes. Scenario A1B assumes continuing globalization with attendant to high incomes and low populations, and thus the highest future income per capita. Scenario A2 assumes a slowdown of globalization, leading to lower incomes than scenario A1B, higher populations, 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 rise in temperature. National GDP growth was deducted from the regional growth available from the IPCC with the assumption that the growth of individual countries converged towards the regional growth rate (Buongiorno et al. 2012, p. 117). Table 1 shows the resulting annual growth rates of GDP for each scenario, by world regions. The corresponding rises in temperature over a century are in Table 2. The highest projected increase is for scenario A2, with an expected value of 3.4^{o}C over 100 years, and the lowest is for scenario B2, with an expected warming of 2.4^{o}C.

Table 1. Projected annual percent GDP growth rate in world regions, by scenario.
Source: Adapted from Buongiorno et al. (2012).

Table 2: Projected global average warming over one century (°C).

	Scenario A1B		Scenario A2		Scenario B2	
	2012-2030	2030-2065	2012-2030	2030-2065	2012-2030	2011-2065
AFRICA	7.1	5.4	3.4	4.1	5.0	5.9
N/C AMERICA	2.6	2.3	1.9	1.8	1.7	1.4
SOUTH AMERICA	5.3	3.3	2.0	2.5	2.7	3.4
ASIA	5.5	3.8	2.5	2.4	3.7	2.8
OCEANIA	2.9	2.1	2.2	1.6	2.2	0.9
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
DEVELOPED	2.3	2.0	1.5	1.4	1.4	1.2
DEVELOPING	6.7	4.2	3.1	3.0	4.6	3.7
WORLD	3.9	3.2	1.9	2.0	2.4	2.4

Scenario	Likely range	Best estimate
B2	1.4 - 3.8	2.4
A1B	1.7 - 4.4	2.8
A2	2.0 - 5.4	3.4

Source: IPCC (2007)

Table 3: Regression coefficients for relationship of total tree mass versus a change in growth temperature. Equations are of the form $y=a+bx+cx^2$, where x=temperature change in °C, and y is the response relative to the control.

Line	*a*	*b*	*c*
Boreal	0.90(+-0.088)	0.091(+-0.014)	
Temperate	0.87(+-0.041)	0.053(+-0.00645	
Tropical	0.98(+-0.052)	-0.0067(+-0.0087)	-0.0064(+-0.0013)

Source: Way and Oren (2010).

Temperature change and forest growth

Way and Oren (2010) find that trees in boreal, temperate, and tropical zones respond differently to increased temperature. The response is positive and largest in boreal ecosystems, much lower but still positive in temperate ones, and negative in tropical zones. Table 3 shows the parameters of linear and quadratic equations reported by Way and Oren (2010) to summarize the results of numerous experiments dealing with tree growth in total mass. In these equations the response to a change in growth temperature (assumed here over the growing season) is measured by dividing the treatment value by the control value. Thus, response of 1 means that the temperature change has no effect on tree growth, a response <1 means that the change in temperature reduces growth, and a response >1 means that the temperature change increases growth (Way and Oren, 2010).

For example, with the equations in Table 3, a rise in temperature of 2.8^{o}C implied by the A1B scenario led to a response of 1.1548, i.e. an increase in total mass of 15.48 percent in boreal forests. Since the 2.8^{o}C rise in temperature was over 100 years, the annual increase in growth rate in total mass was $1.1548^{1/100}$-1=0.0014 or 0.14 percent per year. This was then the predicted impact of the temperature change on the forest growth rate used in the GFPM, the value of the parameter g_u^* in equation (2). In contrast, in tropical forests the same temperature increase of 2.8^{o}C led to a response of 0.9111 i.e. a decrease in total mass of 8.89 percent over a century, and a $g_u^* = -0.09$ percent per year. Figure 3 shows the adjustments of the forest growth rates g_u^* for the temperature changes in the three scenarios and for the boreal, temperate and tropical forests. As the GFPM only deals with national statistics, countries were broadly classified as having mostly forests of the boreal, temperate, or tropical type according to their mean monthly annual temperatures (MAT) from 1961 to 1999 (World Bank 2011). For the 180 GFPM countries, those with MAT≤1.5^{o}C were classified as Boreal, those with 3^{o}C ≤ MAT≤19.7^{o}C as temperate and those with MAT≥20^{o}C as tropical.

Results

Effects on forest stock

Table 4 summarizes the long-term effect of the rise in temperature on the forest stock, by scenario, for major world regions and selected countries. For each region, the effect was measured by the difference in projected forest stock in 2065 between the simulations with and without temperature increase. Globally, the largest predicted effect was a decrease in total forest stock of 4.2x10^9 m^3 (approximately 1%) under scenario B2. This was due to a 10.7 x10^9 m^3 (3%) decrease in growing stock in developing countries, which was only partially compensated by a 6.5 x10^9 m^3 (2%) increase in growing stock in developed countries. The main negative regional effect was in South America, where the growing stock was 6.2 to 8.2 x10^9 m^3 (4% to 5%) lower depending on the scenario, largely due to decreases in growing stock in Brazil. Other large negative impacts were in Africa where the growing stock was 3.1 to 4.3 x10^9 m^3 (4% to 6%) lower depending on the scenario.

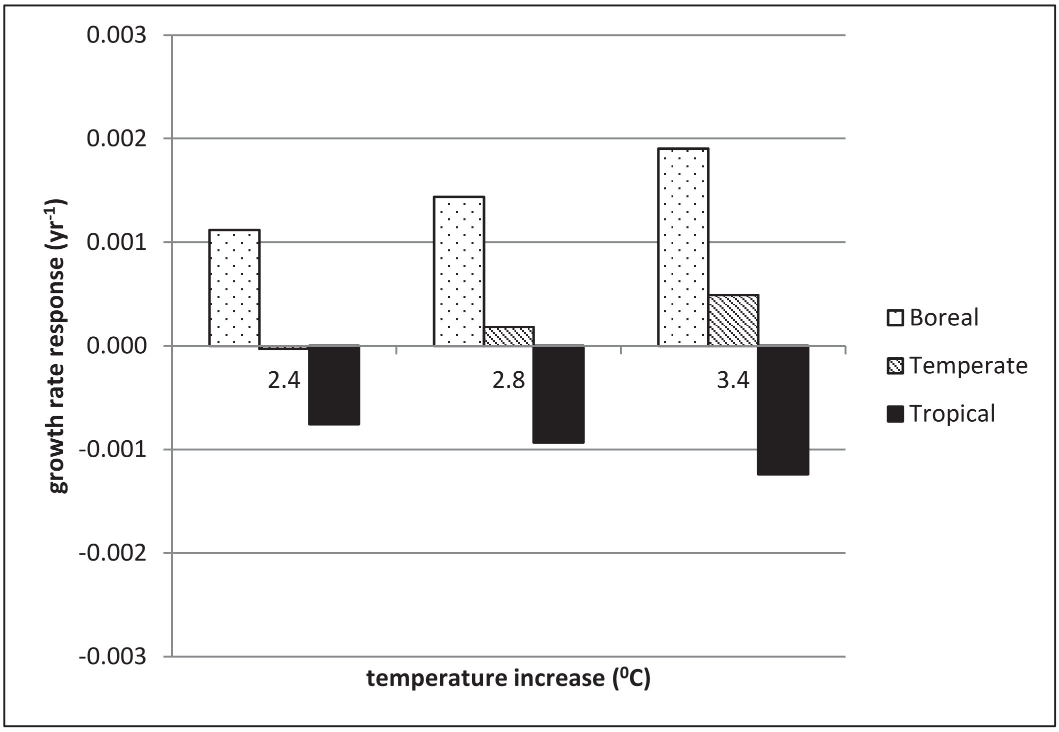

Figure 3: Projected response of forest stock growth rates to temperature changes of 2.4 °C (scenario B2), 2.8 °C (scenario A1B) and 3.4 °C (scenario A2).

In contrast, the rise in temperature led to higher growing stocks in 2065 principally in Europe, and mostly due to the positive impact in Russia: 4.6 to 8.4 x10^9 m^3 (5% to 10%). The growing stock was also higher in North America, but by lesser amounts (1.5 to 4.8 x10^9 m^3 or 1% to 4%), mostly due to changes in Canadian forests, and secondarily to those in the United States. In Asia, the changes in growing stock were negative under scenarios B2 and A1B due principally to changes in India and Indonesia, but under scenario A2 this was totally compensated by the increase in growing stock in China.

Effects on wood production

The differences in annual roundwood production (fuelwood and industrial roundwood) in 2065 due to rising temperatures are in Table 5. The changes were due to the shift of wood supply induced by the changes in growing stock in conjunction with movements along the wood supply curves due to the price changes described below. Globally, production was higher in all three scenarios. The largest increase occurred with scenario A2 (20.1x10^6 m^3/year or 1% difference). But there was a sharp contrast between developed countries where production was 75.2x10^6 m^3/year or 4% higher, and developing countries where production was 55.1x10^6 m^3/year or 3% lower with the A2 scenario.

The major increases in wood production took place in Europe, especially in Russia where it was 25.6 to 41.4x10^6 m^3/year (10% to 17%) higher depending on the scenario due to the rise in temperature. There were also notable rises in production in Canada: 15.2 to 28.1x10^6 m^3/year or 10% to 13%, and in Scandinavian countries: 6% to

12% in Finland and Sweden. Changes were much more modest in temperate regions. In the United States for example, production was slightly lower, due to lower prices, even though growing stock was somewhat higher in conjunction with higher temperatures.

Rising temperature induced major decreases in roundwood production in South America where in Brazil in particular production was 13.5 to 27.5 $x10^6$ m^3/year (5% to 9%) lower depending on the scenario. In Asia production decreased by 16 to $24x10^6$ m^3/year mostly due to the effects in India and Indonesia. Lesser negative changes occurred in Africa and Oceania.

Effects on wood prices

As indicated above and in Figure 1, the price changes induced by a rise in temperature depend on the magnitude of the positive and negative shifts of wood supply induced by changes in the growth rate of forest stock stimulated or hampered by global warming. Figure 4 shows the GFPM predicted differences due to temperature increases for the world prices of fuelwood and industrial roundwood, and the price of one derived product, sawnwood, from 2012 and 2065, according to the three scenarios. In all cases the world price was defined as the unit value of world exports.

For all three scenarios the prices were lower in 2065 than they would have been without temperature change, in accord with the global increase in growing stock induced by the rise in temperatures (Table 4) and the attendant wood supply shift. In all cases, the relative price impact was similar for fuelwood and industrial roundwood, and substantially less for sawnwood, an end product for which a substantial part of the manufacturing cost is due to non-wood inputs: capital, labor, and energy. Regardless, under the B2 scenario, the price impacts in 2065 were hardly noticeable, about -1% for industrial roundwood, and -0.5% for sawnwood.

The largest predicted price effects were observed with scenario A2. As shown in Figure 4, the price differences increased steadily over time as global temperatures increased. By 2065, the prices of fuelwood and industrial roundwood were both approximately 5% lower than they would have been without changes in temperature, and the price of sawnwood was 2% lower.

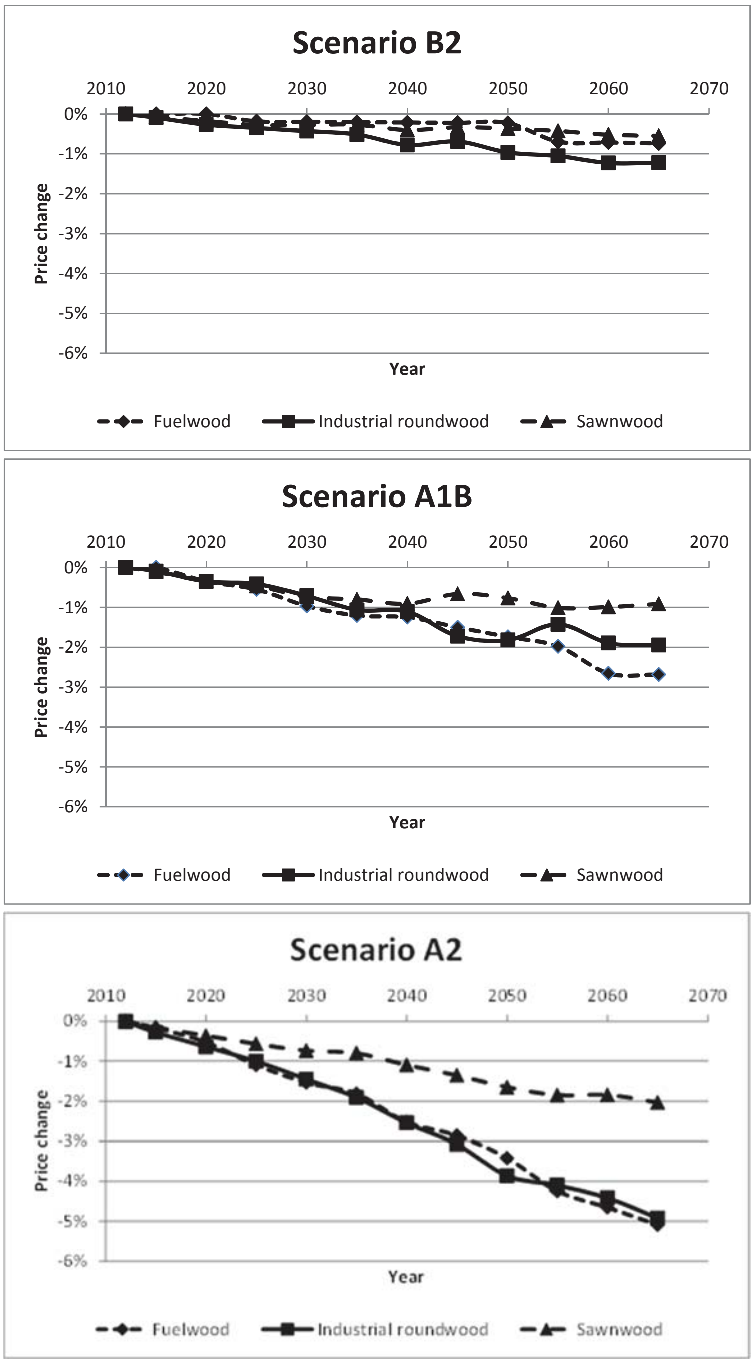

Figure 4. Projected changes in world prices of roundwood and fuelwood due to temperature changes, by scenario.

Table 4: Projected differences in forest growing stock in 2065 due to temperature changes, by region and selected countries (10^6 m^3).

	Scenario					
	B2		A1B		A2	
AFRICA	**-3081**	**-4%**	**-3550**	**-5%**	**-4269**	**-6%**
South Africa	12	1%	20	2%	49	4%
N/C AMERICA	**1523**	**1%**	**2588**	**2%**	**4817**	**4%**
Canada	1637	5%	2096	7%	3116	10%
Mexico	-131	-4%	-145	-5%	-179	-7%
United States	152	0%	808	1%	2070	3%
SOUTH AMERICA	**-6232**	**-4%**	**-6852**	**-4%**	**-8193**	**-5%**
Argentina	3	0%	34	1%	60	3%
Brazil	-4968	-4%	-5546	-4%	-6792	-6%
Chile	15	1%	37	2%	96	4%
ASIA	**-948**	**-1%**	**-620**	**-1%**	**41**	**0%**
China	47	0%	318	1%	1050	2%
India	-360	-3%	-368	-3%	-497	-4%
Indonesia	-336	-4%	-385	-5%	-459	-6%
Japan	7	0%	25	1%	75	3%
Korea, Republic of	3	0%	31	1%	68	2%
Malaysia	-186	-3%	-205	-3%	-240	-4%
OCEANIA	**-398**	**-3%**	**-400**	**-3%**	**-491**	**-3%**
Australia	-306	-4%	-323	-4%	-446	-5%
New Zealand	12	0%	43	2%	104	3%
EUROPE	**4928**	**4%**	**6517**	**5%**	**10111**	**7%**
EU-28	204	1%	474	1%	1238	3%
Austria	6	0%	18	1%	41	3%
Finland	27	1%	22	1%	92	3%
France	26	1%	63	1%	160	3%
Germany	31	0%	91	1%	217	3%
Italy	1	0%	30	1%	77	2%
Russian Federation	4625	5%	5828	7%	8374	10%
Spain	5	0%	12	1%	48	3%
Sweden	45	1%	45	2%	139	4%
United Kingdom	3	1%	7	2%	18	4%
DEVELOPED	**6456**	**2%**	**9220**	**4%**	**15143**	**6%**
DEVELOPING	**-10665**	**-3%**	**-11535**	**-3%**	**-13125**	**-4%**
WORLD	**-4209**	**-1%**	**-2316**	**0%**	**2018**	**0%**

Table 5. Projected differences in roundwood production in 2065 due to temperature changes, by region and selected countries (10^3 m^3).

	Scenario					
	B2		A1B		A2	
AFRICA	**-3887**	**-1%**	**-4624**	**-1%**	**-7452**	**-2%**
South Africa	-171	0%	270	1%	34	0%
N/C AMERICA	**7227**	**1%**	**24367**	**2%**	**14092**	**2%**
Canada	15251	10%	28066	13%	19873	14%
Mexico	-825	-2%	-1269	-3%	-1189	-3%
United States	-6722	-1%	-1101	0%	-3771	-1%
SOUTH AMERICA	**-14563**	**-4%**	**-28319**	**-6%**	**-20496**	**-5%**
Argentina	-73	0%	-175	-1%	141	1%
Brazil	-13535	-5%	-27540	-9%	-19962	-8%
Chile	-255	-1%	325	1%	215	0%
ASIA	**-15937**	**-1%**	**-23769**	**-2%**	**-24222**	**-2%**
China	-1114	0%	1754	0%	4376	1%
India	-3690	-1%	-11027	-3%	-13250	-4%
Indonesia	-5197	-5%	-7460	-6%	-6189	-6%
Japan	-106	-1%	80	0%	63	0%
Korea, Republic of	-81	0%	10	0%	-104	-1%
Malaysia	-2468	-7%	-4135	-9%	-3739	-13%
OCEANIA	**-3012**	**-5%**	**-4811**	**-5%**	**-4345**	**-7%**
Australia	-2195	-8%	-3881	-10%	-3633	-14%
New Zealand	-270	-1%	50	0%	128	1%
EUROPE	**33794**	**3%**	**51097**	**4%**	**62498**	**6%**
EU-28	7334	1%	15389	2%	19472	3%
Austria	-160	-1%	79	0%	73	0%
Finland	5040	6%	6059	8%	9144	12%
France	-843	-1%	133	0%	-402	-1%
Germany	-848	-1%	322	0%	-615	-1%
Italy	-3	0%	-13	0%	61	1%
Russian Federation	25638	10%	33390	11%	41431	17%
Spain	-27	0%	238	1%	36	0%
Sweden	5998	7%	7546	8%	10684	12%
United Kingdom	-75	-1%	94	1%	42	0%
DEVELOPED	**39585**	**2%**	**74592**	**3%**	**75214**	**4%**
DEVELOPING	**-35963**	**-2%**	**-60651**	**-3%**	**-55139**	**-3%**
WORLD	**3622**	**0%**	**13940**	**0%**	**20074**	**1%**

Table 6. Projected differences in roundwood trade in 2065 due to temperature changes, by region and selected countries (10^3 m^3).

	Exports			Imports		
	B2	A1B	A2	A2	A1B	A2
AFRICA	**-814**	**-1239**	**-3031**	**136**	**278**	**94**
South Africa	-507	-254	-2254	0	0	0
N/C AMERICA	**5689**	**16079**	**10431**	**54**	**-102**	**-110**
Canada	13915	21578	16401	-98	-113	-135
Mexico	0	0	0	84	1	3
United States	-8034	-5162	-5614	0	0	0
SOUTH AMERICA	**-373**	**-25116**	**-2172**	**4**	**5**	**18**
Argentina	0	2	0	0	0	2
Brazil	0	-24759	0	1	0	10
Chile	-289	197	-373	0	0	0
ASIA	**-3644**	**-1333**	**-4510**	**574**	**3559**	**1895**
China	0	-2	0	-9	-2803	-9430
India	0	-1	0	2	6888	10773
Indonesia	0	0	0	1	76	76
Japan	0	0	0	150	-618	89
Korea, Republic of	0	0	0	-3	30	0
Malaysia	-1729	-228	-1160	0	0	0
OCEANIA	**-3471**	**-5425**	**-5308**	**4**	**28**	**8**
Australia	-2289	-3972	-4081	4	4	6
New Zealand	-667	-513	-223	0	0	0
EUROPE	**-2039**	**3341**	**-488**	**-5423**	**-17459**	**-6983**
EU-28	-2332	3226	-1377	-5429	-17559	-6993
Austria	0	0	0	810	1130	1927
Finland	0	0	0	-4509	-8168	-8978
France	-508	126	-600	0	0	0
Germany	0	0	0	427	-258	-3108
Italy	0	0	0	-2	-197	-30
Russian Federation	-43	-2898	0	0	0	2
Spain	-25	-1	-5	80	-1126	530
Sweden	0	0	0	-5097	-12378	-451
United Kingdom	-76	493	32	0	0	0
DEVELOPED	**379**	**15020**	**3742**	**-5370**	**-18168**	**-7018**
DEVELOPING	**-5031**	**-28712**	**-8820**	**719**	**4476**	**1940**
WORLD	**-4652**	**-13692**	**-5078**	**-4651**	**-13692**	**-5078**

Table 7. Projected differences in value added in 2065 due to temperature changes, by region and selected countries ($\$10^6$).

	Scenario					
	B2		A1B		A2	
	($\$10^6$)		($\$10^6$)		($\$10^6$)	
AFRICA	**8**	**0%**	**132**	**1%**	**646**	**8%**
South Africa	113	3%	191	6%	599	17%
N/C AMERICA	**934**	**1%**	**4185**	**2%**	**3096**	**2%**
Canada	461	3%	2535	12%	1292	10%
Mexico	-25	0%	-214	-2%	-176	-2%
United States of America	505	0%	1887	1%	1981	2%
SOUTH AMERICA	**-2001**	**-4%**	**-283**	**0%**	**-1097**	**-3%**
Argentina	-21	-1%	-31	-1%	40	2%
Brazil	-1936	-5%	-206	0%	-1502	-5%
Chile	17	1%	50	2%	67	3%
ASIA	**-951**	**0%**	**-4366**	**0%**	**-906**	**0%**
China	363	0%	-514	0%	89	0%
India	-258	-1%	-370	-1%	432	2%
Indonesia	-749	-4%	-1353	-4%	-725	-4%
Japan	45	0%	-442	-1%	235	1%
Korea, Republic of	-46	0%	41	0%	-108	-1%
Malaysia	-158	-2%	-1318	-5%	-489	-6%
OCEANIA	**255**	**2%**	**283**	**2%**	**314**	**3%**
Australia	52	1%	64	1%	134	2%
New Zealand	200	4%	212	2%	148	3%
EUROPE	**3188**	**1%**	**3422**	**1%**	**5555**	**2%**
EU-28	2310	1%	2972	1%	3888	2%
Austria	464	1%	779	2%	655	2%
Finland	208	2%	474	4%	567	6%
France	-65	-1%	-113	-1%	70	1%
Germany	993	2%	1150	1%	561	1%
Italy	-5	0%	-75	-1%	-3	0%
Russian Federation	820	2%	565	1%	1547	5%
Spain	-66	0%	-664	-3%	243	2%
Sweden	144	1%	39	0%	1033	10%
United Kingdom	27	1%	-30	0%	32	1%
DEVELOPED, ALL	**4555**	**1%**	**7875**	**1%**	**9941**	**2%**
DEVELOPING, ALL	**-3122**	**0%**	**-4501**	**0%**	**-2333**	**0%**
WORLD	**1433**	**0%**	**3374**	**0%**	**7608**	**1%**

Effects on trade

Table 6 summarizes the projected effects of temperature changes on imports and exports of wood (fuelwood and industrial roundwood), in major world regions and selected countries. Depending on the scenario, the total world trade was approximately 5 to 14 million m^3 lower in 2065 than it would have been without temperature change. The largest change was in developing countries where with scenario A1B exports decreased by nearly 29 million m^3 while imports increased by 4.5 million m^3. In contrast, the balance of trade improved for developed countries, as exports were 15 million m3 per year higher in 2065 and imports were 18 million m^3 lower. The main increase in exports was in North America where Canadian exports in particular were, depending on the scenario, 14 to 22 million m^3/year higher in 2065 than they would have been without the increase in temperature. Symmetrically, countries in Asia tended to have lower exports and larger imports. India's imports in particular increased by 7 to 11 million m3/year under scenarios A1B and A2. The net trade of Europe improved with higher temperatures mostly due to lower imports, especially in countries of the European Union. However, there was generally little change in Russian imports and exports, despite the rise in production of 10% to 17% induced by temperature increase in 2065 (Table 5).

Effects on value added

The impact of the rises in global temperatures on forest industries are summarized in Table 7. For the purpose of this paper, value added was defined as the difference between the value, at local prices, of the products considered in the GFPM minus the cost of the wood and fiber inputs used in production.

At world level, there was practically no change in value added under scenario A1B and B2. With scenario B2, the world value added was only $1.4x10^9$ (0.1%) higher with the rise in temperature than without it. The largest world increase in value added was with scenario A2, but still no more than 1% higher than without temperature change. However, with all three scenarios there was a marked difference between developed and developing countries. For scenario A2 value added increased by approximately \$$10x10^9$ (2%) in the developed countries while it decreased by \$$2.3x10^9$ (3%) in developing countries. For scenarios B2 the increase in value added was nearly the same as the decrease in developing countries.

The largest regional increase in value added was in Europe under scenario A2, due in large part to positive changes in Russia and Scandinavian countries. The largest decrease was in Asia under A1B, stemming from changes in Indonesia and Malaysia in particular. Due to differences in manufacturing cost and resulting competitive advantage of countries, there was only a rough correlation between the changes in value added in Table 7 and the changes in production in Table 5, R^2=0.69 for the relative changes under A2. For Russia for example, while production was 11% higher due to temperature change, value added was only 5% higher, and in Germany value added actually increased despite a small decrease in production.

Summary and conclusion

The objective of this paper was to explore the potential effects of future global warming on the forest sector. Way and Oren's (2010) synthesis provided quantitative estimates of the effects of temperature changes on tree growth, suggesting a positive and largest response in boreal climates, a slightly positive effect in temperate conditions, and a strong negative effect in tropical environments.

This change in productivity was applied to national forest growth rates in the Global Forest Products Model in accord with the rises in temperature projected by the

International Panel for Climate Change scenarios A1B, A2, and B2, together with the different growth rates of gross domestic product and population attendant to the three scenarios.

For each scenario, projections of forest stock, wood production, wood prices, trade, and value added were obtained with the GFPM for the years from 2012 to 2065, with and without temperature changes.

According to the results, in the three scenarios, the projected global growing stock of forests in 2065 was hardly changed by the rise in temperature. Thus, globally, the temperature change would have little effect on carbon sequestration. However, the forest stock was 2% to 6% higher in developed countries while it was 3% to 4% lower in developing countries.

Consequently the wood supply, the harvest, and the net trade (export minus imports) increased in Europe and North America, but decreased in Asia and South America. In conjunction with this higher supply, world wood prices were lower with global warming, and the value added in wood industries increased in Europe and North America while it decreased in Asia and South America.

These findings rely on strong assumptions; in particular that the effects of rising temperature can be summarized over very different forest types by the equations suggested in Way and Oren (2010). Although the patterns of response that they observe are striking and useful in large spatial scale models like the GFPM where more detailed data are lacking (Ryan 2010), much work is still needed to quantify the effect of temperature apart from or in conjunction with changes in related factors, such as 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 2015).

Despite these limitations, an important result of the present study was to show that the impact of temperature, and thus of climate change in general, depended strongly on the economic and demographic scenarios in which it occurred. But regardless of scenario, the study predicted that while temperature change had a neutral effect on global carbon sequestration, it had a series of strong beneficial effects in developed countries, from increase in growing stock to more value added, but harmful effects in developing countries for the same components.

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References

Boisvenue, C., and S.W. Running. 2006. Impacts of climate change on natural forest productivity-evidence since the middle of the 20th century. Global Change Biology 12: 862–882, doi: 10.1111/j.1365-2486.2006.01134.x

Buongiorno, J. 2014. Global modeling to predict wood production and prices: The GFPM approach. Forestry 88:291-303.

Buongiorno, J. 2015. Income and time dependence of forest product demand elasticities and implications for forecasting. Silva Fennica 49(5) id 1395 (Available at http://dx.doi.org/10.14214/sf.1395).

Buongiorno J, Zhu S, Raunikar R, Prestemon JP (2012) Outlook to 2060 for world forest and forest industries: a technical document supporting the Forest Service 210 RPA assessment. USDA Forest Service Southern Research Station, General Technical Report SRS-151, 119p.

Buongiorno, J., and S. Zhu. 2015a. Technical change in forest sector models: the global forest products model approach. Scand. J. For. Res., 2015 30(1):30-48.

Buongiorno, J., and S. Zhu. 2015b. Calibrating and Updating theGlobal Forest Products Model(GFPM version 2015 with BPMPD). Staff Paper Series #84, Department of Forest and WildlifeEcology, University of Wisconsin-Madison Madison. 29p. http://labs.russell.wisc.edu/buongiorno/ Accessed 19 Jan 2016.

Buongiorno J, Zhu S. 2016. Using the Global Forest Products Model (GFPM version 2016 with BPMPD). Staff Paper Series # 85. Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 35p. http://labs.russell.wisc.edu/buongiorno/ Accessed 19 Jan 2016.

FAO 2010. Global forest resources assessment. FAO Forestry Paper 163. Food and Agriculture Organization of the United Nations. Rome. 340pp.

FAO 2015. FAOSTAT, Food and Agriculture Organinzation of the United Nations. http://faostat3.fao.org/download/F/FO/E (last accessed December 2015).

IPCC. 2007. International Panel on Climate Change. Climate Change 2007: Working Group I: The Physical Science Basis. Available at: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html (last accessed December 11, 2015).

Kirilenko AP, Sedjo RA (2007) Climate change impacts on forestry. Proceedings of the National Academy of Sciences 104: 19697-19702.

Koop, G, and L. Tole. 1999. Is there an environmental Kuznets curve for deforestation ? *J. Dev. Econ.* **58**, 231-244.

McCarl B, Adams DM, Alig RJ, Burton D, Chen CC (2000) Effects of global climate change on the US forest sector: response functions derived from a dynamic resource and market simulator. Climate Research 15:195-205.

Mészáros, C. 1999. The BPMPD interior point solver for convex quadratic problems: *Opt. Meth. and Software* 11&12:431-449.

Nabuurs GJ, Prussinen A, Karjalainen T, Herhard M, Kramer K (2002) Stem volume increment changes in European forests due to climate change—a simulation study with the EFISCEN model. Global Change Biology 8:304-316.

Nakicenovic N, Davidson O, Davis G, Grübler A, Kram T, Lebre La Rovere E, Metz B, Morita T, Pepper W, Pitcher H, Sankovski A, Shukla P, Swart R, Watson R, Zhou D (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press,

Cambridge, U.K., 599 pp. http://www.grida.no/climate/ipcc/emission/index.htm Accessed 3 Dec 2014.
NASA. 2015. Global temperature. National Aeronautic and Space Administration. Available at: http://climate.nasa.gov/vital-signs/global-temperature/ (last accessed December 2015).
Perez-Garcia J, Joyce LA, McGuire AD, Xiao X (2002) Impacts of climate change on the global forest sector. Climatic Change 54: 439-461.
Ryan, M.G. 2010. Temperature and tree growth. Tree Physiology 30:667-668.
Samuelson, P.A. 1952. Spatial price equilibrium and linear programming. *Am. Econ. Rev.* **42**, 283-303.
Sohngen B, Sedjo R (2005) Impacts of climate change on forest product markets: Implications for North American producers. The Forestry Chronicle 81(5): 689-674.
Solberg B, Moiseyev A, Kallio AMI (2003) Economic impacts of accelerating forest growth in Europe. Forest Policy and Economics 5:157-171.
Takayama, T., and Judge, G. 1971. *Spatial and temporal price and allocation models*. North-Holland, Amsterdam. 528p.
Turner, J., J. Buongiorno, and S. Zhu. 2006. An economic model of international wood supply, forest stock and forest area change. *Scand. Journal . For. Res.* **21**,73-86.
USDA Forest Service (2012) Future of America's forest and rangelands: Forest Service 2010 Resources Planning Act Assessment. United States Department of Agriculture, Forest Service, General Technical Report WO-87, Washington DC.
Way, D.A., and R. Oren. 2010. Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data. Tree Physiology 30:669–688 doi:10.1093/treephys/tpq015
Woodbury, P.B., J.E. Smith and L.S. Heath. 2007. Carbon sequestration in the US forest sector from 1990 to 2010. For. Ecol. Manage. 241:14–27.
World Bank. 2011. Historical temperature and precipitation data. Climate Research Unit, World Bank. Available at: http://data.worldbank.org/developers/climate-data-api (last accessed December 2015).
WTO. 2013. Tariffs data. World Trade Organization. http://tariffdata.wto.org/ReportersAndProducts.aspx (Accessed July 9, 2013).