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Can the Global Forest Sector Survive 11°C Warming?

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Can the Global Forest Sector Survive 11°C Warming?

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Summary

It is well known that the forestry sector is sensitive to climate change but most studies have examined impacts only through 2100 and warming of less than 4°C. This is the first timber analysis to consider possible climate change impacts out to 2250 and warming up to 11°C above 1900 levels. The results suggest that large productivity gains through 2190 lead to a continued expansion of the global timber supply. However, as carbon fertilization effects diminish and continued warming causes forestland to continue to shrink, warming above 8°C is predicted to become harmful to the forest sector.

Keywords: Climate change, RCP 8.5, Forestry, Dynamic optimization, Timber market

JEL Classification: Q5, Q23

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1. Introduction

The forestry sector is sensitive to climate change and it is likely that changing temperature and precipitation pattern will produce a strong direct impact on both natural and managed forests (Kirilenko and Sedjo 2007). On the one hand, climate change can accelerate vegetation growth with a warmer climate, longer growth seasons, and elevated atmospheric CO_2 concentrations as well as affect forest composition (Harsch et al. 2009). On the other hand, the climate change can increase the frequency and intensity of forest wildfires, insect and pathogen outbreaks, and shifting biomes (Scholze et al 2006, Bachelet et al 2008, Gonzalez et al 2010).

The way in which markets adapt to climate change-induced changes in forest growth and dieback will have important effects on projections of timber outputs, forest stocks, and the carbon stored in forested ecosystems. A number of models have been developed to capture ecological impacts and to assess the potential economic effects of climate change on the forestry sector (e.g., Joyce et al 1995, Sohngen and Mendelsohn 1998, Sohngen et al. 2001; Perez-Garcia et al., 2002; Hanewinkel et al., 2014; Tian et al. 2016; see Appendix I). These studies show that climate change could have a large impact on timber supply, altering global timber prices, and changing the incentives to manage forests.

All of the existing studies have focused on a century or less of potential climate changes, assuming that carbon emissions ultimately will fall, and climate will stabilize in the long run. However, given the difficulties of organizing global mitigation strategies, it is possible that greenhouse gas concentrations will not stabilize and will in fact lead to continued warming beyond 2100.

This study examines the severe warming associated with the Representative Concentration Pathway (RCP) scenario of 8.5 W/m^2 radiative forcing level in 2100 along with the Shared Socio-economic Pathway (SSP5) that could possibly cause it. By utilizing climate model forecasts that have been made through 2300, this study assesses how ecosystems will change and how this could affect the forest sector under an extreme climate change scenario. The much longer time frame opens up the possibility of much more severe warming scenario than the literature has examined before such as warming up to 11°C above 1900 levels. The RCP 8.5 scenario is compared to a scenario without climate change (Baseline). These scenarios are examined in the context of an ever evolving ecosystem and forestry sector.

The dynamic ecosystem response is captured by the LPX-Bern Global Dynamic Vegetation Model (Stocker et al. 2013; Mendelsohn et al. 2016). The LPX-Bern Model predicts three changes in ecosystems as a result of climate change. First, the growth of timber will change, first rising and then stabilizing. Second, some of the standing stock will be lost to dieback from direct temperature effects, forest fires, and insects. Third, the distribution of biomes and timber species over space will change radically as species move poleward and to higher altitudes. All of this happens at particular dynamic rates which are part of the ecosystem model.

An extended version of the Global Timber Model GTM (Sohngen et al. 2003) is developed to study how the forest sector will respond to these future challenges. The timber model is a forward looking model that examines what changes should be made in advance of all these future effects. For example, the model predicts increasing harvest rates of stands that have an ever increasing rate of dieback. The model encourages planting of new trees that will prosper given the future climate that they will endure. The model intensifies management in places that become more productive and will reduce management intensity in places that become less productive. Finally, the model predicts future timber prices that will dictate the amount of forestland that will be managed and the amount of forestland that will remain natural (unmanaged).

The paper is organized as follows. Section 2 describes the method and the model used for the analysis. Section 3 analyzes the results of the model in terms of changes in timber market and forestland under the RCP 8.5 and compares them with the Baseline scenario (without climate change). Finally, Section 4 summarizes the results and discusses their implications.

2. Methods

2.1. Model

The Global Timber Model GTM (Sohngen et al. 2001; 2003) used in this study contains 200 forest types *i* in 16 regions that can be aggregated into four broad categories: boreal, temperate hardwood, temperate softwood, and tropical. The model assumes there is a social planner maximizing the present value of the net difference between consumer surplus and the costs of holding timberland and managing it over time. It is an optimal control problem given the aggregate demand function, starting stock, costs, and changing growth functions of forest stocks. It endogenously solves for timber prices and the global supply of timber and optimizes the harvest of each age class, management intensity, and the area of forestland at each moment in time. GTM is forward looking with complete information.

The problem is written formally as:

$$\max \sum_0^{\infty} \rho^t \left\{ \int_0^{Q_t} \{D(Q_t, Z_t) - f(Q_t)\} dQ_t - \sum_i p_m^i m_t^i G_t^i - \sum_i C^i(N_t^i) - \sum_i R^i\left(\sum_a X_{a,t}^i\right) \right\} \quad (1)$$

where ρ is a discount factor, $D(Q_t)$ is wood demand, $f(Q_t)$ is the cost of harvesting and transporting timber to the mill, p_m is the price of management intensity m_i, G_t is planted acreage, $C(N_t)$ is the cost of new forestland, $R(\sum X_{a,t})$ is the opportunity cost of land $X_{a,t}$. The model assumes that management intensity is determined at the moment of planting and planting costs vary depending upon management intensity.

The timber demand function, Q_t, is assumed to grow over time as the global economy grows:

$$Q_t = A(Z_t)^{\theta}(P_t)^{\omega}, \quad (2)$$

where *A* is a constant, Z_t is the projected global consumption per capita over time, θ is the income elasticity of 0.87, P_t is the international price of wood and ω is the price elasticity. We use the consumption per capita forecasts of the SSP's to predict Z_t (see Section 2.2).

To determine the quantity produced in each region, the model chooses the age class to harvest trees. Thus, the total quantity harvested Q_t will be obtained by summing the volume of timber on each hectare harvested in each age class and species type. The total timber area is tracked by the stock variable $X_{a,t}$ and it adjusts over time. Timber shifts from one age class to the next, unless harvests occur.

GTM takes into account the competition of forestland with farmland using a rental supply function for land (Sohngen and Mendelsohn, 2003). In Equation (1) R is the rental cost function for holding timberland $X_{a,t}$. This supply function is restricted to farmland that is naturally suitable for forests according to the ecological model. It reflects the opportunity cost of agricultural rents lost when land is moved from farmland to forestland. It presumes that the forest will acquire the least productive farmland first in each region of the world.

In order to include climate change impacts on world forests, we include in the model three expected impacts of climate change as predicted by the LPX-Bern Global Dynamic Vegetation Model (GDVM): (a) changes in the growth of timber; (b) changes in dieback; (c) changes in the distribution of biomes and timber types. The LPX-Bern GDVM generates outputs at the 0.5° spatial resolution at a yearly time step, the outputs were then aggregated to decadal averages across world regions for use in the forestry model.

In the forestry model the volume of timber V_t is a function of the cumulative effect of the annual change in net primary productivity (NPP) θ_t as predicted by LPX-Bern Model and management intensity, m_{t0}. The changes in the growth of timber is calculated as:

$$V_t\left(m_{t0}^i, \theta_t^i\right) = \int_{t0}^{t} \dot{V}_s\left(m_{t0}^i, \theta_s^i\right) ds \tag{3}$$

The forestry literature has examined the impact climate is expected to have on timber through 2100 (Sohngen et al. 2001; Reilly et al. 2007; Buongiorno 2015; Tian et al 2016). However, the warming that can happen through 2100 is quite limited so that no scenario has ever explored warming above 4°C. By extending the analysis to 2250, this analysis will include both longer term ecological effects as well as a climate scenario that reaches much higher temperatures. There is more time for higher cumulative emissions, higher temperatures, and more complete ecosystem responses.

We include the effect of dieback by using dieback rates from the GDVM which affect all existing stocks as follows:

$$X_{a,t}^i = (1-\delta_t^i) X_{a-1,t-1}^i - H_{a-1,t-1}^i + G_{a=1,t-1}^i + N_{a=1,t-1}^i \tag{4}$$

where δ is the annual mortality rate from dieback from direct temperature effects, forest fires, and insects as predicted by the vegetation model. We assume that all age classes have equal probability of dieback. Dieback also alters timber harvests because some of the stock that dies back will be salvaged. The salvage enters the equation for net market surplus through harvests.[1]

[1] The proportion of salvage in each timber type varies from zero to 0.60 and it is chosen endogenously by the timber model.

Finally, forest stock is also a function of the movement of biomes across the land. In this study, we include the changes in biomes due to climate change from the vegetation model. In the model, we separate the timber stocks into stocks which shift from one type to another during climate change and stocks which remain in their initial timber type. The distribution of biomes from the vegetation model is derived from the simulated vegetation composition and structure following Prentice et al. (2011). Initial forest stocks are given, and all choice variables are constrained to be nonnegative.

The scenarios are written and solved using GAMS software and the MINOS solver. The models include a nonlinear objective function. The model is solved in decadal time steps starting in 2010. Terminal conditions are imposed on the system for 2300 in order to solve the model and results are shown until 2250.

2.2. Climate and Socio-economic Scenarios

The study compares the future potential climate impacts on global forests under the RCP 8.5 (Riahi et al. 2011; van Vuuren et al. 2011) with a no climate change scenario (Baseline). The CO_2e concentrations in the RCP 8.5 rapidly rise to 1240 ppme by 2100 and to 1686 ppme by 2150, and then start to stabilize reaching 2222 ppme by 2300 (Meinshausen et al 2011). For this study we use a future climate projection from the climate model, HadGEM2. The RCP 8.5 concentration path is entered into HadGEM2 which predicts the future climate across the planet through 2300. The HadGEM2 model predicts that under the RCP 8.5 scenario temperatures increase at a rapid rate through 2150 and then begin to slow down, stabilizing at 11°C above 1900 by 2300.

The LPX-Bern GDVM is then used to simulate the vegetation response to climate change from the present to year 2300 (Mendelsohn et al. 2016). Importantly, the results from the GDVM are provided for potential vegetation. As shown in Table 1, the increase in CO_2 fertilization and warming during the twenty-first century under the RCP 8.5 scenario will increase forest productivity at the aggregate level through 2150 compared to the Baseline. Beyond 2150, productivity stabilizes. On average the increase in forest productivity is greater in boreal and temperate forests than tropical forests. As boreal forest is replaced by temperate forests, productivity rapidly increases.

For the Baseline scenario, we assume the dieback rate is fixed at the current (2010) level. As shown in Table 1, under RCP 8.5, the absolute dieback rate is higher for temperate and boreal regions than tropical regions. However, dieback declines over time in the boreal and temperate regions whereas it is more stable in tropical regions.

The ecosystem model also predicts that the share of each biome will change over time. The changes under the RCP 8.5 scenario are dramatic as shown in Figure 1. The boundaries of each biome shift with warming causing some biomes to contract and others to expand. Overall, global forest potential shifts from the current level of 3,473 million ha to 2,423 by 2150 and then to 1,900 million ha by 2250. Forests are replaced by savanna, parkland, and woodlands which contain only scattered trees and grassland. Potential tropical forests are relatively stable through 2150 declining by 17% and then shrinking from 1,320 to 1,062 million ha by 2250.

Boreal forests decline more rapidly almost disappearing by the end of the 22nd century. Temperate and warm temperate forests grow through 2200 and then stabilize. Temperate forests often replace boreal forests in Canada, Europe, and Russia.

A country and regional level description of these forestland changes is shown over time in Table 2. The changes under RCP 8.5 are dramatic for some countries: Russia, Europe, East Asia, and the United States see the biggest losses of forestland in percentage terms. On the other hand, many tropical regions are unaffected (Central America) or even gain forestland (South Asia and Southeast Asia). Table 2 also reveals that there is not much forestland lost this century. The biggest forestland losses occur in the 22nd century as temperatures begin to exceed 8°C.

For both the RCP 8.5 scenario and the Baseline scenario, we use the 2010-2100 consumption and population from the SSP 5 to calculate global consumption per capita. This increase in income per capita drives global timber demand (Z in Equation 2). We use the SSP 5 because it is the only SSP with enough growth in GDP to generate the greenhouse gas emissions assumed in the RCP 8.5 scenario.[2] For 2100-2300, we follow earlier analyses that assume continued but declining population growth (Interagency Working Group on Social Cost of Carbon, 2010). These assumptions lead to an S-shaped growth in population over time with a 2100 global population of 7.4 billion that then stabilizes. We also assume continued but declining economic growth rate which also leads to an S- shaped growth in GDP over time (Interagency Working Group on Social Cost of Carbon, 2010). This leads to a global GDP of $1,000 trillion in 2100. By 2100, average global consumption has risen to $60,000 per capita and by 2250, consumption has risen to $315,000 per person.

3. Results

The dramatic increase in income causes the demand for timber to increase over time under the climate and no climate scenarios. Even without climate change, the timber prices have to increase in order to supply more wood. The higher timber prices encourage a larger fraction of the forest to be managed for timber and it encourages agricultural land to be converted to forestland. By 2250, under the Baseline scenario, managed land has increased by 20% and natural forestland has decreased by 10% with respect to current levels. The higher timber prices also increase management intensity, increasing supply. By 2100 global average timber yield/ha will be about 50% higher than 2010 levels and by 2250, it will be more than double. Of course, the higher timber prices also serve to temper demand. In the no climate change baseline scenario, timber prices nearly triple over the next 200 years (Figure 2). Wood price peaks in 2190 at 403 $/m^3$ and then declines.

[2] Most of the Integrated Assessment Models reviewed by the IPCC AR5 predict lower concentrations than RCP 8.5 for a no mitigation scenario (Figure 6.7, Clarke et al. 2014) and Riahi et al. (2017) shows that only the SSP 5 baseline scenarios of three models (AIM/CGE, REMIND-MAGPIE and WITCH-GLOBIOM) can reach the 8.5 W/m^2 radiative forcing level by 2100.

The forestry model takes the large shift in demand from the SSP 5 scenario and recognizes it will need more productive forestland in the future to meet demand. The forest model consequently shifts forestland from natural to managed forest. Under the Baseline scenario, the amount of managed forestland increases from 1,200 to 1,500 Mha and the amount of natural forestland falls from 2,290 to 2,105 Mha. The remainder of the increase in managed forestland comes from marginal agricultural lands.

The picture changes under the RCP 8.5 where global forestland will be reduced by 47%. In this case, the forest model requires an even larger fraction of natural forestland which declines by 60% with respect to the Baseline by 2250 (Figure 3). Boreal forest almost disappears because of the ecosystem response to higher temperatures. However, the ecosystem model replaces a great deal of boreal forests with faster growing temperate forest. Most of this temperate forest will be managed. For instance, 95% of the natural forest in Russia (664 Mha) and 75% of the natural forest in Canada (158 Mha) are lost by 2250. There will also be a large loss of natural tropical forestland (570 Mha) with the largest decrease happening in Brazil (Figure 4).

Under the RCP 8.5 scenario, the large gain in forest productivity is more important than the substantial loss in forestland area. Global timber supply increases. The results support the findings in the literature that climate change will increase timber output through 2100. Climate change causes global timber to increase 19% above the Baseline by 2100. The study reveals that this beneficial effect of the climate scenario continues to 2190 where global timber supply peaks at 26% above Baseline. However, further warming after 2190 no longer expands timber supply. Productivity has stabilized as CO_2 concentrations stabilize. Temperatures have reached 8°C. Further increases of temperature are causing continued losses of forestland. Further changes in climate are harmful. By 2250, timber supply under the RCP8.5 is just 21% above Baseline (Figure 5).

Table 3 compares the average annual supply of wood for each period and each region under the RCP 8.5 to the supply in the Baseline. The climate scenario is generally more beneficial to the temperate regions than the tropical regions. Under the RCP 8.5 temperate and boreal forest regions increase their average annual timber supply for 2010-2250 by 34% while tropical regions increase their supply by 9% with respect to the Baseline. This is due to a more significant increase in natural forest productivity and management intensity in the northern forest regions compared to the tropics. The timber model intensifies management especially in the areas where productivity is rapidly rising. For instance, under the RCP 8.5 global average timber yield/ha for 2010-2250 increases by 69% with respect to the Baseline. Tropical forest yield/ha increases 25% while boreal and temperate forests yield/ha increase by 104%. The replacement of boreal forests by temperate forests and carbon fertilization caused a great deal of this increased productivity.

Under the RCP 8.5 scenario, in 2190, timber supply has shifted up and so timber prices are 24% lower than the baseline. Prices stabilize at around 300 $/m^3. The analysis supports earlier findings that climate change leads to an expansion of timber supply through 2100 and therefore lower timber prices. The analysis suggest that this continues until about 2190 where the difference between the prices with no climate change and with climate change are maximized. After 2190, continued warming gradually becomes harmful shrinking the difference in price between the baseline and the climate change scenario. However, the price gap between the baseline and the climate change scenario does not disappear by the end of the analysis in 2250.

4. Conclusions

It is well known that the forestry sector is sensitive to climate change but most studies have examined impacts through 2100 (e.g., Joyce et al 1995; Sohngen and Mendelsohn 1998; Sohngen et al. 2001; Perez-Garcia et al. 2002; Hanewinkel et al. 2014; Tian et al. 2016) and so they have only looked at temperature changes up to 4°C. Within this time frame, global forests are projected to generally expand and become more productive which will be beneficial to the global timber supply.

This is the first timber analysis to consider possible climate change impacts out to 2250. By extending the analysis to 2250, using the rapid emission scenario of RCP 8.5 and the climate model HadGEM2, this study explores the impacts of a severe climate scenario reaching 11°C. Combining the dynamic ecosystem response of LPX-Bern GDVM with the forward thinking dynamic Global Timber Model (GTM), we compare a Baseline no climate change scenario with the RCP 8.5 outcome. The study explores long run adjustments of forests that may occur well beyond 2100 and have been not included in other analysis. In addition, by focusing on the RCP 8.5, the analysis considers possible "catastrophic" ecosystem outcomes. Although the RCP 8.5 scenario may not be a likely outcome for the future, the scenario allows us to explore what would happen if such an extreme scenario came to pass.

The results show that forest ecosystems will be significantly affected by climate change due to changes in forest productivity and biome spatial distribution in the long run. Warming through 2190 appears to be beneficial. The ecosystem model projects big productivity gains from biome shifts towards more productive species and from carbon fertilization. These productivity effects dwarf the loss of forestland as some forests become savannah, parkland, and woodlands. Climate change causes an increase in global timber supply through 2190 as temperatures reach 8°C. Timber prices are lower than the Baseline implying a benefit in this sector. Beyond this point, however, there are no more productivity increases as carbon concentrations stabilize. Additional warming continues to shrink forestland, reducing global timber supply.

Under the RCP 8.5, global forestland will be reduced by 47% and natural forestland will decline by 60% with respect to the Baseline by 2250. The largest losses are in boreal forest which almost disappears. Some of this boreal forest becomes temperate forest. But, Russia loses 664 Mha of total forestland and Canada loses 158 Mha. A great deal of this lost forest is natural forestland. The global forest sector will survive an 11°C warming, but one cost of adaptation is the loss of vast natural forestland of 1,240 Mha. Most of this decline will occur in the 22nd century when the increase in warming is the greatest.

There remain some important topics to study in this field. This study presents one extreme outcome focusing only on the RCP 8.5 emission scenario caused by SSP5. Future research will explore more climate change scenarios and corresponding socio-economic pathways to provide the full range of plausible outcomes for the timber market in the far future. Second, this study did not include climate change mitigation strategies involving the use of forest such as woody biomass production for energy and forest carbon sequestration (Favero et al. 2017). Future research should integrate climate change effects into the decision to use forests for climate change mitigation. Third, the GDVM and the GTM do not examine how future climate and other forces might change agriculture. Climate change, policy, and other future changes could easily change the balance between farmland and forestland. A complete land use model would take into account not only changes in forestland but also changes in farmland. It is important to carefully model the interaction between these two large land-using sectors.

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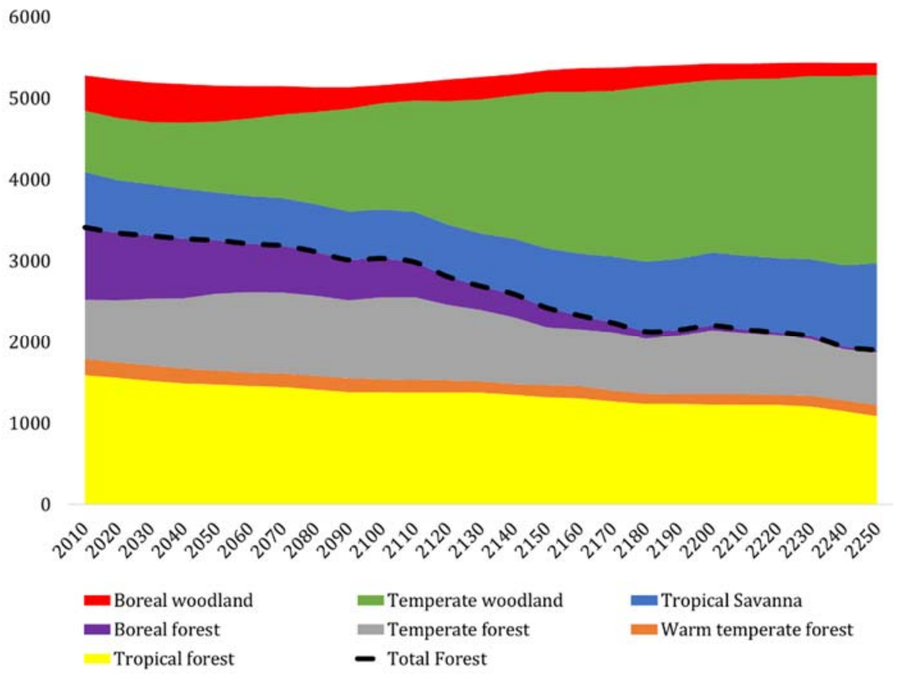
6. List of Figures



Notes: These values do not take into account moving land from agriculture

Figure 1: Distribution of potential natural forestland and woodland under the RCP 8.5 scenario (Mha), data from LPX-Bern Global Dynamic Vegetation Model

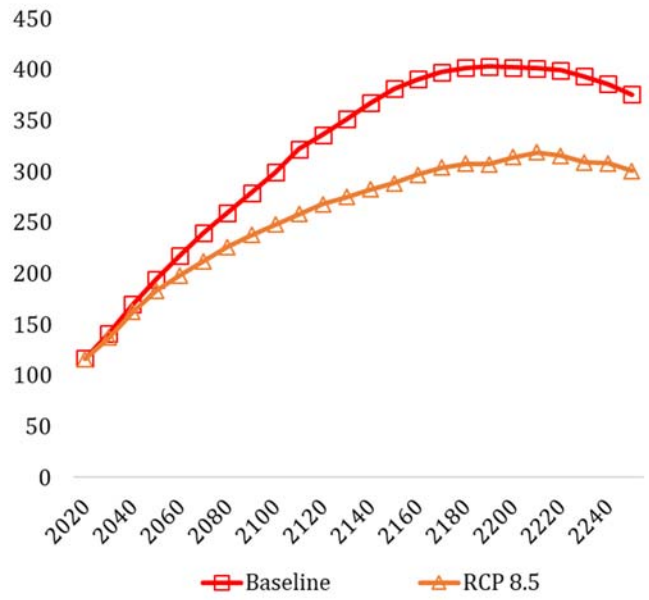


Figure 2: International price of wood (USD/m^3) under the Baseline scenario and the RCP 8.5 climate change scenario.

(a) Managed Forestland **(b) Natural Forestland**

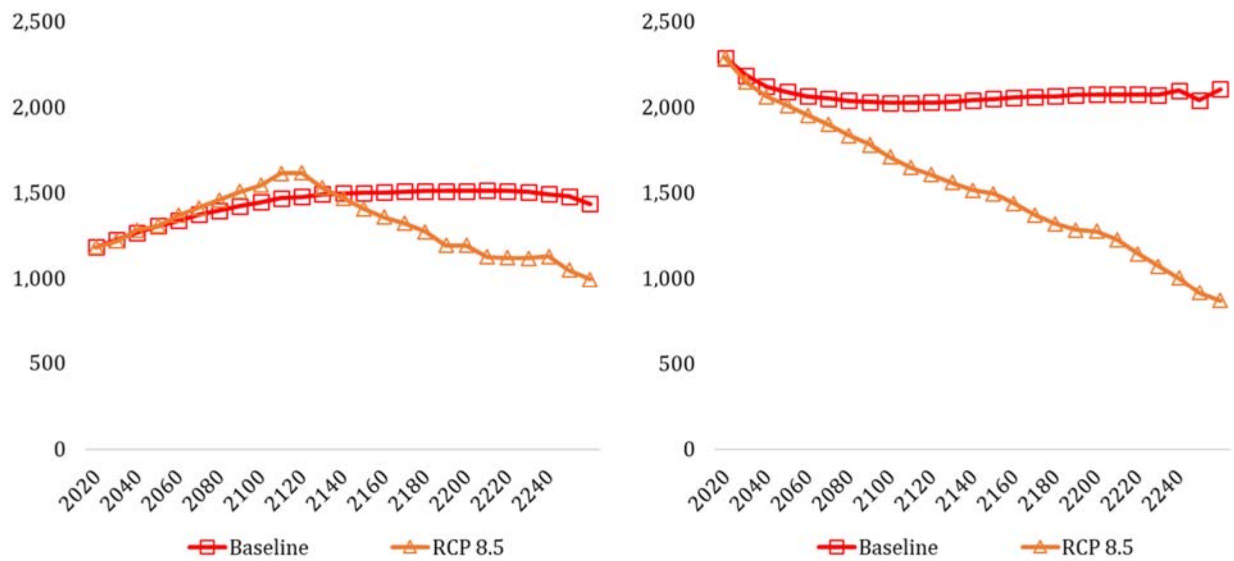


Figure 3: (a) Managed forestland and (b) Natural forestland under the RCP 8.5 and the Baseline scenarios (Mha)

(a) Managed Forestland **(b) Natural Forestland**

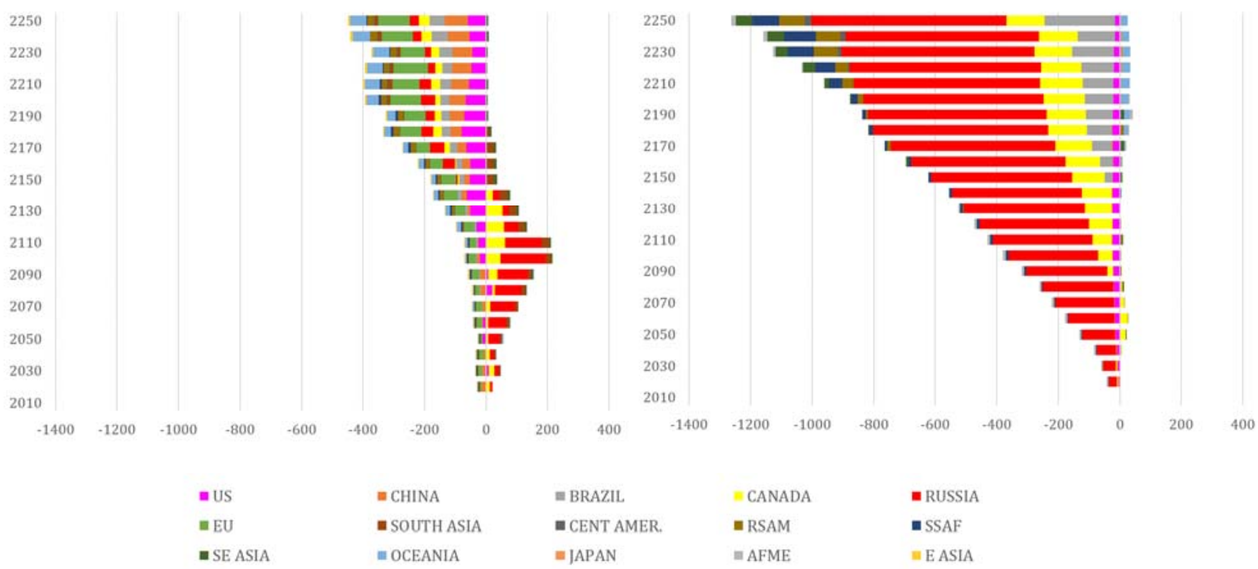


Figure 4: Regional changes in (a) managed and (b) natural forestland under the RCP 8.5 relative to the Baseline scenario (Mha)

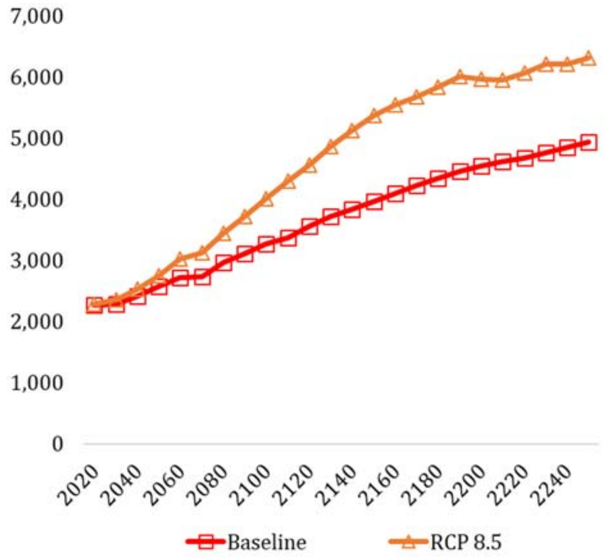


Figure 5: Global wood supply (million m^3/yr) under the Baseline scenario and the RCP 8.5 climate change scenario.

7. List of Tables

a) NPP		**2050**	**2100**	**2150**	**2200**	**2250**
Boreal and Temperate		**14%**	**31%**	**43%**	**45%**	**44%**
US		8%	25%	40%	33%	38%
China		9%	22%	27%	30%	33%
Canada		16%	35%	56%	65%	66%
Europe		14%	35%	40%	39%	37%
Russia		16%	34%	47%	47%	44%
Oceania		15%	33%	37%	40%	33%
Japan		12%	26%	41%	42%	43%
East Asia		11%	37%	49%	50%	49%
Tropical		**9%**	**15%**	**16%**	**14%**	**13%**
Brazil		6%	11%	13%	8%	3%
South Asia		17%	33%	33%	33%	35%
Central America		10%	17%	11%	4%	2%
Rest of South America		10%	18%	20%	20%	22%
Sub-Saharan Africa		9%	16%	17%	15%	14%
South East Asia		8%	16%	16%	14%	15%
North Africa and Middle East		33%	44%	43%	34%	32%
Global		**11%**	**23%**	**29%**	**28%**	**28%**

b) Dieback	**2010**	**2050**	**2100**	**2150**	**2200**	**2250**
Boreal and Temperate	0.7%	**0.7%**	**0.6%**	**0.5%**	**0.4%**	**0.4%**
US	0.9%	0.9%	0.8%	0.7%	0.5%	0.4%
China	0.5%	0.6%	0.5%	0.6%	0.9%	0.8%
Canada	0.8%	0.8%	0.5%	0.3%	0.3%	0.3%
Europe	0.7%	0.6%	0.6%	0.5%	0.4%	0.4%
Russia	0.8%	0.8%	0.6%	0.4%	0.3%	0.2%
Oceania	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%
Japan	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
East Asia	0.4%	0.4%	0.3%	0.2%	0.1%	0.1%
Tropical	0.4%	**0.4%**	**0.4%**	**0.5%**	**0.5%**	**0.5%**
Brazil	0.3%	0.4%	0.4%	0.4%	0.4%	0.6%
South Asia	1.0%	1.0%	1.2%	1.2%	1.2%	1.2%
Central America	0.4%	0.4%	0.5%	0.6%	0.7%	0.7%
Rest of South America	0.3%	0.4%	0.4%	0.4%	0.4%	0.4%
Sub-Saharan Africa	0.5%	0.5%	0.6%	0.5%	0.5%	0.5%
South East Asia	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
North Africa and Middle East	0.7%	0.8%	0.7%	0.9%	1.0%	0.9%
Global	0.6%	**0.6%**	**0.5%**	**0.5%**	**0.5%**	**0.5%**

Table 1: (a) Projected percentage changes in NPP under the RCP 8.5 with respect to the baseline scenario; (b) Projected average dieback rate for each region under the RCP 8.5.

	2010 values (Mha)	2050	2100	2150	2200	2250
Boreal and Temperate Average	**2,492**	**-4%**	**-12%**	**-38%**	**-47%**	**-55%**
US	335	-9%	-24%	-45%	-58%	-54%
China	379	-8%	-12%	-18%	-38%	-46%
Canada	367	6%	1%	-30%	-37%	-31%
Europe	365	-10%	-27%	-43%	-57%	-62%
Russia	918	-2%	-8%	-49%	-51%	-70%
Oceania	79	-2%	-7%	-16%	-10%	-11%
Japan	29	0%	-11%	-17%	-17%	-17%
East Asia	19	-7%	-13%	-19%	-30%	-59%
Tropical Average	**2,344**	**-2%**	**-5%**	**-8%**	**-14%**	**-23%**
Brazil	717	-1%	-8%	-22%	-36%	-55%
South Asia	38	-4%	3%	39%	56%	62%
Central America	84	-2%	-1%	1%	1%	1%
Rest of South America	466	-4%	-5%	-11%	-16%	-26%
Sub-Saharan Africa	692	-2%	-8%	-7%	-10%	-13%
South East Asia	318	2%	8%	14%	14%	10%
North Africa and Middle East	29	-28%	-44%	2%	52%	70%
Global	**4,836**	**-3%**	**-9%**	**-24%**	**-31%**	**-39%**

Table 2: Percent change in potential forestland with respect to 2010 levels.

	2010-2059	2060-2109	2110-2159	2160-2209	2210-2250
US	5	24	61	12	43
China	7	3	23	56	4
Canada	22	149	272	450	436
Russia	5	16	151	81	(13)
Europe	25	136	283	417	306
Oceania	11	64	178	232	207
Japan	5	30	74	124	170
East Asia	1	2	1	9	4
Temperate	80	425	1,043	1,381	1,158
Brazil	2	12	6	(32)	0
South Asia	8	18	44	55	82
Central America	0	2	1	5	(12)
Rest of South America	2	16	14	(17)	90
Sub-Saharan Africa	0	6	10	12	(4)
South East Asia	2	22	35	62	66
North Africa and Middle East	(0)	4	5	7	4
Tropical	14	80	115	93	225
Global	94	504	1,158	1,474	1,383

Table 3: Change in average annual timber production under the RCP 8.5 scenario relative to the Baseline scenario (million m^3/yr).

8. Appendix A

Study	Time	Models	Scenario	Results
Global				
Sohngen et al. (2001)	2000-2140	GTM[1], two GCMs and BIOME3	GHGs stabilization level of 550 ppmv in 2060	Climate change is predicted to increase global timber production as producers in low-mid latitude forests (South America and Oceania) react quickly with more productive short rotation plantations, driving down timber prices. Producers in mid-high latitude forests are likely to be hurt by the lower prices, dieback, and slower productivity increases because of long-rotation species. Consumers in all regions benefit from the lower prices, and the overall impacts of climate change in timber markets are expected to be beneficial, increasing welfare in those markets from 2% to 8%.
Perez Garcia et al. (2002)	1994-2040	CGTM[2], Terrestrial Ecosystem Model (TEM), EPPA model	GHGs stabilization levels of 592 ppmv , 745 ppmv and 936 ppmv in 2100	The global changes in welfare are positive, but small across all scenarios. At the regional level, the changes in welfare can be large and either negative or positive. Regions with the lowest wood fiber production cost (America West, New Zealand and South America) are able to expand harvests and force higher-cost regions (Canada) to decrease their harvests. Trade produces different economic gains and losses across the globe even though, globally, economic welfare increases
Lee and Lyon (2004)	1990-2085	TSM2000[3], Hamburg global circulation model and ecological model (BIOME3)		Global warming has a positive effect on the global timber market through an increase of timber production (most substantially in the US and Russia) causing pulpwood and solid wood prices to be (25% and 34%) lower than they otherwise would have been. Global warming is economically beneficial to society with a global welfare 4.8% higher than in no climate change scenario through the global timber market.
Reilly et al. (2007)	2000-2100	MIT Integrated Global Systems Model (IGSM) and Emissions Prediction and Policy Analysis (EPPA)	A baseline scenario and alternative climate mitigation policy scenarios	Climate and CO2 effects are generally positive for forestry yields over most of the world and controlling GHG emissions tends to reduce these beneficial effects. National and regional economic effects are strongly influenced by trade effects such that yield effects that are positive for a region, may lead to negative economic effects if the other countries gain more.
Buongiorno (2015)	2000-2065	GFPM[4] and exogenous change in forest growth	IPCC AR4, A1B, A2, and B2.	CO_2 fertilization will raise the level of the world forest stock in 2065 by 9-10 % for scenarios A2 and B2 and by 20% for scenario A1B. The rise in forest stock will be in part counteracted by its stimulation of the wood supply which resulted in lower wood prices and increased harvests.
Tian et al. (2016)	2010-2100	GTM[1], MIT Integrated Global Systems model (IGSM) and MC2 DGVM	9 W/m^2, 4.5 W/m^2 , 3.7 W/m^2	Climate change will cause forest outputs (such as timber) to increase by approximately 30% and timber prices fall by 15-30% over the century. In the mitigation scenarios: saw timber prices are 1.5% higher and pulpwood prices are 3.5% higher than in the 9 W/m^2 scenario.

United States				
Joyce et al. (1995)	1990-2040	ATLAS[5] and TEM (Terrestrial Ecosystem Model)	temperature range: 2.4-4.2°C and precipitation range: +7.8-11%	The effects of climate change in productivity was positive for all timber types. The largest increases in NPP occurred in the northerly ecosystems with some responses exceeding 40%. Productivity responses for the maximum and minimum scenarios varied more than 10% from the average response in the eastern forests in both the north and southern regions.
Sohngen and Mendelsohn (1998)	1990-2100	GTM[1], two GCMs, three biogeographical models and three biogeochemical models		Climate change expanded long run timber supply under all scenarios. Welfare effects were relatively small, with an average present value of about +$20 billion. Across the different model combinations, they exhibited a wide range, from $1 billion to $33 billion of benefits.
Irland et al. (2001)	1990-2100	FASOM[6], two GCMs and two EPMs		Climate change scenarios would be generally beneficial for the timber-products sector over the 120-year projection. Increased forest growth leads to increased log supply and hence to reductions in log prices that, in turn, decrease producers' welfare (profits) in the forest sector.
McCarl et al. (2000)	40 years	FASOM[6] and exogenous change in forest growth		The aggregate forest sector welfare effects are relatively limited even under extreme scenarios, this arises because of marked economic welfare shifts between producers and consumers. Yield increases induced by climate change were found to benefit consumers but not producers, while yield decreases have the opposite effect.
Alig et al. (2002)	2000-2100	FASOM[6] and combinations of two GCMs and two vegetation models		Less cropland is projected to be converted to forests, forest inventories generally increase, and that aggregate economic impacts (across all consumers and producers in the sector) are relatively small. The overall yield increases induced by climate change were found to benefit consumers but not producers. Producers' income is most at risk.
Wear et al. (2013)	2010-2060	Forest Dynamic Model and three general circulation models (GCMs)	IPCC SRES A1B, A2 and B2	While climate change will have important impacts in the future, the dominant impacts on forests are related to shifts in demand due to climate mitigation policy and changes in human use of land.
Beach et al. (2015)	2010-2100	FASOM-GHG[6] and MC1 dynamic global vegetation model	set of stabilization scenarios developed under the US EPA's Climate Change Impacts and Risk Analysis (CIRA) project	Climate change has a net positive impacts on forests due to CO2 fertilization that largely outweighs negative climate impacts and reallocation of forests amongst other marketable species. Reducing global GHG emissions under the Policy case is found to increase total surplus in the forest by a cumulative $32.7 billion for the 2015–2100.

Europe				
Nabuurs et al. (2002)	1990-2050	EFISCEN[7] and climate scenario HadCM2	IS92a emission scenarios: Increase in temperature of 2.5C (1990-2050) and increase in annual precipitation of 5-15%	18% Increase in stemwood growth by 2030, slowing down on a long term (2050)
Solberg et al. (2003)	2000-2020	EFI-GTM[8]	Three alternative forest growth (baseline, 20-40% increase in forest growth by 2020)	The output in western parts of Europe will increase, while they forecast a reduction in the eastern parts. The overall positive welfare effect is derived from lower prices of forest products.
Schroeter et al. (2004)	2000-2100	EFISCEN[7] and four general circulation models (GCMs; PCM, CGCM2, CSIRO2, HadCM3)	IPCC SRES emissions scenarios (A1f, A2, B1, B2)	All investigated climate scenarios increased forest growth throughout Europe. Management had a greater influence on the development of growing stock than climate or land use change: depending on the scenario, management accounted for 60 – 80% of the stock change between 2000 and 2100, climate change explained 10 – 30% of the difference, and land use change had the smallest impact of 5 – 22%.
Hanewinkel et al. (2013)	2010-2100	EFFISCEN[7] and 8 different combinations of GCMs and RCMs	IPCC SRES scenario: A1FI, A1B, B2	Large reduction (14 and 50%) in the value of forests in the EU by 2100. By 2100, between 21 and 60% of EU forest lands will be suitable only for a Mediterranean oak forest type with low economic returns for forest owners and the timber industry and reduced carbon sequestration.
Canada				
Ochuodho et al. (2012)	2010-2080	a series of regional CGE models and exogenous change in forestry and logging sector output (according to each scenario considered)	IPCC SRES B1 and A2	Timber supplies in Canada could change in the range of −30.8% to 1.6% by 2080, depending on the climate change scenario and region considered. British Columbia and Rest of Canada bear the largest negative percentage changes in GDP while Atlantic Canada and Alberta experience mostly moderate negative GDP impacts; Ontario and Quebec GDP impacts oscillate from moderately positive to negative values. The most negative impacts on output, GDP, and compensating variation occur under rapid economic growth, high climate change, and pessimistic scenarios. When adaptation activities are included in the analysis, the negative regional economic impacts of climate change on Canadian forests is reduced significantly.
India				
Aaheim et al. (2010)	2005-2085	Economic model GRACE-IN and ecological model IBIS	Reference scenario without climate change and climate impact scenario based on the IPCC A2-scenario	Biomass stock increases in all zones but the Central zone. The increase in biomass growth is smaller, and declines in the South zone, despite higher stock. In the four zones with increases in biomass growth, harvest increases by only approximately 1/3 of the change in biomass growth due to more harvest and higher supply of timber. As a result, also the rent on forested land decreases.

Notes: [1] GTM = Global timber model; [2]CGTM = CINTRAFOR Global Trade Model; [3]TSM2000 = Timber supply model; [4]GFPM = Global Forest Products Model; [5]ATLAS = Aggregate Timberland Assessment Model; [6] FASOM = Forest and Agriculture Optimization Mode, [7]EFISCEN= Forest resource scenario model; [8]EFI-GTM = Global forest sector model

Table A1: Summary of studies on climate change impacts on forests

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