Can the Global Forest Sector Survive 11 °C Warming?

Alice Favero, Robert Mendelsohn, and Brent Sohngen

Although most global forest economic studies have found that warming is likely to increase forest supply, these studies have examined only the limited warming expected through 2100. This study extends the analysis out to 2250 to test much higher levels of warming to examine very long term effects. Future warming is predicted to steadily increase forest productivity, with global timber supply predicted to increase through 2250, even with warming up to 11 °C warming. However, natural forestland and biomass will shrink. This result suggests far future forests will not be able to hold the same stock of carbon they hold today.

***Key Words*:** climate change, dynamic optimization, forestry, RCP 8.5, timber market

The forestry sector is sensitive to climate change, and it is likely that changing temperature and precipitation patterns 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 growing seasons, and elevated atmospheric CO_2 concentrations (Harsch et al. 2009). On the other hand, 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 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 bio-economic 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, Mendelsohn, and Sedjo 2001; Perez-Garcia et al. 2002; Hanewinkel et al. 2013; Tian et al. 2016; see Appendix 1). These studies show that climate change will tend to increase timber supply, reduce global timber prices, and change the incentives to manage forests. However, these existing studies have studied climate effects only through 2100 and so cannot predict long-term outcomes or the effects of higher temperature increases. Given the history of global mitigation to date, it is not likely that climate will be stabilized before 2100.

Alice Favero, Georgia Institute of Technology, Atlanta, Georgia. Robert Mendelsohn Yale University, New Haven, Connecticut. Brent Sohngen, The Ohio State University, Columbus, Ohio. Correspondence: *Alice Favero ▪ Georgia Institute of Technology ▪ Atlanta ▪ Georgia ▪ Email: alice.favero@gatech.edu.*

The views expressed are the author's and do not necessarily represent the policies or views of any sponsoring agencies.

Agricultural and Resource Economics Review 47/2 (August 2018) 388–413

It is therefore imperative to examine possible warming scenarios that extend beyond 2100 to both understand long-run timber implications and to explore possible climate scenarios that are far more severe.

This study examines the high-emission IPCC scenario associated with the representative concentration pathway (RCP) scenario that leads to 8.5 W/m^2 radiative forcing (Riahi et al. 2011). Combining this emission scenario with the HadGEM2 climate model (Martin et al. 2011) yields a severe warming scenario through 2300, with eventual temperatures that are 11 °C above 1900 levels. The RCP 8.5 scenario is compared to a (Baseline) scenario without climate change.

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 net primary productivity of vegetation will change, first rising and then (after 2150) stabilizing. Second, some of the standing stock will be lost to dieback from direct temperature effects and forest fires. 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 that are part of the ecosystem model.

We then use five shared socioeconomic pathways (SSPs) (Riahi et al. 2017) that represent alternative growth rates of population and income to explore the consequence to future possible outcomes. The climate and ecosystem outcomes are examined using alternative socioeconomic projections to provide a full range of plausible outcomes for the timber market in the far future. Although the model does take into account how SSPs affect demand for timberland, the model is not well suited to study how SSPs might also change demand for farmland. This is a topic for future research.

An extended version of the global timber model (GTM) (Sohngen and Mendelsohn 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 selects where to plant new trees under the future climate conditions. The model predicts increasing harvest rates of stands that have an ever-increasing rate of dieback. The model changes the intensity of management according to the future plants' productivity by intensifying it in places that become more productive and reducing it in places that become less productive. Finally, the model forecasts 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 "Methods" describes the method and the model used for the analysis. Section "Economic Results" 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 "Conclusions" summarizes the results and discusses their implications.

Methods

Model

The GTM (Sohngen, Mendelsohn, and Sedjo 2001; Sohngen and Mendelsohn 2003; Favero and Mendelsohn 2014) used in this study contains 200 forest types *i* in 16 regions[1] 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.

We change the original GTM model to include time steps to the year 2350. We do not report the final time steps of the model because they are sensitive to the assumptions made about terminal conditions. We consequently only report the results to 2250. These results are sufficiently far in front of 2350 that they are no longer sensitive to the terminal conditions.

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 the global demand function for industrial timber[2], $f(Q_t)$ is the cost of harvesting and transporting timber to the mill, p_m is the price of management intensity m, G_t is planted acreage, $C(N_t)$ is the cost of new forestland N at time t, $R(\sum X_{a,t})$ is the opportunity cost of land X in age class a at time t. The objective function in (1) is nonlinear.[3] The model assumes that management intensity is determined at the moment of planting, and planting costs vary depending upon management intensity.

[1] Our study focuses on presenting aggregate effects across the timber types modeled in eleven regions of the world. These regions include the United States, Canada, Europe (Eastern and Western Europe), Russia, Oceania (Australia and New Zealand), China (including Mongolia), Asia-Pacific (most countries except small island states), India, Brazil, Central and South America (including Central America and Mexico), and Africa.

[2] The global demand function is assumed to be the sum of the regional demand functions from the eleven regions. Regional demand functions are calculated assuming a uniform price elasticity of −1.1 and then allocating global shares given the 2017 observed shares of consumption in each region [World Bank (2017)].

[3] The scenarios are written and solved using GAMS software and the MINOS solver. The model is solved in decadal time steps starting in 2010.

Timber demand Q_t, is assumed to grow over time as the global economy grows:

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

where A is a constant, Z_t is the projected global consumption per capita over time, β is the income elasticity, P_t is the international price of wood, and ω is the price elasticity. To predict Z_t ,we use the global consumption per capita from the SSPs[4] (see Section "Climate and Socioeconomic Scenarios").

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.[5]

We include in the forestry model three expected impacts of climate change as predicted by the LPX-Bern global dynamic vegetation model (DGVM): (a) changes in the net primary productivity (NPP) that measures the net carbon stored annually by an ecosystem; (b) changes in dieback; and (c) changes in the distribution of biomes and timber types. The LPX-Bern DGVM generates outputs at the 1° spatial resolution at a yearly time step. Outputs are then aggregated to decadal averages across world regions for use in the forestry model.

As in Sohngen, Mendelsohn, and Sedjo (2001), we assume changes in merchantable timber growth rates are proportional to predicted changes in NPP (θ_t) as predicted by LPX-Bern Model and management intensity, m_{t0}. The changes in the timber volume V_t are calculated as:

(3) $$V_t(m^i_{t0}, \theta^i_t) = \int_{t0}^{t} \dot{V}_s(m^i_{t0}, \theta^i_s)ds.$$

The forestry literature has examined the impact climate is expected to have on timber through 2100 (Sohngen, Mendelsohn, and Sedjo 2001; Reilly et al. 2007;

[4] SSP database is available at https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about#intro.

[5] In the model, rental supply functions are assumed to be exogenous and independent of the SSP. However, similar forces that affect the demand for wood in this study might affect the demand for agricultural goods and, hence, the land use competition between agriculture and forestry. Endogenizing changes in the demand for agricultural goods could alter the results.

Buongiorno 2015; Tian et al. 2016). However, warming that can happen through 2100 is quite limited so that no scenario has ever explored warming above 4 °C. By extending the timeline to 2250, this analysis will include both longer-term ecological effects and 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 DGVM, which affect all existing stocks of forest as follows:

$$X^i_{a,t} = (1 - \delta^i_t)X^i_{a-1,t-1} - H^i_{a-1,t-1} + G^i_{a=1,t-1} + N^i_{a=1,t-1}, \quad (4)$$

where X is the area of land, H is the area of timberland harvested, G is the area of land regenerated, N is the area of new land established, and δ is the annual mortality rate from dieback from direct temperature effects and forest fires as predicted by the vegetation model. We assume that all age classes a have equal probability of dieback because the ecological model cannot predict which age classes are more vulnerable. Dieback also alters timber harvests H because some of the stock that dies back will be salvaged. The salvage enters the equation for net market surplus through harvests.[6]

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 that 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, Harrison, and Bartlein (2011). Initial forest stocks are given, and all choice variables are constrained to be nonnegative.

Climate and Socioeconomic 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 ppm by 2100 and to 1686 ppm by 2150, and then start to stabilize reaching 2222 ppm 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 global average temperature increases at a

[6] The proportion of salvage in each timber type varies from zero to 60 percent, and it is chosen endogenously by the timber model depending on access and land value. For instance, in inaccessible regions throughout the world, we assume there is no salvage; but in highly valuable timber regions such as the southern United States, salvage is assumed to be 60 percent.

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. Data from LPX-Bern global dynamic vegetation Model.

a) Net Primary Productivity	2050 (%)	2100 (%)	2150 (%)	2200 (%)	2250 (%)
High-Latitude Forests					
U.S.	8	25	40	33	38
Canada	16	35	56	65	66
Europe	14	35	40	39	37
Russia	16	34	47	47	44
China	9	22	27	30	33
Oceania	15	33	37	40	33
Low-Mid Latitude Forests					
Brazil	6	11	13	8	3
Central and South America	10	18	18	17	18
India	17	33	33	33	35
Asia-Pacific	8	18	20	17	19
Africa	9	17	17	15	14
Global	11	23	29	28	28

b) Dieback	2010 (%)	2050 (%)	2100 (%)	2150 (%)	2200 (%)	2250 (%)
High-Latitude Forests						
U.S.	0.9	0.9	0.8	0.7	0.5	0.4
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

Continued

Table 1. Continued

b) Dieback	2010 (%)	2050 (%)	2100 (%)	2150 (%)	2200 (%)	2250 (%)
Russia	0.8	0.8	0.6	0.4	0.3	0.2
China	0.5	0.6	0.5	0.6	0.9	0.8
Oceania	0.4	0.3	0.3	0.2	0.2	0.2
Low-Mid Latitude Forests						
Brazil	0.3	0.4	0.4	0.4	0.4	0.6
Central and South America	0.3	0.4	0.4	0.5	0.5	0.5
India	0.3	1.0	1.2	1.2	1.2	1.2
Asia-Pacific	0.3	0.3	0.3	0.3	0.3	0.3
Africa	0.5	0.5	0.6	0.5	0.5	0.5
Global	0.6	0.6	0.5	0.5	0.5	0.5

rapid rate through 2150 and then begins to slow down, stabilizing at 11 °C above 1900 by 2300.

The LPX-Bern DGVM is then used to simulate the vegetation response to climate change from the present to year 2300 (Mendelsohn et al. 2016). 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 global level through 2150 compared to the Baseline. Beyond 2150, productivity stabilizes. On average the increase in forest productivity is greater in high latitude forests than low-mid latitude forests. As boreal forest is replaced by temperate forests, productivity rapidly increases. As shown in Table 1, under RCP 8.5, the absolute dieback rate is higher for high-latitude regions than low-mid latitude regions. However, dieback declines over time in the boreal and temperate regions, whereas it is more stable in tropical regions. For the Baseline scenario, we assume the dieback rate is fixed at the current (2010) level.

The ecosystem model also predicts that the share of each vegetation type will change over time. The changes under the RCP 8.5 scenario are dramatic as shown in Figure 1a. The boundaries of each biome shift with warming, causing some biomes to contract and others to expand. Overall, the potential of land available for forest will be reduced by 29 percent in 2150 and by 44 percent in 2250 relative to current levels. 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 percent and then shrinking by 32 percent in 2250. Boreal forests decline more rapidly, almost disappearing by the end of the 22^{nd} century. Temperate and warm temperate forests grow through 2100 and then stabilize. Temperate forests often replace boreal forests in Canada, Europe, and Russia.

Table 2 shows these forestland changes at the regional level. The changes under RCP 8.5 are dramatic for some countries: Russia, Europe, and the United States see the biggest losses of forestland in percentage terms. In Brazil forestland is projected to decrease by 55 percent relative to 2010 by 2250. The harm done in the Amazon is due to the strong drying that HadGEM2 predicts in the RCP 8.5 scenario. On the other hand, other regions are less affected or even gain forestland (Asia Pacific). For instance, in Southeast Asia, tropical forestland potential will increase at the expense of tropical savanna. Table 2 also reveals that there is not much forestland lost this century and that the biggest forestland losses occur in the 22^{nd} century, when the change in global average temperature relative to preindustrial levels starts 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 five SSPs to calculate global consumption per capita[7]. Global consumption per capita drives global timber

[7] 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,

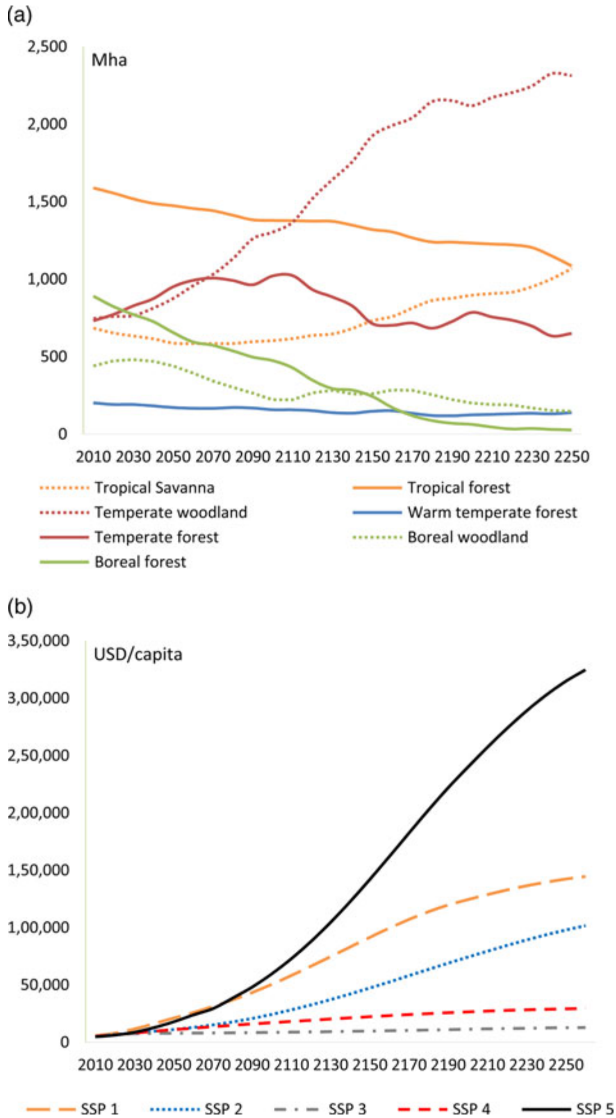

Figure 1. (a) Distribution of potential world vegetation under the RCP 8.5 scenario (Mha), data from LPX-Bern global dynamic vegetation model; (b) GDP per capita under the five socioeconomic scenarios.

REMIND-MAGPIE and WITCH-GLOBIOM) can reach the 8.5 W/m^2 radiative forcing level by 2100. However, we simulate all the five SSPs to assess if and how our results are sensitive to the socioeconomic scenarios.

Table 2. Percent change in potential forestland with respect to 2010 levels. Data from LPX-Bern Global Dynamic Vegetation Model

	Current Values (2010) Million hectares	2050 (%)	2100 (%)	2150 (%)	2200 (%)	2250 (%)
Mid-High Latitude Forests						
U.S.	335	−9	−24	−45	−58	−54
Canada	367	6	1	−30	−37	−31
Europe	365	−10	−27	−43	−57	−62
Russia	918	−2	−8	−49	−51	−70
China	379	−8	−12	−18	−38	−46
Oceania	79	−2	−7	−16	−10	−11
Low-Mid Latitude Forests						
Brazil	717	−1	−8	−22	−36	−55
Central and South America	550	−3	−4	−9	−13	−22
India	38	−4	3	39	56	62
Asia-Pacific	366	1	6	10	9	4
Africa	721	−3	−9	−6	−7	−10
Global	4836	−3	−9	−24	−31	−39

demand (see Z in Equation 2). In order to extend our analysis to 2300, we follow earlier analyses that assume continued-but-declining population growth beyond 2100, which finally stabilizes in 2200 (IAWG US, 2010). These assumptions lead to an S-shaped growth in population over time with a 2100 global population of 7–12.6 billion that then stabilizes. We also assume continued-but-declining economic growth rates reaching zero in 2300. This assumption also leads to an S-shaped growth in GDP over time (IAWG, 2010). By 2100, average global consumption has risen to $8,700–60,000 per capita and by 2250, consumption has risen to $12,700–315,000 per person, depending on the SSP (Figure 1b).

Economic Results

The increase in global per capita consumptions in the SSP1, SSP2, and SSP5 scenarios causes the demand for timber to increase over time in these socioeconomic scenarios. This increased demand for timber causes timber prices to rise, in order to supply more wood. The higher timber prices assure sufficient land is used to produce future timber and also to encourage more intensive land management. Managed forestland can potentially come from agricultural land or natural forest land. Of course, the higher timber prices also serve to temper demand.

In 2010, managed forestland accounts for 34 percent of total forestland. As the demand for timber increases under the SSP 1, SSP 2, and SSP 5, the amount of managed land increases, both in absolute and in relative terms. In 2250, under the Baseline scenario, the share of managed forestland increases to 36–41 percent depending on the SSPs. The most significant increase occurs under the SSP 5, when the dramatic increase in income requires more conversion of natural forests into managed forest: in 2250 the amount of managed forestland increases by 249 Mha, and the amount of natural forestland falls by 189 Mha (Table 3). The remaining 60 Mha of managed forestland came from marginal agricultural lands. The higher timber prices also increase management intensity, increasing supply. For instance, under the SSP 5, global average timber yield/ha will be about 50 percent higher than 2010 levels by 2100 and by 2250, it will be more than double.

The small increase in global consumption per capita under the SSP 3 and SSP 4 produces only a slight increase in the demand for timber. Under these scenarios, the increase in productivity outpaces the increase in demand and the price of timber rises only slightly and then starts to decline. As a result, under these two socioeconomic scenarios there is no incentive to convert additional land to managed forest, and the share of managed versus natural forest remains almost unaffected.

The picture changes under the RCP 8.5 climate scenario where global forests will experience (on average) a substantial gain in productivity. The managed forest no longer needs as much land as it did in the Baseline. The only scenario where managed land increases is in the SSP 5 scenario, and this increase is only temporary. So the RCP 8.5 scenario does not entail much land being shifted into managed forest and in fact becomes a source of land in most cases. It is the climate scenario itself that is taking a toll on natural forest. The HadGEM2 model predicts a shrinkage of global forest, all at the expense of the natural forest. In 2250, global forestland is reduced by 28–32 percent relative to the Baseline. Boreal forest almost disappears because of the ecosystem response to higher temperatures. Russia takes the largest hit and under SSP 5 loses 80 percent of its natural forest by 2250. However, the ecosystem model replaces a great deal of boreal forests with faster growing temperate forest. Most of this temperate forest will be managed. The ecological vegetation model predicts a large loss of natural tropical forest in the Amazon. This result is specific to the HADGEM2 climate model that predicts significant drying in the Amazon basin (Table 4).

Under the RCP 8.5 scenario, the large gain in forest productivity outweighs the loss in forest area. As illustrated by Figures 2 and 3, GTM predicts that global timber supply increases, and prices decline under all socioeconomic climate change scenarios relative to their correspondent baseline projections. Climate change causes global timber supply to increase by 19–24 percent above the Baseline by 2100. The results support the findings in the literature

Table 3. Global managed and natural forestland in (a) the Baseline scenario and (b) the RCP 8.5 Scenario.

	(a) Baseline Scenario			(b) RCP 8.5 Scenario		
	2050	2150	2250	2050	2150	2250
SSP 1						
Managed						
Million ha	1,341	1,407	1,242	1,341	1,284	1,024
% Forestland	39	41	38	40	38	44
Natural						
Million ha	2,073	2,061	2,067	2,052	1,676	1,318
% Forestland	61	59	62	60	62	56
SSP 2						
Managed						
Million ha	1,201	1,314	1,142	1,180	1,137	929
% Forestland	37	39	36	37	41	41
Natural						
Million ha	2,073	2,025	2,055	2,042	1,670	1,314
% Forestland	63	61	64	63	59	59
SSP 3						
Managed						
Million ha	908	768	796	888	682	601
% Forestland	30	28	28	30	28	31
Natural						
Million ha	2,087	1,995	2,022	2,075	1,712	1,322
% Forestland	70	72	72	70	72	69
SSP 4						
Managed						
Million ha	1,102	1,033	889	1,075	898	686
% Forestland	35	34	30	34	34	34
Natural						
Million ha	2,093	2,005	2,037	2,079	1,707	1,346
% Forestland	65	66	70	66	66	66
SSP 5						
Managed						
Million ha	1,351	1,507	1,433	1,356	1,414	1,245
% Forestland	40	42	41	40	46	49
Natural						
Million ha	2,052	2,053	2,099	2,027	1,659	1,300
% Forestland	60	58	59	60	54	51

Table 4. Regional changes in managed, natural and total forest under the RCP 8.5 relative to the Baseline scenario in 2250 (Mha)

	High-Latitude Regions						Low-Mid Latitude Regions					
Scenario	**U.S.**	**Canada**	**Europe**	**Russia**	**China**	**Oceania**	**Brazil**	**Central and South America**	**India**	**Asia-Pacific**	**Africa**	**Global**
SSP 1												
Managed	(0.9)	(8.0)	(83.1)	(10.3)	(60.5)	21.7	(43.8)	(19.6)	(2.2)	(0.8)	(11.2)	(218.6)
Natural	(11.6)	9.2	(0.0)	(573.7)	(0.4)	(18.8)	(196.5)	9.9	0.0	15.4	17.1	(749.4)
Total	(12.5)	1.2	(83.1)	(584.0)	(60.8)	2.9	(240.3)	(9.7)	(2.2)	14.6	5.9	(967.9)
SSP 2												
Managed	(4.4)	(11.8)	(84.0)	(5.5)	(60.4)	9.0	(42.7)	(15.9)	(2.0)	8.8	(4.3)	(213.3)
Natural	(10.9)	14.5	(0.0)	(573.7)	0.8	(18.1)	(188.2)	23.3	0.0	6.0	4.6	(741.8)
Total	(15.3)	2.7	(84.0)	(579.2)	(59.6)	(9.1)	(230.9)	7.4	(2.0)	14.8	0.2	(955.1)
SSP 3												
Managed	0.1	(39.3)	(57.8)	(19.1)	(36.6)	14.4	(24.5)	(21.8)	(2.7)	(1.0)	(6.8)	(195.2)
Natural	(10.6)	51.2	(2.0)	(571.4)	(8.7)	(38.8)	(160.8)	18.8	0.0	6.7	16.3	(699.1)
Total	(10.6)	11.9	(59.8)	(590.5)	(45.3)	(24.4)	(185.3)	(3.0)	(2.7)	5.7	9.5	(894.3)
SSP 4												
Managed	7.4	(41.0)	(73.0)	(9.9)	(42.3)	17.1	(36.3)	(18.6)	(3.6)	0.9	(3.6)	(202.9)
Natural	(11.2)	51.2	(1.5)	(574.9)	(4.7)	(37.5)	(169.7)	26.8	0.0	8.5	21.8	(691.3)
Total	(3.8)	10.2	(74.5)	(584.8)	(47.0)	(20.5)	(206.0)	8.2	(3.6)	9.4	18.2	(894.2)
SSP 5												
Managed	(7.1)	19.8	(77.4)	(4.5)	(49.1)	(1.4)	(45.2)	(23.5)	5.1	(2.0)	(2.8)	(188.1)
Natural	(10.6)	(21.0)	(0.0)	(578.2)	(3.3)	4.3	(221.1)	(0.2)	0.0	33.3	(1.8)	(798.4)
Total	(17.7)	(1.2)	(77.4)	(582.8)	(52.3)	3.0	(266.3)	(23.7)	5.1	31.3	(4.5)	(986.5)

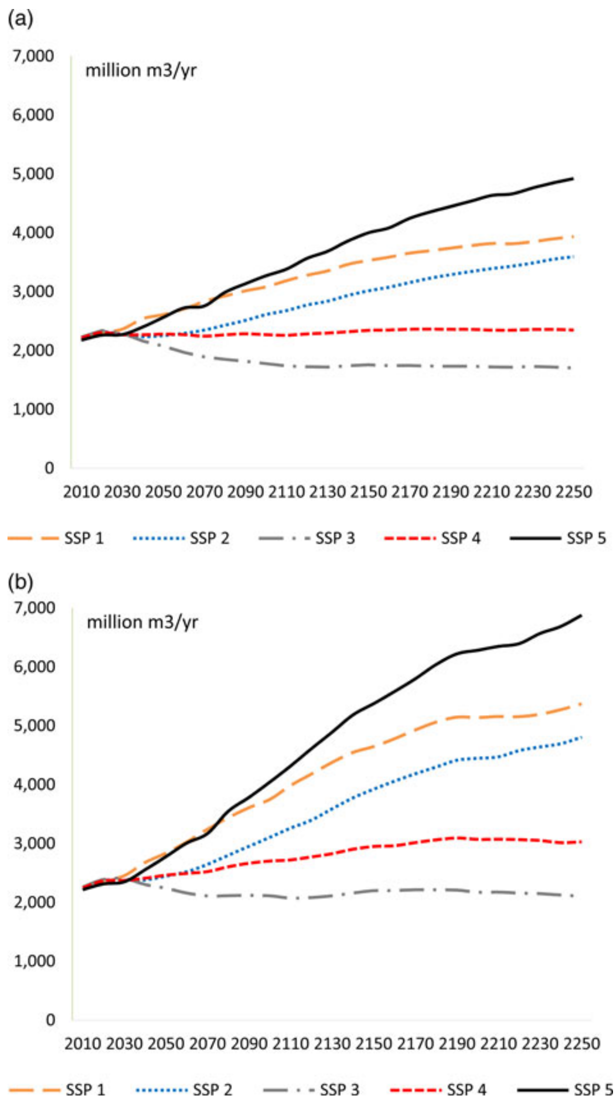

Figure 2. Global timber harvested in (a) the Baseline scenario and (b) the RCP 8.5 Scenario.

that climate change will increase timber output through 2100. The study reveals that this positive effect of climate change on timber supply continues through 2190 and then begins to slow (Figure 2a, b). The increasing timber supply from climate change leads to lower timber prices. The analysis supports earlier findings that climate change leads to lower timber prices

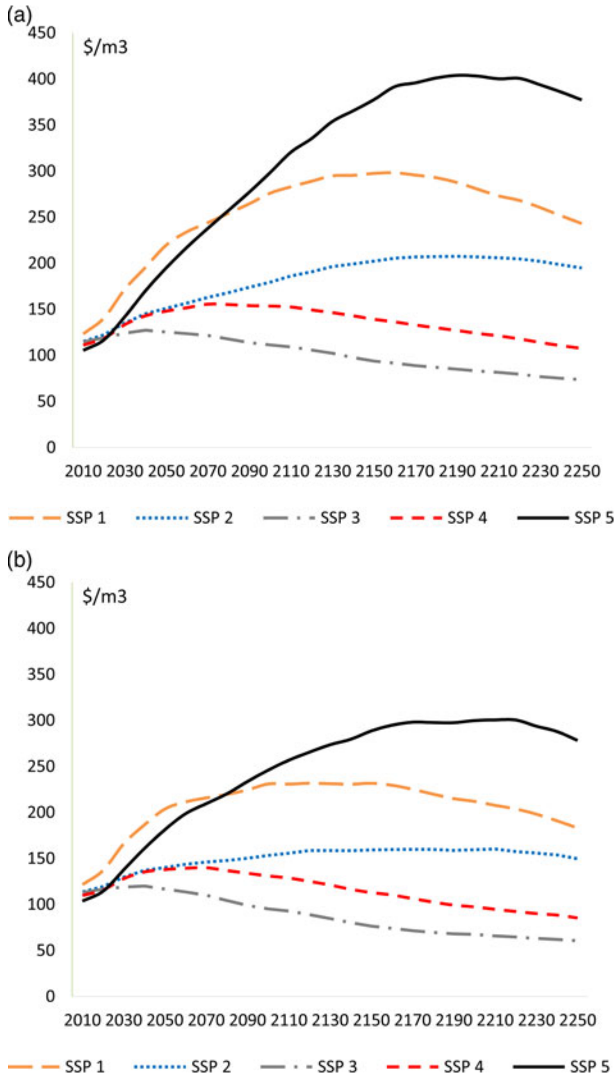

Figure 3. International price of wood in (a) the Baseline scenario and (b) the RCP 8.5 Scenario.

through 2100. This effect continues through 2250 despite the very high temperatures associated with the 23rd century (Figure 3a, b).

Global net surplus is expected to increase in all socioeconomic scenarios under the RCP 8.5, ranging from $232 billion under the SSP 3 scenario to $512 billion in the SSP 5 scenario (Table 5). Benefits accrue mostly to consumers because of the lower prices. Climate change would be mildly beneficial to producers in high latitude regions because the productivity

Table 5. Present value of Regional Welfare effects under five SSP scenarios (USD Billions, $r = 5\%$)

	High-Latitude Regions						Low-Mid Latitude Regions					
Scenario	**U.S.**	**Canada**	**Europe**	**Russia**	**China**	**Oceania**	**Brazil**	**Central and South America**	**India**	**Asia-Pacific**	**Africa**	**Global**
SSP 1												
Consumer Surplus	129.7	11.6	114.9	10.5	79.1	10.5	15.8	26.4	26.4	69.6	32.7	527.2
Producer Surplus	(31.9)	70.2	19.6	2.8	(13.4)	16.1	(43.7)	(16.1)	9.5	(12.5)	(15.3)	(14.9)
Net Surplus	97.8	81.8	134.5	13.4	65.6	26.6	(27.9)	10.3	35.8	57.1	17.4	512.3
SSP 2												
Consumer Surplus	82.5	7.4	73.1	6.7	50.3	6.7	10.1	16.8	16.8	44.3	20.8	335.4
Producer Surplus	(19.1)	47.9	10.2	0.8	(10.4)	5.4	(29.0)	(10.5)	3.9	(9.1)	(10.2)	(20.2)
Net Surplus	63.4	55.3	83.3	7.5	39.9	12.1	(19.0)	6.3	20.7	35.1	10.6	315.2
SSP 3												
Consumer Surplus	62.5	5.6	55.4	5.1	38.1	5.1	7.6	12.7	12.7	33.5	15.7	253.9
Producer Surplus	(17.8)	42.7	5.3	(0.2)	(7.2)	1.2	(23.5)	(8.0)	2.4	(8.0)	(8.2)	(21.3)
Net Surplus	44.7	48.3	60.6	4.8	30.9	6.2	(15.9)	4.7	15.1	25.5	7.6	232.6

Continued

Table 5. Continued

Scenario	High-Latitude Regions						Low-Mid Latitude Regions					Global
	U.S.	Canada	Europe	Russia	China	Oceania	Brazil	Central and South America	India	Asia-Pacific	Africa	
SSP 4												
Consumer Surplus	75.9	6.8	67.3	6.2	46.3	6.2	9.3	15.4	15.4	40.7	19.1	308.6
Producer Surplus	(21.6)	47.1	9.6	0.2	(9.4)	4.1	(27.0)	(9.5)	3.5	(8.9)	(9.6)	(21.4)
Net Surplus	54.3	53.9	76.8	6.4	36.9	10.3	(17.7)	5.9	19.0	31.9	9.5	287.1
SSP 5												
Consumer Surplus	123.2	11.0	109.2	10.0	75.1	10.0	15.0	25.0	25.0	66.1	31.1	501.0
Producer Surplus	(31.3)	66.6	15.8	2.7	(13.8)	16.5	(41.1)	(15.8)	7.8	(13.1)	(14.4)	(20.0)
Net Surplus	92.0	77.6	125.0	12.8	61.3	26.6	(26.1)	9.2	32.9	53.0	16.7	481.0

gains outweigh the lower prices and the potential losses in stock in most cases. For instance, the yield/ha of tropical forests increases by 13–14 percent but the yield/ha of boreal and temperate forests increases by 53–78 percent depending on the socioeconomic scenario. The replacement of boreal forests by temperate forests and carbon fertilization caused a great deal of this increased productivity in high latitudes. In mid-latitudes, the timber model intensified management. Under the RCP 8.5, temperate and boreal forest regions increase their average annual timber supply for 2010–2250 by 23–40 percent while tropical regions increase their supply by only 7–8 percent relative to the Baseline.

Note that producer surplus depends on the regional stock of forest, forest productivity, and the costs of producing timber and holding timberland. Consumer surplus, in contrast, follows timber demand that depends upon where people are located and where incomes are high enough to buy timber. The regions that enjoy the benefits of lower timber prices are not necessarily the regions with the highest forest production. The United States, Europe, and the Asian Pacific (including China) get most of the benefits from higher global timber production.

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, Mendelsohn, and Sedjo 2001; Perez-Garcia et al. 2002; Hanewinkel et al. 2013; Tian et al. 2016) and so they have only looked at temperature changes up to 4 °C. Within this timeframe and level of warming, global forests are projected to generally expand and become more productive, increasing the net surplus in timber markets.

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 DGVM 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, shifting timber supply and lowering timber prices with respect to the Baseline. 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. Beyond this point, however, productivity increases shrink as carbon concentrations stabilize and temperature damage increases. Additional warming continues to shrink forestland and biomass.

Outside the timber market, the RCP 8.5 reduces global forestland by 30 percent and natural forestland by 34–38 percent 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 approximately 580 Mha of forestland. A great deal of this lost forest is natural forestland. The global forest sector will survive an 11 °C warming, but one cost of rapid warming is the loss of vast natural forestland of about 750 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 future climate projection from the climate model HadGEM2. Future research will explore more emission scenarios and other climate-model scenarios.

Second, this study finds that biomass falls in the RCP 8.5 scenario. This has huge implications for storing carbon in forests. This study did not explore carbon sequestration policies or efforts to use forests for bioenergy (Favero, Mendelsohn, and Sohngen 2017). But analyses of these mitigation strategies in the context of extensive warming is clearly an important topic for future research.

Third, the DGVM and the GTM do not examine how future climate and other forces might change agriculture. In general, the study found that climate change led the forest sector to intensify production allowing it to use less land. But a future world with extensive warming may need ever more land for agriculture. An exploration of the implications of extensive warming on land use is another useful extension.

Finally, the modeling suggests that there will be an extensive loss of natural forestland in a rapid warming scenario. This has huge implications for conservation policies to protect habitat and wildlife species as well as carbon sequestration. It may also have large implications for recreation and tourism.

References

Aaheim, A., R.K. Chaturvedi, and A.A. Sagadevan. 2011. “Integrated Modelling Approaches to Analysis of Climate Change Impacts on Forests and Forest Management.” *Mitigation and Adaptation Strategies for Global Change* 16(2): 247–266.

Alig, R.J., D.M. Adams, and B.A. McCarl. 2002. “Projecting Impacts of Global Climate Change on the US Forest and Agriculture Sectors and Carbon Budgets.” *Forest Ecology and Management* 169(1–2): 3–14.

Bachelet, D., J. Lenihan, R. Drapek, and R. Neilson. 2008. "VEMAP vs VINCERA: A DGVM Sensitivity to Differences in Climate Scenarios." *Global and Planetary Change* 64(1–2): 38–48.

Beach, R.H., Y. Cai, A. Thomson, X. Zhang, R. Jones, B.A. McCarl, A. Crimmins, J. Martinich, J. Cole, S. Ohrel, B. DeAngelo, J. McFarland, K. Strzepek, and B. Boehlert. 2015. "Climate Change Impacts on US Agriculture and Forestry: Benefits of Global Climate Stabilization." *Environmental Research Letters* 10(9): 095004.

Buongiorno, J. 2015. "Modeling Some Long-Term Implications of CO2 Fertilization for Global Forests and Forest Industries." *Forest Ecosystems* 2(1): 29.

Clarke, L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Loschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C. C. van der Zwaan, and D.P. Van Vuuren. 2014. "Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change." Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Favero, A., and R. Mendelsohn. 2014. "Using Markets for Woody Biomass Energy to Sequester Carbon in Forests." *Journal of the Association of Environmental and Resource Economists* 1(1/2): 75–95.

Favero, A., R. Mendelsohn, and B. Sohngen. 2017. "Using Forests for Climate Mitigation: Sequester Carbon or Produce Woody Biomass?" *Climatic Change* 144(2): 195–206.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. "Global Patterns in the Vulnerability of Ecosystems to Vegetation Shifts due to Climate Change." *Global Ecology and Biogeography* 19(6): 755–768.

Hanewinkel, M., D.A. Cullmann, M.-J. Schelhaas, G.-J. Nabuurs, and N.E. Zimmermann. 2013. "Climate Change may Cause Severe Loss in the Economic Value of European Forest Land." *Nature Climate Change* 3(3): 203–207.

Harsch, M.A., P.E. Hulme, M.S. McGlone, and R.P. Duncan. 2009. "Are Treelines Advancing? A Global Meta-Analysis of Treeline Response to Climate Warming." *Ecology Letters* 12(10): 1040–1049.

IAWG, US. 2010. "Technical support document: Social cost of carbon for regulatory impact analysis under executive order 12866." Interagency Working Group on Social Cost of Carbon, United States Government, Washington, DC.

Irland, L.C., D. Adams, R. Alig, C.J. Betz, C.-C. Chen, M. Hutchins, B.A. McCARL, K. Skog, and B.L. Sohngen. 2001. "Assessing Socioeconomic Impacts of Climate Change on US Forests, Wood-Product Markets, and Forest Recreation: The Effects of Climate Change on Forests Will Trigger Market Adaptations in Forest Management and in Wood-Products Industries and May Well Have Significant Effects on Forest-Based Outdoor Recreation." *BioScience* 51(9): 753–764.

Joyce, L.A., J.R. Mills, L.S. Heath, A. David McGuire, R.W. Haynes, and R.A. Birdsey. 1995. "Forest Sector Impacts from Changes in Forest Productivity under Climate Change." *Journal of Biogeography* 22: 703–713.

Kirilenko, A.P., and R.A. Sedjo. 2007. "Climate Change Impacts on Forestry." *Proceedings of the National Academy of Sciences* 104(50): 19697–19702.

Lee, D.M., and K.S. Lyon. 2004. "A Dynamic Analysis of the Global Timber Market Under Global Warming: An Integrated Modeling Approach." *Southern Economic Journal* 70(3): 467–489.

Martin, G.M., N. Bellouin. W.J. Collins, I.D. Culverwell, P.R. Halloran, S.C. Hardiman, T.J. Hinton, C. D. Jones, R.E. McDonald, A.J. McLaren, F.M. O'Connor, M.J. Roberts, J.M. Rodriguez, S. Woodward, M.J. Best, M.E. Brooks, A.R. Brown, N. Butchart, C. Dearde, S.H. Derbyshire, I. Dharssi, M. Doutriaux-Boucher, J.M. Edwards, P.D. Falloon, N. Gedney, L.J. Gray, H.T. Hewitt, M. Hobson, M.R. Huddleston, J. Hughes, S. Ineson, W.J. Ingram, P.M. Pames, T.C. Johns, C.E. Johnson, A. Jones, C.P. Jones, M.M. Joshi, A.B. Keen, S. Liddicoat, A.P. Lock, A.V. Maidens, J.C. Manners, S.F. Milton, J.G.L. Rae, J.K. Ridley, A. Sellar, C.A. Senior, I.J. Totterdell, A. Verhoef, P.L. Vidale, A. Wiltshire. 2011. "The HadGEM2 Family of Met Office Unified Model Climate Configurations." *Geoscientific Model Development* 4(3): 723–757.

Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J.-F. Lamarque, K. Matsumoto, *et al*. 2011. "The RCP Greenhouse gas Concentrations and Their Extensions From 1765 to 2300." *Climatic change* 109(1–2): 213.

Mendelsohn, R., I.C. Prentice, O. Schmitz, B. Stocker, R. Buchkowski, and B. Dawson. 2016. "The Ecosystem Impacts of Severe Warming." *American Economic Review* 106(5): 612–14.

Nabuurs, G., A. Pussinen, T. Karjalainen, M. Erhard, and K. Kramer. 2002. "Stemwood Volume Increment Changes in European Forests Due to Climate Change—A Simulation Study with the EFISCEN Model." *Global Change Biology* 8(4): 304–316.

Ochuodho, T.O., V.A. Lantz, P. Lloyd-Smith, and P. Benitez. 2012. "Regional Economic Impacts of Climate Change and Adaptation in Canadian Forests: A CGE Modeling Analysis." *Forest Policy and Economics* 25(C): 100–112.

Perez-Garcia, J., L.A. Joyce, A. David McGuire, and X. Xiao. 2002. "Impacts of Climate Change on the Global Forest Sector." *Climatic Change* 54(4): 439–461.

Prentice, I.C., S.P. Harrison, and P.J. Bartlein. 2011. "Global Vegetation and Terrestrial Carbon Cycle Changes after the Last Ice Age." *New Phytologist* 189(4): 988–998.

Reilly, J., S. Paltsev, B. Felzer, X. Wang, D. Kicklighter, J. Melillo, R. Prinn, M. Sarofim, A. Sokolov, and C. Wang. 2007. "Global Economic Effects of Changes in Crops, Pasture, and Forests due to Changing Climate, Carbon Dioxide, and Ozone." *Energy Policy* 35(11): 5370–5383.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj. 2011. "RCP 8.5—A Scenario of Comparatively High Greenhouse gas Emissions." *Climatic Change* 109(1–2): 33.

Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, C.J. Crespo, K.C. Samir, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. Doelman, J. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, and M. Tavoni. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42: 153–168.

Scholze, M., W. Knorr, N.W. Arnell, and I. Colin Prentice. 2006. "A Climate-Change Risk Analysis for World Ecosystems." *Proceedings of the National Academy of Sciences* 103 (35): 13116–13120.

Sohngen, B., and R. Mendelsohn. 1998. "Valuing the Impact of Large-Scale Ecological Change in A Market: The Effect of Climate Change on US Timber." *American Economic Review* 88(4): 686–710.

Sohngen, B., and R. Mendelsohn. 2003. "An Optimal Control Model of Forest Carbon Sequestration." *American Journal of Agricultural Economics* 85(2): 448–457.

Sohngen, B., R. Mendelsohn, and R. Sedjo. 2001. "A Global Model of Climate Change Impacts on Timber Markets." *Journal of Agricultural and Resource Economics* 26(2): 326–343.

Solberg, B., A. Moiseyev, A. Maarit, and I. Kallio. 2003. "Economic Impacts of Accelerating Forest Growth in Europe." *Forest Policy and Economics* 5(2): 157–171.

Stocker, B.D., R. Roth, F. Joos, R. Spahni, M. Steinacher, S. Zaehle, L. Bouwman, and I.C. Prentice. 2013. "Multiple Greenhouse-Gas Feedbacks from the Land Biosphere under Future Climate Change Scenarios." *Nature Climate Change* 3(7): 666.

Tian, X., B. Sohngen, J.B. Kim, S. Ohrel, and J. Cole. 2016. "Global Climate Change Impacts on Forests and Markets." *Environmental Research Letters* 11(3): 035011.

Van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, *et al*. 2011. "The Representative Concentration Pathways: An Overview." *Climatic Change* 109(1–2): 5.

Wear, D.N. 2011. "Forecasts of county-level land uses under three future scenarios: a technical document supporting the Forest Service 2010 RPA Assessment." Gen. Tech. Rep. SRS-141. Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station. 41 p. 141: 1–41.

Appendix 1

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

Study	Time	Models	Scenario	Results
Global				
Sohngen, Mendelsohn, and Sedjo (2001)	2000–2140	GTM, 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, 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, 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

Continued

Table A1. Continued

Study	Time	Models	Scenario	Results
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 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, 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 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, 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 worth of benefits

Irland et al. (2001)	1990–2100	FASOM, 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 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, Adams, and McCarl (2002)	2000–2100	FASOM 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 (2011)	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 and MC1 dynamic global vegetation model	set of stabilization scenarios developed under the U.S. 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

Continued

Table A1. Continued

Study	Time	Models	Scenario	Results
Europe				
Nabuurs et al. (2002)	1990–2050	EFISCEN 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	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 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 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, Chaturvedi, and Sagadevan (2011)	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

GTM, global timber model; CGTM, CINTRAFOR Global trade model; TSM2000, timber supply model; GFPM, global forest products model; ATLAS, aggregate timberland assessment model; FASOM, forest and agriculture optimization mode, EFISCEN, forest resource scenario model; EFI-GTM, global forest sector model.