

Global climate change impacts on forests and markets

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 Environ. Res. Lett. 11 035011

(<http://iopscience.iop.org/1748-9326/11/3/035011>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 98.232.198.77

This content was downloaded on 31/05/2017 at 23:17

Please note that [terms and conditions apply](#).

You may also be interested in:

[Climate change impacts on US agriculture and forestry: benefits of global climate stabilization](#)

Robert H Beach, Yongxia Cai, Allison Thomson et al.

[Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios](#)

John B Kim, Erwan Monier, Brent Sohngen et al.

[US major crops' uncertain climate change risks and greenhouse gas mitigation benefits](#)

Ian Sue Wing, Erwan Monier, Ari Stern et al.

[Carbon savings with transatlantic trade in pellets: accounting for market-driven effects](#)

Weiwei Wang, Puneet Dwivedi, Robert Abt et al.

[Predicting pan-tropical climate change induced forest stock gains and losses—implications for REDD](#)

Marlies Gumpenberger, Katrin Vohland, Ursula Heyder et al.

[Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects](#)

Ulrich Kreidenweis, Florian Humpenöder, Miodrag Stevanovi et al.

[Drivers and patterns of land biosphere carbon balance reversal](#)

Christoph Müller, Elke Stehfest, Jelle G van Minnen et al.

[Investigating afforestation and bioenergy CCS as climate change mitigation strategies](#)

Florian Humpenöder, Alexander Popp, Jan Philip Dietrich et al.

[Disturbance-induced reduction of biomass carbon sinks of China's forests in recent years](#)

Chunhua Zhang, Weimin Ju, Jing M Chen et al.

Environmental Research Letters



LETTER

Global climate change impacts on forests and markets

OPEN ACCESS

RECEIVED

28 November 2015

REVISED

10 February 2016

ACCEPTED FOR PUBLICATION

15 February 2016

PUBLISHED

3 March 2016

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Xiaohui Tian¹, Brent Sohngen², John B Kim³, Sara Ohrel⁴ and Jefferson Cole⁴¹ Renmin University, Beijing, China, 59 Zhongguancun Avenue, Room 919 Mingde Main Building, Haidian District Beijing, 100872, People's Republic of China² Ohio State University, 2120 Fyffe Rd, Columbus Ohio 43210, USA³ Pacific Northwest Research Station, USDA Forest Service, 3200 SW Jefferson Way, Corvallis, OR 97330, USA⁴ Climate Change Division, US Environmental Protection Agency, 1200 Pennsylvania Avenue, NW (6207-J), Washington, DC 20460, USAE-mail: tianxiaohui@ruc.edu.cn and Sohngen.1@osu.edu

Keywords: climate change, dynamic optimization, markets

Abstract

This paper develops an economic analysis of climate change impacts in the global forest sector. It illustrates how potential future climate change impacts can be integrated into a dynamic forestry economics model using data from a global dynamic vegetation model, the MC2 model. The results suggest that climate change will cause forest outputs (such as timber) to increase by approximately 30% over the century. Aboveground forest carbon storage also is projected to increase, by approximately 26 Pg C by 2115, as a result of climate change, potentially providing an offset to emissions from other sectors. The effects of climate mitigation policies in the energy sector are then examined. When climate mitigation in the energy sector reduces warming, we project a smaller increase in forest outputs over the timeframe of the analysis, and we project a reduction in the sink capacity of forests of around 12 Pg C by 2115.

Introduction

Climate change is expected to have large impacts on forests globally. The recent Intergovernmental Panel on Climate Change report (IPCC 2014) suggests that ecosystems are likely to undergo substantial change in structure and composition in the future as climate change unfolds. The IPCC also reports that there is evidence that these types of changes are already occurring. A number of dynamic global vegetation models (DGVMs) have now been developed to project the potential changes to ecosystems on a global basis (Scholze *et al* 2006, Bachelet *et al* 2008, Gonzalez *et al* 2010). These models suggest that forest growth tends to increase globally, but forest dieback also increases globally, with the net effects varying over time and space. The IPCC (2014) suggests that climate change will be a powerful stressor on forests, and that adaptation is an important response. IPCC (2014), however, does not consider the market response to climate change. Markets will adjust harvest rates and planting intensity in response both to ecological (growth rates/dieback) and economic (price) signals, and these adaptations will in turn influence the resulting structure and function of forested

ecosystems. The way in which markets adapt to climate change-induced shifts in forest growth and dieback will have an important impact on projections of timber outputs, forest stocks, and carbon.

A number of economic models have been developed now to capture ecological impacts, but these studies are limited in that they focus on specific regions, are static economic approaches, or they rely on static ecosystem models. The earliest economic analyses focused on the United States, and suggested that climate change would increase timber supply and reduce timber prices (Joyce *et al* 1995, Sohngen and Mendelsohn 1998). The largest economic impacts in the US were projected to occur in the South and Pacific Northwest, which makes sense given that these regions also have the largest timber sectors. Sohngen and Mendelsohn (1998) incorporate numerous adaptations, and consider species movement across the landscape, dieback, and changes in timber yield. Joyce *et al* (1995) focus only on net yield changes, and assume that forest types remain in the same location over time.

One important limitation of these studies is that they consider only the United States. Because climate change is a global phenomenon, the effects of climate change on markets in any given region are a function

of the effects of climate change elsewhere. For instance, adaptations that would be efficient in the United States when evaluated by a model of only the US may not be efficient if evaluated with a global model that considers the effects of climate change elsewhere. Sohngen *et al* (2001) and Perez Garcia *et al* (2002) link global ecosystem models to global economic models, but their analysis is based on earlier equilibrium studies of climate impacts and ecosystem impacts. These earlier studies suggest that climate change will cause global forest stocks and growth to increase, and as a result, global timber supply will also increase. The increases are not even across the world, however, with stronger increases in outputs in tropical and subtropical areas. For instance, managers are able to adapt some forests in subtropical and tropical regions fairly rapidly to climate change because many species there have short timber rotation periods. As a result, earlier studies suggested that timber prices would decline relative to the no climate change scenario. Lower timber prices then caused some adaptation options in temperate regions, with forests that have longer rotations, to become inefficient. Earlier ecosystem models also projected that temperate and boreal regions would experience greater dieback with climate change than without, a factor which also reduced forest investments in temperate zones (see Sohngen *et al* 2001).

Most recently, Hanewinkel *et al* (2013) used newer dynamic ecosystem modeling with a static economic model to assess climate impacts in Europe. They suggest that the steady state outcomes would differ across climate outcomes, and that timber outputs in Europe would most likely decline. Haim *et al* (2011) examined the impacts of climate change on US land uses and found that climate change will have relatively modest impacts on land use. Their results suggest that other changes associated with conversion of land from forests to agriculture will have far bigger impacts in the future. Wear *et al* (2013) similarly find that while climate change will have important impacts in the future, the dominant impacts on forests in the future relate to shifts in demand due to climate policy (e.g., increases in biofuel demands), and changes in human use of land. While these newer approaches use dynamic ecosystem modeling, they do not use dynamic economic modeling and they are not global in scope.

To fully address climate change, one must develop economic models that account for dynamic ecological and economic features (Sohngen and Mendelsohn 1998), and they must consider global impacts in order to measure the effects in particular regions (Sohngen *et al* 2001). Dynamics in economics means capturing more than just changes over time. It implies that economic decision-making is modeled with forward looking expectations. When humans manage forests now, they do so with an eye on the future. The harvesting decision, for example, is based not only on the current stock of timber available to harvest, but it is

also based on an understanding about the growth of the trees and the likely change in timber prices in future years (Brazee and Mendelsohn 1988). Landowners will make different decisions depending on whether their trees are currently growing quickly or slowly, and whether they anticipate prices to increase, stay the same, or fall over the coming year. Planting decisions also require very long time horizons. Many species will not mature for 20, 30 or more than 50 years. Any decision to spend resources planting or managing forests that cannot be harvested for such long time horizons require some information or assumptions about what future market conditions will be (Sedjo and Lyon 1990). Dynamic decision-making in economics requires modelers to account for these long-term considerations of landowners and managers in their current decisions.

In this paper, we examine the effects of climate change on timber production, timber prices, and carbon sequestration globally by linking the MC2 DGVM with the Global Timber Model (GTM), an updated version of a dynamic global forest model (Daigneault *et al* 2012). The MC2 DGVM is described in Kim *et al* (2015). GTM has also been updated from earlier versions to include additional forest types in the United States and heterogeneous products (sawtimber and pulpwood demands are modeled independently). The climate scenarios are based on the modeling in Monier *et al* (2013), and the scenarios consider three different future radiative forcing scenarios, a business-as-usual reference scenario with a high level of radiative forcing (approximately 9.0 W m^{-2}), and two lower scenarios representing adoption of climate change mitigation policies.

Methods

The climate scenarios for this analysis are developed using climate change projections from the MIT Integrated Global Systems Model (IGSM) (Monier *et al* 2013). The outputs from IGSM are downscaled to the 0.5° spatial resolution, and used by the MC2 DGVM to simulate vegetation response to climate change from the present to year 2100 (Kim *et al* 2015). Although MC2 DGVM generates outputs at the 0.5° spatial resolution at a monthly time step, its outputs were aggregated to decadal averages across major global regions for use in the economic model. A number of outputs from the MC2 model are then utilized in the economic model. Specifically, we use outputs on net primary productivity (NPP) to perturb forest growth, outputs on the area of land burned each decade to model dieback, and information on the area of vegetation types to provide overall constraints on the area of land available for the timber types in our model. Because the economic model does not model outputs at the 0.5° gridded level, but instead models outputs at a more aggregated level, the results from the

MC2 model are aggregated over larger areas for inclusion in the economic model.

For the analysis in this paper, the reference climate change scenario allows greenhouse gas concentrations (GHG) in the atmosphere to rise to a level such that radiative forcing rises slightly above 9 W m^{-2} . Two additional scenarios are then considered, where GHG mitigation policies are adopted to limit warming to 4.5 and 3.7 W m^{-2} . The two mitigation scenarios assume that the policies focus on reducing carbon emissions in the energy sectors (e.g., cap and trade policies, carbon taxes, or other carbon regulations), but not in the forestry or land use sectors. That is, any changes in global carbon emissions implied by GTM does not feed back to the two mitigation scenarios.

One of the key outputs of the MC2 model for economic modeling is NPP, the amount of carbon fixed through photosynthesis minus carbon expended through respiration. We use changes in NPP simulated by MC2 relative to a baseline period (1980–2009) as a general measure of the change in forest productivity due to climate change in GTM. According to the MC2 model, large areas of the world's ecosystems experience an increase in NPP, although reduction in NPP is possible for some regions (Kim *et al* 2015).

The vegetation types simulated by MC2 correlate closely with land cover types simulated by GTM. Changes in area of each MC2 vegetation type was used to change the GTM land cover type. Yield changes in GTM, represented as $\text{m}^3 \text{ ha}^{-1}$, are adjusted based on MC2 projections of changes in NPP. Importantly, when implemented in GTM, the growth perturbations from MC2 affect only future forest growth, not past growth.

The change in forest area burned by wildfire projected by the MC2 model is also incorporated in our model. This dieback effect alters standing stocks of trees. For example, if MC2 projects 3% of the area of a given land class burned in a given year, we assume that 3% of the area of our stock in that land class burns each year. We assume that all age classes have equal probability of burning.

The MC2 projections for changes in NPP and dieback are linked directly into GTM. Specifically, we determine an effect for the change in NPP (timber yield) and dieback for each forest type in each region of GTM using the results from MC2. We then project a baseline case in which we assume that there is no climate change (i.e., no yield changes and dieback consistent with conditions from the 1980–2009 as calculated by MC2). The three climate scenarios, as discussed above are a reference case which allows climate change to occur without any mitigation, and two global climate mitigation scenarios.

The GTM model is a dynamic optimization model of forests and land use that maximizes the net present value of consumer's and producer's surplus in timber markets (Sohngen *et al* 1999, 2001, Daigneault *et al* 2008). The model optimizes the age class of harvesting

forests (all forests are modeled age in delimited vintages), the area of forests, and the investment in managing forests through replanting, fertilizing, competition suppression, thinning, and other traditional forest management practices. The methods for integrating ecosystem impacts into the timber model follow the methods described in Sohngen and Mendelsohn (1998) and Sohngen *et al* (2001), although the results here are updated with new climate model, new dynamic vegetation modeling, new and updated data on forest inventories, yields, and areas, and new assumptions about economic growth and their implications for forest products demand. Importantly, the GTM is not a stochastic model, so we are unable to address differences in adaptive behavior that may arise with potentially stochastic shocks to the ecological or economic system (i.e., business cycles or thresholds in ecosystem responses).

In GTM, timber demand is modeled as a globally aggregated function of regional demands. Aggregate demand growth is driven by increases in global average income per capita, which we assume increases at 2%–3% per year over the coming century. Income elasticity in our model is set to 0.87, so income increases translate directly into fairly large increases in demand. This is consistent with Simanunsong and Buongiorno (2001) and Turner and Buongiorno (2004) who estimate that income elasticity is around 1.0. In addition to considering the overall growth in demand due to income growth, it is important to recognize that our demand function is the derived demand for timber logs. Logs are used by pulp or sawtimber mills to produce outputs demanded by society. We assume that timber and pulp mills become more efficient over time at converting timber from the forest into wood products consumed by society. This technological progress is assumed to slow the growth in demand for timber inputs over time by 0.9% per year. The combination of rising income and the fairly high income elasticity we use plus the slowdown in growth due to technological change means that overall demand for wood products shifts outward at about 1.1% per year.

Aside from the demand functions, there also are a number of parameters in the model, and the results could be sensitive to some of them. An earlier study with an earlier version of the economic and ecological models used here conducted thorough sensitivity analysis and did not find that the results differed qualitatively (see Sohngen and Mendelsohn 1998 and Sohngen *et al* 2001).

The climate models and MC2 models both terminate their projections after 100 years. We terminate the dynamic forestry model after 200 years, or 20 decades. Because we do not have results from MC2 for years after 2110, we assume that ecological and climate conditions are stable, or fixed at their year 2110 conditions, but we continue to allow economic growth to continue (i.e., demand to grow), and forestry markets to adapt and adjust forests. Forest growth continues as

well, with the growth and dieback impacts from the last period fixed for the last 100 years of the simulation. Demand is stabilized after 150 years and terminal conditions are imposed on the entire model at year 200. The terminal conditions are calculated by assuming a steady state to calculate marginal values for all stock variables. These marginal values then are used to value forests at the terminal period, although we do not assume that forests are in a normal rotation (e.g., even age classes). We present results only for the first 100 years of our model runs. We note that any choice of terminal conditions is arbitrary, but by running our model for 200 years, the impact of this choice of terminal conditions on our model results is limited given the important influence of discounting.

Results and discussion

The aggregate regional predictions for the yield change and dieback from MC2 are shown in tables 1(a) and (b). NPP increases in the reference case by around 12% globally by 2050 and 30% globally by 2110, with modestly larger increases in temperate forests on average. Temperate regions like the EU and the United States appear to experience the largest increases in NPP. Interestingly, China gains less and even experiences a modest reduction in NPP by 2050. Stronger climate change seems to provide larger increases in yields, with the reference level results suggesting larger increases in NPP than either the 3.7 or 4.5 W m^{-2} scenarios. Forest dieback also increases under each of the climate scenarios, with the largest increases occurring in the reference scenario in general (tables 1(b)). Proportionally, the increases are greatest in the tropics, although dieback is greatest in the temperate zone.

In the baseline, sawtimber and pulpwood prices are projected to increase at about 0.7% per year over the coming century (figure 1). This is slower than historical rates of price change globally, but consistent with recent trends. Globally, sawtimber output increases by 37%, and pulpwood output increases by 43% over the century. This is roughly consistent with the expansion in global output that occurred from the 1960s to the 2000s, suggesting that our model is projecting that output growth slows in the future relative to the last half of the last century. The largest increase in pulpwood output occurs in the tropics (figure 2). The increase in output is perhaps surprising, given that total land area in forests declines by around 550 million ha over the century, with 80% of this loss occurring in tropical regions. Output however, increases due to investments in plantation forests in tropical and subtropical regions.

Under the reference climate change scenario, there is a 32% increase in global sawtimber and pulpwood output relative to the no climate change baseline by 2115, and a 15%–30% reduction in prices, with the

largest reduction in prices occurring in pulpwood markets. The largest expansion in sawtimber output for the reference scenario occurs in northern regions, such as Russia, the EU and Canada (figure 3). Tropical countries do not make significant increases in sawtimber output in the reference scenario. In contrast, the gains in pulpwood production are shared more broadly. Brazil and SE Asia increase pulpwood production in response to climate change, as do the United States and China. One reason why China and the US increase output is that they have relatively fast-growing plantations in the south that are particularly well suited to grow pulpwood and adapt to climate change. These increases in pulpwood production in the temperate zone occur mostly in the latter half of the century.

One of the critical results of the MC2 model is the projected increase in the area of forest dieback (figure 4). In the temperate zone, Russia experiences a large increase in forest fire and dieback activity. The EU, US and Canada also face proportionally similar increases in dieback, although they have less forest area and thus less increase. SE Asia and Brazil experience increases in forest fires, although the increases are relatively modest compared to those that occur in the temperate and boreal zones. Salvage timber also increases (figure 4), and it turns out to be a fairly important component of the adaptation process. Initially, salvage amounts to 70% of the increase in harvest that occurs under the climate change case. Over time, as foresters adjust forest management and adapt to the changes, salvage becomes a smaller proportion of the total change in harvest.

Total carbon storage as projected by the economic model is expected to increase in the future as a result of climate change (figure 5). The EU, China, Russia, and Canada receive the greatest apparent benefits of climate change in terms of increased carbon sequestration. The US initially gains some benefits, but over the long run, the net effects in the US are small. Oceania experiences a reduction in carbon storage. Most tropical regions similarly gain carbon storage over time. These increases occur even as the total area of forestland declines and the amount of dieback increases. The increase in carbon storage suggests that forests potentially provide a net sink.

In comparison to the reference case, the climate mitigation scenarios reduce NPP in most regions and reduce forest dieback. The net effect of these changes on timber prices, however, is fairly modest (see figure 1). On average, sawtimber prices are about 1.5% higher in the two mitigation scenarios, and pulpwood prices are about 3.5% higher in the two mitigation scenarios. Given that the warming that occurs in the reference scenario is more than double these two mitigation scenarios, i.e., above 9 W m^{-2} by the end of the century, it is interesting that the price effect is not greater. The small change in prices between the reference scenario and the mitigation scenarios occurs

Table 1. (a) Projected percentage changes in net primary productivity (NPP) relative to the no climate change case by forests for the regions modeled by the global forestry model. (b) Projected dieback in 2010, 2050, and 2110 for forests in each region. The percentage is the percent of forest stocks predicted to dieback each year due to fires under natural (no fire-fighting) conditions.

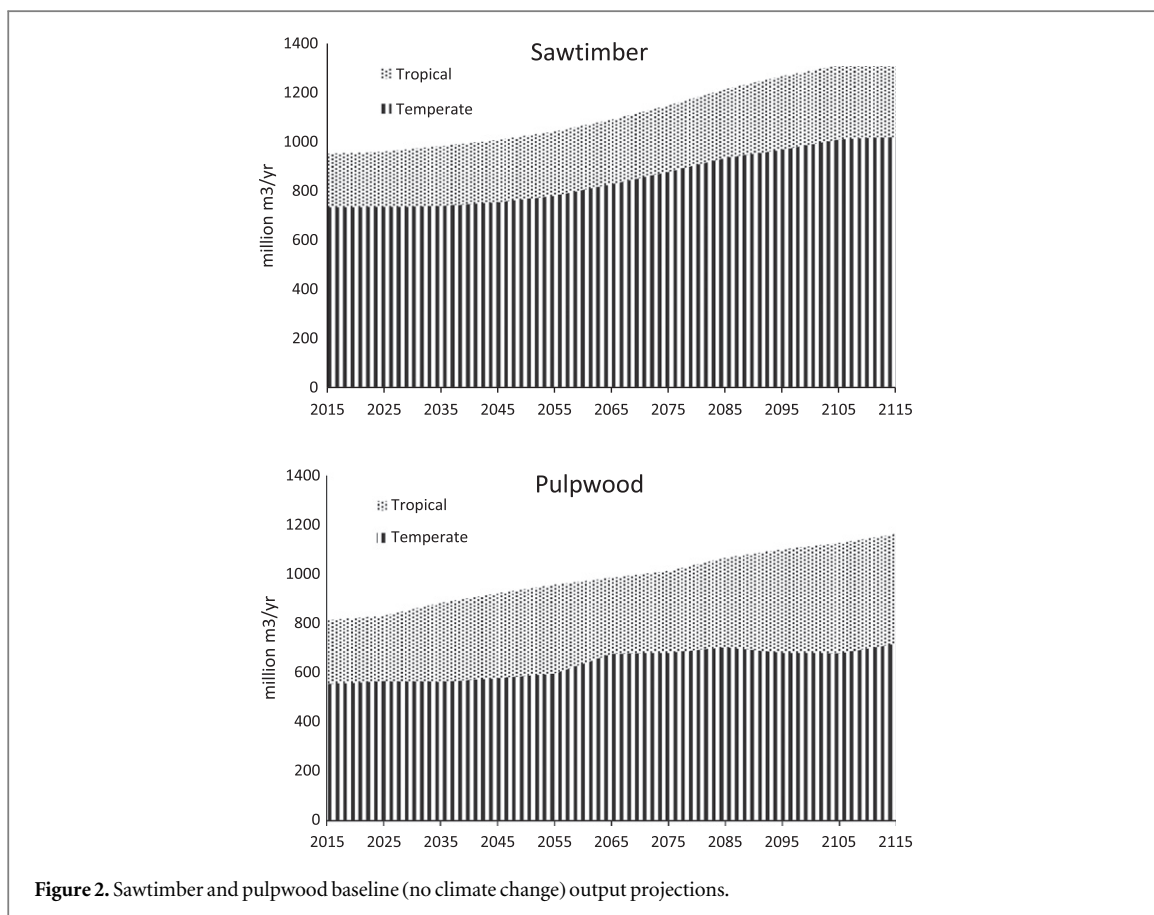
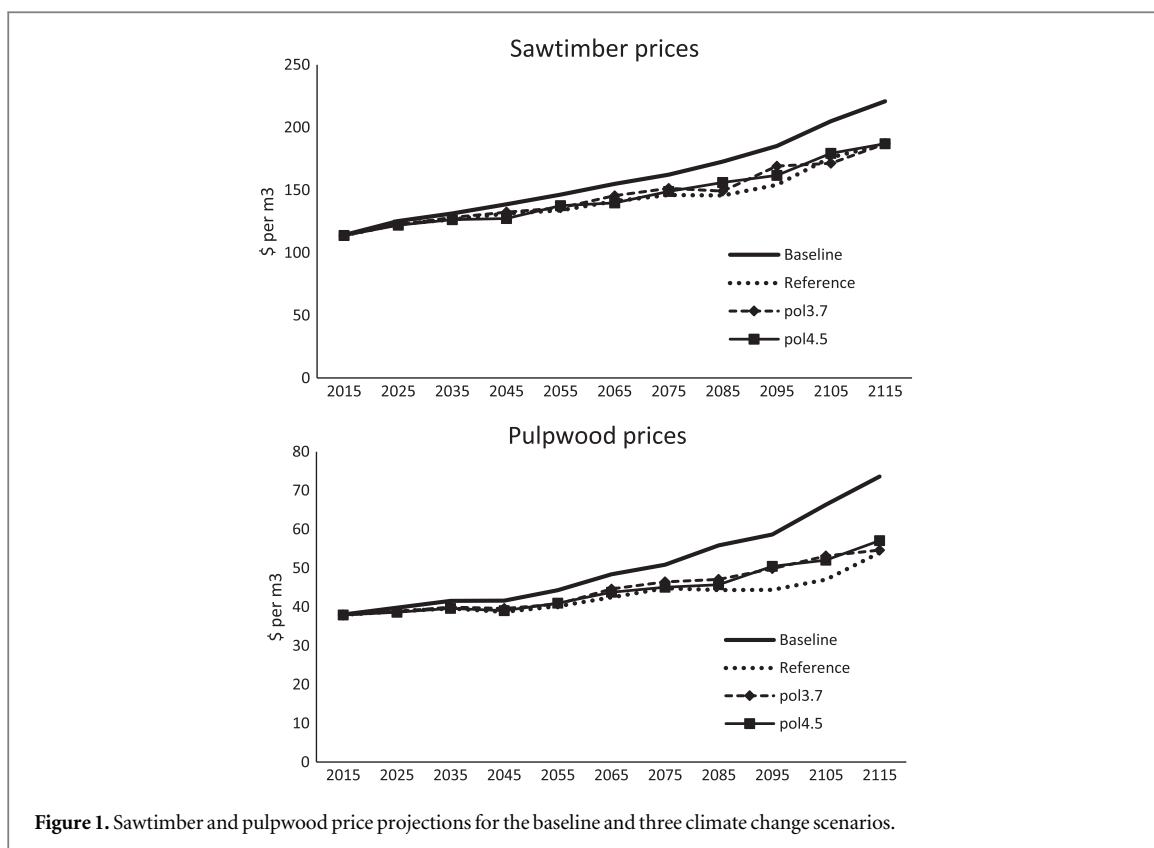
(a)							
	Reference		4.5 w m ^{−2}		3.7 w m ^{−2}		
	2050	2110	2050	2110	2050	2110	
Temperate							
US	24%	58%	18%	27%	24%	22%	
China	12%	7%	−3%	12%	4%	9%	
Canada	14%	26%	9%	18%	10%	11%	
Russia	9%	27%	14%	18%	9%	9%	
EU	21%	81%	13%	16%	12%	11%	
Oceania	4%	13%	0%	6%	4%	8%	
Japan	8%	0%	8%	0%	10%	0%	
East Asia	14%	24%	5%	3%	16%	18%	
Temperate Avg	12%	32%	11%	17%	10%	11%	
Tropical							
Brazil	16%	31%	9%	16%	9%	13%	
South Asia	8%	35%	8%	9%	6%	10%	
Central America	2%	−7%	14%	12%	−5%	6%	
Rest of SA	11%	29%	8%	14%	8%	12%	
SE Asia	9%	19%	7%	9%	6%	7%	
SubSaharan Af.	11%	22%	7%	9%	7%	6%	
Africa/ME	9%	22%	4%	7%	4%	3%	
Tropical Avg.	12%	26%	8%	13%	7%	10%	
Global	12%	30%	10%	16%	9%	11%	
(b)							
		Reference		4.5 w m ^{−2}		3.7 w m ^{−2}	
	2010 ^a	2050	2110	2050	2110	2050	2110
Temperate							
US	0.7%	3.3%	3.9%	2.2%	1.9%	3.0%	4.1%
China	0.1%	0.5%	1.1%	0.3%	0.3%	0.4%	0.5%
Canada	0.2%	0.7%	1.5%	0.4%	0.5%	0.6%	0.6%
Russia	0.6%	2.3%	1.6%	1.5%	3.1%	2.0%	3.8%
EU	1.0%	2.8%	6.7%	2.3%	6.8%	2.0%	3.5%
Oceania	0.7%	1.6%	1.3%	2.2%	1.3%	2.1%	2.4%
Japan	0.4%	0.4%	0.3%	0.4%	0.3%	0.4%	0.3%
East Asia	0.2%	1.1%	1.0%	0.9%	1.2%	0.6%	0.8%
Temperate Avg	0.5%	1.9%	2.3%	1.4%	2.3%	1.7%	2.6%
Tropical							
Brazil	0.0%	0.8%	0.5%	0.6%	0.4%	0.3%	0.3%
South Asia	0.5%	11.9%	11.6%	5.7%	5.9%	6.6%	7.8%
Central America	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Rest of SA	0.0%	0.1%	0.6%	0.1%	0.4%	0.1%	0.1%
SE Asia	0.2%	3.1%	1.8%	1.6%	0.9%	0.9%	1.1%
SubSaharan Af.	0.1%	0.4%	0.3%	0.8%	1.1%	0.9%	0.8%
Africa/ME	0.0%	0.1%	0.1%	0.2%	0.1%	0.1%	0.1%
Tropical Avg.	0.1%	1.2%	1.1%	0.8%	0.8%	0.6%	0.7%
Global	0.3%	1.6%	1.9%	1.2%	1.8%	1.3%	1.9%

^a The year 2010 results are the same for each scenario.

because global outputs do not change very much, although outputs in some regions change quite dramatically. For instance, timber outputs in Russia are higher in the two mitigation scenarios versus the reference, while they are lower in the EU for the two mitigation scenarios versus the reference (figure 6). Outputs in Russia are higher in the mitigation scenarios

because dieback is, surprisingly, greater in the mitigation scenarios, and salvage harvesting is greater. In contrast, the MC2 model suggests a larger increase in productivity in the EU under the reference scenario than in the two mitigation scenarios.

In general, the largest effects of climate mitigation policies occur in the temperate region, likely due to the



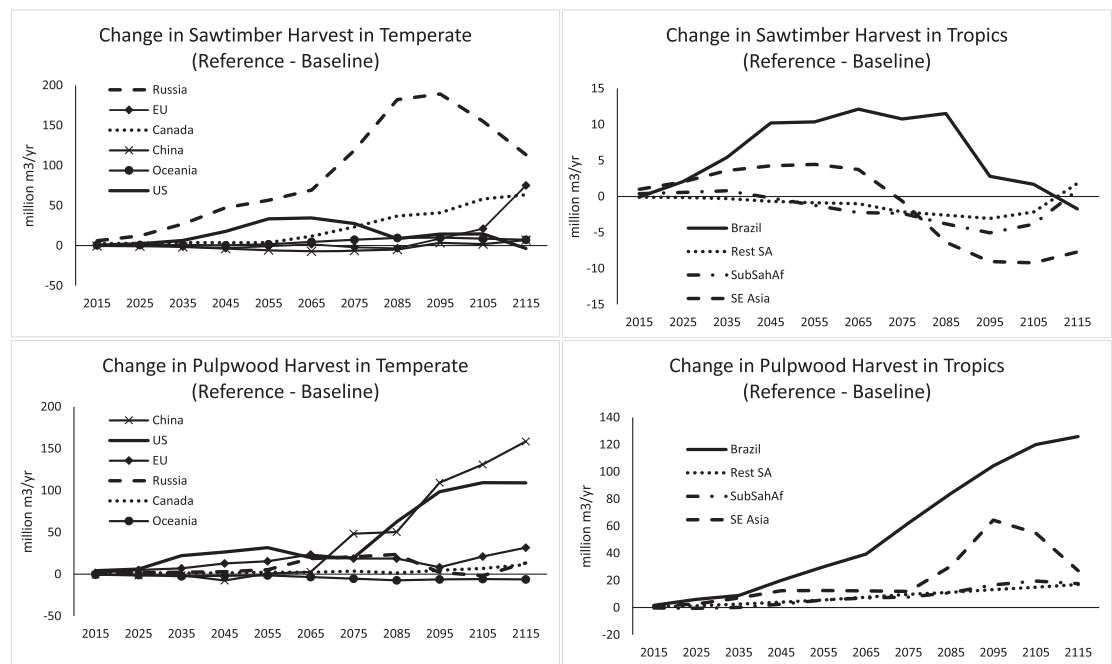


Figure 3. Change in timber harvest for reference climate scenario relative to the baseline (no climate change case).

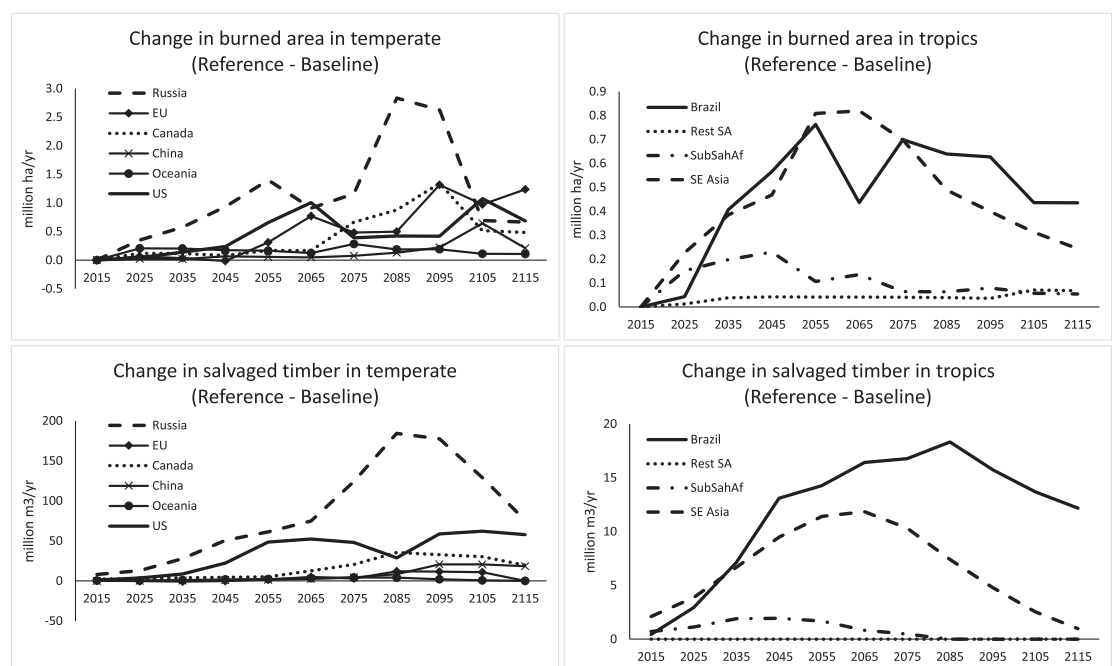


Figure 4. Change in burned area change in salvaged timber (reference climate scenario minus the baseline, no climate change). Change in burned area is directly from MC2 and change in salvaged timber is based on GTM integrated results.

important influence of reducing forest fires and burning (figure 6). Under the 3.7 W m^{-2} case, total output increases over the early part of the century in most of the temperate zone relative to the reference and 4.5 W m^{-2} case. The effects are not linear. By the end of the century, output falls everywhere, except Russia and SE Asia. The output effects are driven not only by changes in productivity but also by changes in dieback. Higher dieback can increase output through salvage,

but it also reduces the net benefits of rising NPP. These effects accumulate over time.

In aggregate, forests are expected to sequester an additional 26 Pg C over the century in the reference scenario compared to no climate change. The effects grow over the century with their largest cumulative impact occurring in the temperate and boreal zones in 2115. Carbon storage in forested ecosystems, however, is lower in the two mitigation policy scenarios, by

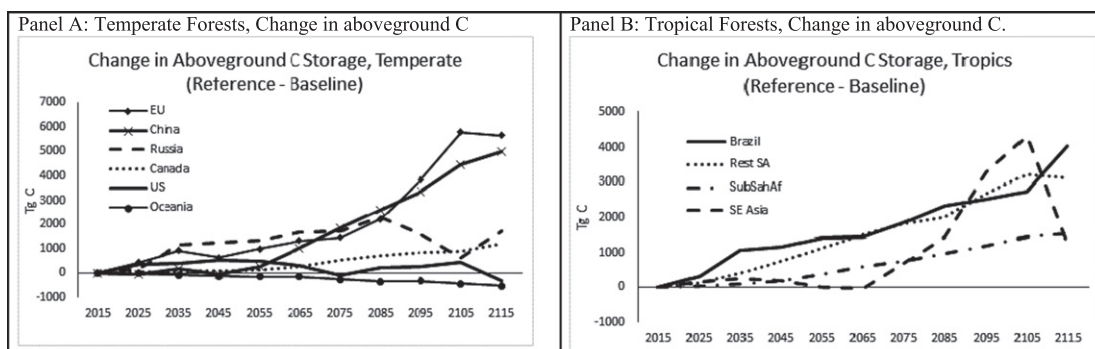


Figure 5. Cumulative change in aboveground carbon storage, reference scenario minus the baseline (no climate change). Carbon measured in Tg C.

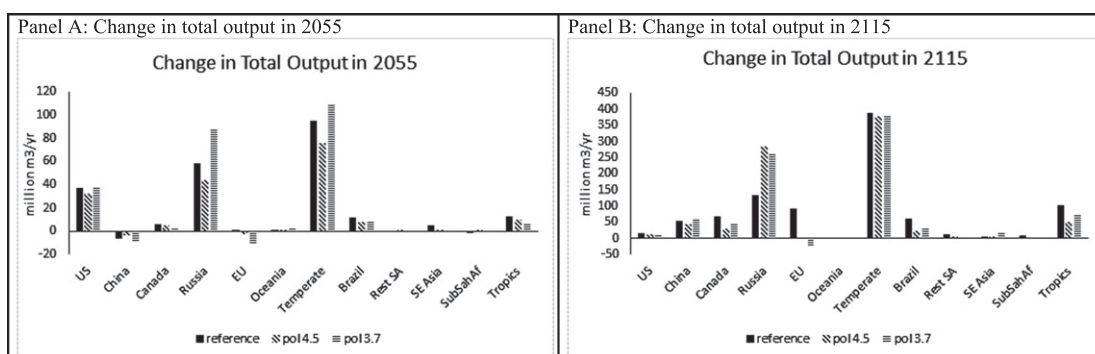


Figure 6. Change in total timber output by region for 2055 and 2115 in the reference, 4.5 and 3.7 W m^{-2} cases. The data for 'temperate' accounts for all regions in the temperate zone, even those not shown, and the tropics accounts for the tropical countries.

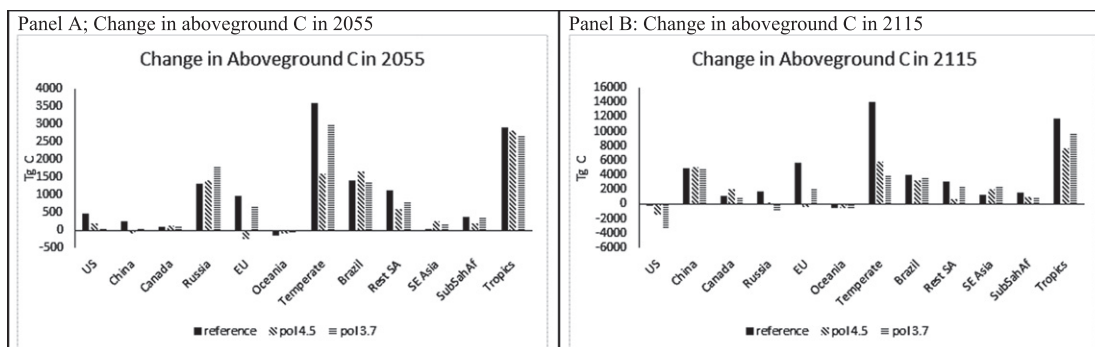


Figure 7. Change in aboveground C for reference, and mitigation scenarios, 2055 and 2115.

13–14 Pg C compared to the reference case (figure 7). Russia sequesters up to 2.5 Pg C less carbon over the century in the mitigation policy scenarios, while the US sequesters up to 3.0 Pg C less. In contrast, China and Canada both become stronger net sinks, although the effects in those two countries are relatively modest. In the tropics, the results of climate mitigation vary, but policies that mitigate carbon in the energy sector generally reduce the sink capacity of forests in those regions. These results suggest that if society undertakes climate mitigation in the energy sector without considering forests, forests will be a smaller net sink. It is

important to recall, however, that we have not explored the effects of carbon sequestration programs in forestry in this analysis, as examined in Sohngen and Mendelsohn (2003).

Conclusion

This paper examines the implications of climate change on forested ecosystems. The paper presents a general economic model for integrating ecological effects of climate change into a dynamic optimization model of global forestry. We then use a set of results

from a recent DGVM to illustrate how climate change impacts can be integrated into a dynamic global forestry model. The global dynamic vegetation model is simulated with a General Circulation Model over a reference case and two carbon mitigation policy simulations.

The results of the numerical model suggest that global timber output increases with climate change and timber prices fall. Pulpwood prices fall the most due to climate change, although prices fall for sawtimber as well. Output increases throughout the century, with the strongest gains at the end of the century. Climate mitigation policies have important impacts, slowing the changes in forests and reducing the impacts in markets. The impact of climate mitigation on timber outputs, however, are not all that consequential globally. The reason for this is that forests are affected both by dieback and changes in forest growth. While climate change mitigation reduces the gains in forest growth, it also reduces dieback. Lower dieback leads to less timber output due to the reduction in dieback.

The model suggests that forests will become a larger reservoir of carbon with climate change than without climate change. By the middle of the century, carbon storage in forests is projected to increase by around 6.6 Pg C, while it is projected to increase by over 25 Pg C by the end of the century. Most of this increase is due to shifts in forest growth and timber management, as we do not currently allow forest types to shift over space, so land use change in these results is limited. Climate mitigation policies in the energy sector reduce the overall response of forests by 1–2 Pg C by mid-century and by over 12 Pg C by 2115.

Our global estimates of climate change impacts based on dynamic models are some of the first since earlier work by Sohngen *et al* (2001) and Perez-Garcia *et al* (2001). Both of those earlier studies used static climate and ecosystem models and projected increased timber output. The Sohngen *et al* (2001) analysis is most similar because it used an earlier version of the global forestry model used in this study. Their finding that timber production increased by about 30% in the long-run (beyond 2100), is about the same change as projected by our model. The Sohngen *et al* (2001) study, however, suggested that the largest increases in timber production would occur in the tropics, while our modeling indicate that the timber market benefits are shared more evenly. Our results are in contrast to the recent study by Hanewinkel *et al* (2013) that indicated there would be a large reduction in the value of forests in the European Union. We similarly find that value falls in the EU, but our results suggest a much smaller impact due to the dynamic nature of our study. Further, we find evidence that the longer term impact in Europe could be positive and the impact seems to become larger with more climate change.

There are of course a number of important limitations in this analysis. First, we consider only

adaptation through forest management. Adaptation can occur in other ways, for instance, if relative prices between forest products and substitutes change due to climate change, then overall demand for wood products can increase or decrease. We have not incorporated this type of adaptation or change. Second, the dynamic vegetation models assume that ecosystems are natural. Climate change could have differential impacts upon managed and unmanaged stands, and it would be useful to conduct additional analysis to determine if the effects of climate change differ across managed and unmanaged stands. It also would be interesting to integrate the economic results back into the dynamic vegetation models.

Acknowledgments

The authors appreciate funding from the US Environmental Protection Agency Climate Change Division although the analysis and conclusion do not in any way represent the views of the US Environmental Protection Agency Climate Change Division. John B Kim is supported in part by the US Forest Service Western Wildland Environmental Threat Assessment Center, and by US Environmental Protection Agency's Climate Change Division, under interagency agreement DW-012-92388301.

References

- Bachelet D, Lenihan J, Drapek R and Neilson R 2008 VEMAP versus VINCERA: a DGVM sensitivity to differences in climate scenarios *Glob. Planet. Change* **64** 38–48
- Brazee R and Mendelsohn R 1988 Timber harvesting with fluctuating prices *Forest Sci.* **34** 359–72
- Daigneault A, Sohngen B and Sedjo R 2008 Exchange rates and the competitiveness of the United States timber sector in a global economy *Forest Policy Econ.* **10** 108–16
- Daigneault A, Sohngen B and Sedjo R 2012 Economic approach to assess the forest carbon implications of biomass energy *Environ. Sci. Technol.* **46** 5664–71
- Gonzalez P, Neilson R P, Lenihan J M and Drapek R J 2010 Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change *Glob. Ecology Biogeography* **19** 755–68
- Haim D, Alig R J, Plantinga A J and Sohngen B 2011 Climate change and future land use in the United States: an economic approach *Clim. Change Econ.* **2** 27–51
- Hanewinkel M, Cullmann D A, Schelhaas M J, Nabuurs G J and Zimmermann N E 2013 Climate change may cause severe loss in the economic value of European forest land *Nat. Clim. Change* **3** 203–7
- IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A: Global and sectoral aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed C B Field *et al* (Cambridge: Cambridge University Press) p 1132 (www.ipcc.ch/)
- Joyce L A, Mills J R, Heath L S, McGuire A D, Haynes R W and Birdsey R A 1995 Forest sector impacts from changes in forest productivity under climate change *J. Biogeography* **22** 703–13
- Kim J B, Monier E, Sohngen B, Pitts G S, Drapek R, Ohrel S and Cole J 2015 *Simulating Climate Change Impacts on Major Global Forestry Regions Under Multiple Socioeconomic and Emissions Scenarios, Working Paper* US Forest Service, Pacific Northwest Laboratories

- Monier E, Scott J R, Sokolov A P, Forest C E and Schlosser C A 2013 An integrated assessment modeling framework for uncertainty studies in global and regional climate change: the MIT IGSM-CAM (version 1.0) *Geoscientific Model Dev.* **6** 2063–85
- Perez-Garcia J, Joyce L A, McGuire A D and Xiao X 2002 Impacts of climate change on the global forest sector *Clim. Change* **54** 439–61
- Scholze M, Knorr W, Arnell N W and Prentice I C 2006 A climate-change risk analysis for world ecosystems *Proc. Natl Acad. Sci. USA* **103** 13116–20
- Sedjo R and Lyon K S 1990 *The Long-Term Adequacy of World Timber Supply* (Washington, DC: RFF Press)
- Simangunsong B C H and Buongiorno J 2001 International demand equations for forest products: a comparison of methods *Scand. J. For. Res.* **16** 155–72
- Sohngen B and Mendelsohn R 1998 Valuing the market impact of large scale ecological change: the effect of climate change on US timber *Am. Econ. Rev.* **88** 689–710 (www.jstor.org/stable/117001)
- Sohngen B and Mendelsohn R 2003 An optimal control model of forest carbon sequestration *Am. J. Agric. Econ.* **85** 448–57
- Sohngen B, Mendelsohn R and Sedjo R 1999 Forest management, conservation, and global timber markets *Am. J. Agric. Econ.* **81** 1–13
- Sohngen B, Mendelsohn R and Sedjo R 2001 A global model of climate change impacts on timber markets *J. Agric. Resour. Econ.* **26** 326–43 (www.jstor.org/stable/40987113)
- Turner J A and Buongiorno J 2004 Estimating price and income elasticities of demand for imports of forest products from panel data *Scand. J. For. Res.* **19** 358–73
- Wear D N, Huggett R, Li R, Perryman B and Liu S 2013 Forecasts of forest conditions in regions of the United States under future scenarios: a technical document supporting the Forest Service 2012 RPA assessment *Gen. Tech. Rep. SRS-170* (Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station) p 101