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Climate Change and Forests

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Abstract

Forests have become an important carbon sink in the last century, with management and carbon fertilization offsetting nearly all of the carbon emitted due to deforestation and conversion of land into agricultural uses. Society appears already to have decided that forests will play an equally ambitious role in the future. Given this, economists are needed to help better understand the efficiency of efforts society may undertake to expand forests, protect them from losses, manage them more intensively, or convert them into wood products, including biomass energy. A rich literature exists on this topic, but a number of critical information gaps persist, representing important opportunities for economists to advance knowledge in the future. This article reviews the literature on forests and climate change and provides some thoughts on potential future research directions.

INTRODUCTION

Forested ecosystems are likely to undergo substantial change in structure and composition in the future as climate change unfolds (IPCC 2014). Increases in carbon dioxide in the atmosphere due to industrial carbon emissions will have multiple direct and indirect effects on forests. While additional carbon may increase forest growth in the future, changes in temperature and precipitation patterns as a result of rising CO_2 levels could alter forest disturbance patterns and forest location. Some forests may experience increased drought and dieback, while improved growing conditions where precipitation increases could open to new forest areas that are currently too dry. In short, forests in some regions may benefit from climate change, while other areas will experience increases in drought-induced mortality and potentially greater forest fire activity.

As these changes unfold across the landscape, forest landowners and managers will adapt through a variety of actions. Some managers will leave their forests to adapt naturally, while others will take actions in direct response to the new climate they observe. Yet others may collect information on future conditions and start to adapt their forests to future conditions through shifts in management, including changes in the age of harvesting forests, through altered thinning regimes, or through modifications in what is planted. Regardless of the approach that foresters take, the structure and function of future forests will differ from forests today as management actions collide with climate change to produce novel future forest conditions.

In addition to considering how climate change may affect forests, it is useful to consider the role of forests in the global carbon budget, how that role has changed over time, and how society may take actions using forests to mitigate climate change in the future. Emissions from fossil fuel and cement production, of course, have been the largest source of carbon into the atmosphere, amounting to emissions of 1,281 billion tons of CO_2 from 1900 to 2010 (**Figure 1**), but deforestation has also been a significant source of carbon, accounting for 448 billion tons of CO_2 emissions from 1900 to 2010, or about 26% of the total emissions during that time period (Houghton et al. 2012, Le Quéré et al. 2018). Although the scale of deforestation is large, forest regrowth has

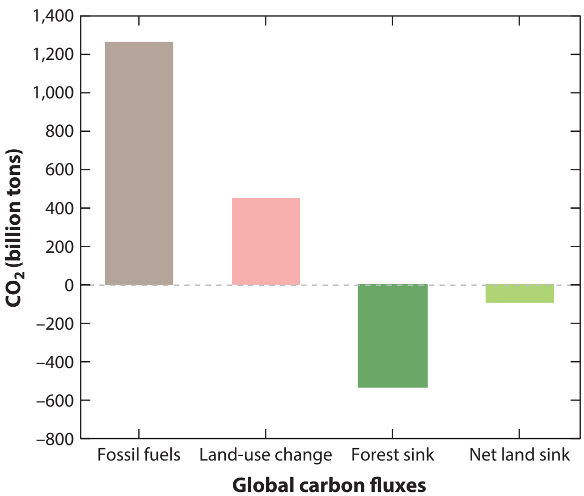

Figure 1

Global carbon fluxes from fossil fuels, land-use change, forest sink, and net land sink from 1900 to 2010 (data from Le Quéré et al. 2018, Mendelsohn & Sohngen 2019). Positive numbers are emissions to the atmosphere, and negative numbers are removals from the atmosphere.

encouraged an even more impressive carbon sink, removing over 540 billion tons of CO_2 from the atmosphere since 1900 (**Figure 1**). This sink emerged as large areas of former agricultural land reverted back to forests in the temperate zone (Kauppi et al. 2006), carbon fertilization enhanced growth, and forests were managed more intensively for timber products (Mendelsohn & Sohngen 2019, Pan et al. 2011). As a result, all the emissions from deforestation between 1900 and 2010 were more than offset by regrowth in forests due to market processes and carbon fertilization (Mendelsohn & Sohngen 2019). The net effect of forests over the last century has been to reduce carbon in the atmosphere with increased biomass in forest stocks. Given this historical feat, there is widespread hope that future efforts to increase the area of land in forests by returning additional land from agriculture to forests, as well as improved management, could increase global climate mitigation (Griscom et al. 2017). Forests may also be used as an input into bioenergy production, with the resulting CO_2 emissions sequestered underground through carbon capture and storage (Favero & Mendelsohn 2014).

Given the important role that forests play in the global carbon budget, this article reviews the state of economic analysis into the impacts of climate change on forests, forest management and forest investments, and the economic literature on studies investigating the costs of carbon sequestration. A large number of studies have been conducted over the past 20 or so years, addressing a number of critical issues, including assessment of adaptation on the intensive (e.g., harvesting) and extensive margins (e.g., replanting), the effect of changes in disturbance patterns on management, and integrated assessment analysis that combines ecosystem studies with economic studies. Although the existing literature suggests that climate change likely benefits the timber market over the next century by increasing forest productivity and increasing the supply of timber, the role of climate change impacts and forest management on carbon stocks is less well understood. This may be particularly important in extensive margin regions of the Arctic and the tropics given the potential scale of climate change impacts in those regions that are relatively unmanaged, or at least managed much less intensively than other forested regions.

This review begins with an assessment of the potential ecological impacts of climate change on forests. It then considers how economists have modeled the impacts of climate change in forests, as well as the role of adaptation. Because forests are an important part of the global carbon cycle, and climate change threatens the stability of forested carbon stocks, the article then describes the literature on mitigation, or the use of forests to reduce the effects of climate change. The final sections provide some ideas for future research.

CLIMATE CHANGE AND FORESTS

Climate change will affect forests by altering the growth rate of trees, by changing disturbance patterns, and by shifting the optimal location where trees can grow. Each of these effects will be influenced by increases in carbon concentrations and the resulting shifts in temperature and precipitation patterns. While changes in temperature and precipitation could have direct effects on forests by making them more or less susceptible to disturbances from pests or fire, climate change could also influence forest disturbance by changing weather patterns, for example, by changing the intensity or path of hurricanes. Although the current structure of forest ecosystems is determined in large part by historical disturbance patterns, climate change is expected to have large influences on future forest structure because future changes in climate will occur more rapidly than past changes (IPCC 2014).

It is important to recognize that forests already have been influenced by the effects of climate change. This is not surprising given the dominant role that climate plays in the functioning of ecosystems. Fei et al. (2017) and Knott et al. (2019) document how forests have already migrated in North America using data from the US Forest Service forest inventory (**https://www.fia.fs.fed.us/**). Boisvenue & Running (2006) provide evidence that forest growth has changed as a result of carbon fertilization and climate change over the last half century. Although drought and disturbance have always affected forested ecosystems, Allen et al. (2010) and Kurz et al. (2008) examine how climate change has affected the intensity and scale of drought and how forested ecosystems have responded to those changes.

Looking forward, three types of impacts on forested ecosystems are important for economists to factor into their models of forestry: changes in forest growth rates, impacts on stocks through disturbances, and the spatial movement in species locations. Dynamic global vegetation models (DGVMs), such as the MC2 model (Kim et al. 2017a) or the LPX model (Stocker et al. 2013), have become a widely used tool to assess future impacts of climate change on forests and thus measure these changes. DGVMs use climate inputs from downscaled general circulation models to project the spatial distribution of plant functional types (biomes), biogeochemical cycles, disturbances, and other components of ecosystem structure and function over historical periods or the future. The models can operate at a variety of scales, depending on the downscaled climate data. Often when used at the global scale, they will be projected for 0.5° grid cells. **Figure 2** presents estimates of forest gains and losses relative to the baseline for the latter part of the century under a reference case (high warming) and a policy case (POL3.7) from the MC2 model described (Kim et al. 2017).

Importantly, DGVMs focus on how climate perturbations influence ecosystems without the intervening effects of forest management. They do not account for the role and influence of adaptation and thus likely overstate the ecological effects. Economists use these results to assess adaptation. For example, Mendelsohn et al. (2016) and Favero et al. (2018) used the LPX model to assess potential large-scale effects of climate change on forests globally, while Tian et al. (2016) used the MC2 model.

Ecological changes due to climate change will affect market and nonmarket outcomes. Market impacts will in turn influence management activity on private and public lands that are managed for timber, as well as lands that are not managed for timber but that could be depending on future price trends. Because timber outputs are traded in markets, price changes can be used to measure the cost of transitioning the world's forests in response to climate change. The climate impacts on nonmarket services will also influence management activity on private and public lands, but efforts to adapt forests for these activities will be harder to measure because nonmarket activities often do not have prices that can be readily observed. Shifts in consumer surplus can still be measured for nonmarket goods and services, but these changes are more difficult to measure in part because data are not as readily available. Other nonmarket activities will involve trade-offs with species or ecosystem services that are unique to individual sites, which could be experiencing large-scale changes due to climate change. The impacts of such nonlinearities, of course, can still be measured, but this will require adopting techniques for the measurement of nonmarginal welfare effects, such as the decision whether to abandon species living in a particular location.

There are widespread concerns about large-scale effects of climate change on forests. The Intergovernmental Panel on Climate Change in 2014 (IPCC 2014), for instance, suggested that forests in the Amazon basin and the Arctic were susceptible to tipping points, although they assigned only medium confidence to this potential outcome (Settele et al. 2014a). Because the Amazon and the Arctic combined provide only about 10% of global timber production, a large shift or tipping point there would have a minimal impact on timber markets. These regions, however, contain large pools of forest ecosystem carbon and biodiversity, which could be released or lost if a tipping point is hit and if large-scale, widespread fires occur. Such a tipping point could dramatically alter the global carbon cycle with a large release of carbon. Given efforts underway at present to maintain stocks of carbon in tropical regions by reducing deforestation and forest degradation

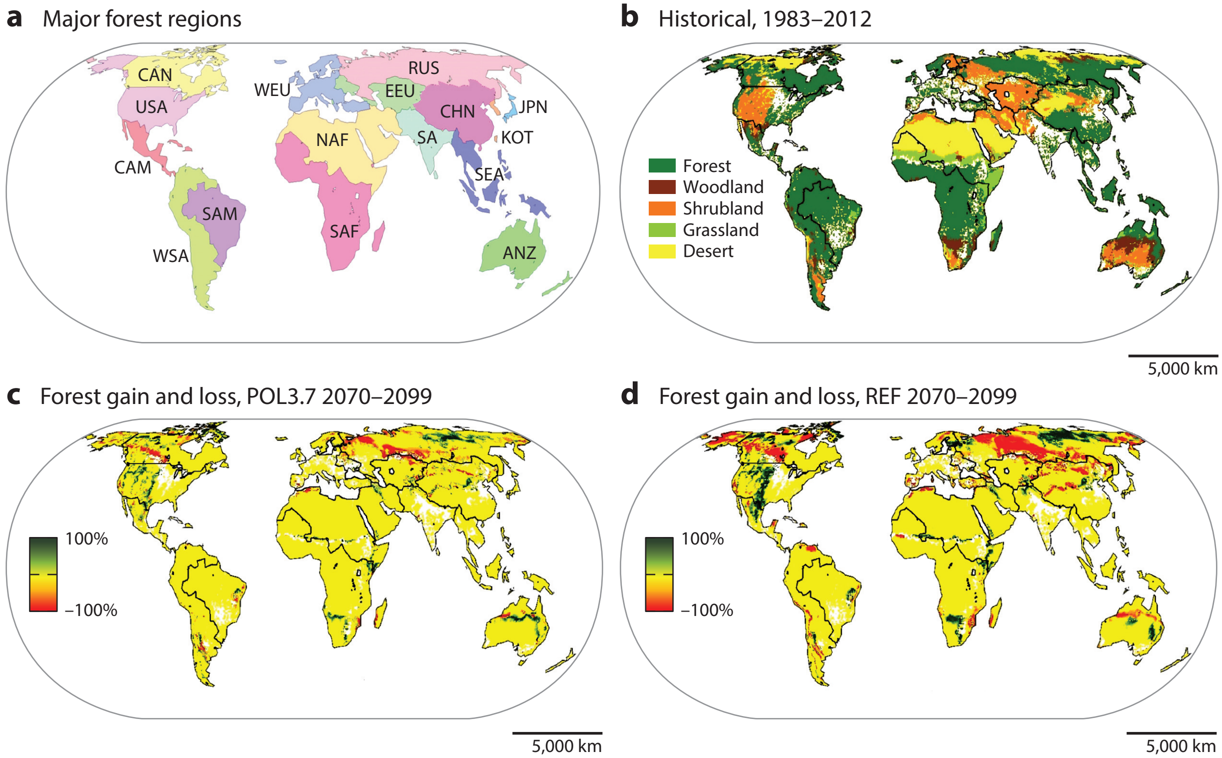

Figure 2

Global forest regions and forest change projections. (*a*) The sixteen major forest regions (Sohngen et al. 2001) are Canada (CAN), United States of America (USA), Central America (CAM), Western South America (WSA), South America (SAM), Western Europe (WEU), Eastern Europe (EEU), North Africa (NAF), Southern Africa (SAF), Russia (RUS), China (CHN), Korea and Taiwan (KOT), Japan (JPN), South Asia (SA), Southeast Asia (SEA), and Australia and New Zealand (ANZ). (*b*) Biomes projected by the MC2 dynamic global vegetation model for 1983–2012 and (*c*,*d*) forest gain and loss for 2070–2099 under the POL3.7 and REF climate change scenarios, where REF is the reference climate that includes no climate mitigation activities. Forest gain and loss maps show percentage of simulations across multiple climate realizations and replicate that simulated conversion into or out of forest biome type. Agricultural and developed areas per GLC2000 have been masked out. Figure adapted from Kim et al. (2017) under the terms of the Creative Commons Attribution (CC BY) License, **http://creativecommons.org/licenses/by/3.0**.

(e.g., REDD+), the potential for these tipping points presents a challenge for carbon markets and policy.

CLIMATE CHANGE, TIMBER MARKETS, AND TIMBER INVESTMENTS

Given the types of ecosystem changes described above, it is clear that both harvesting and regeneration decisions will be affected by the ecological effects of climate change. When assessing the effects of climate change on timber markets and timber investments, it is important to keep track of the types of ecological effects that influence harvesting decisions and those that influence regeneration and long-term forest investments, including shifts in the types of species regenerated. These changes will include shifts in both forest growth rates and disturbance.

To get a sense of the potential effect of climate change on forests, consider the following example of potential steady-state impacts of shifts in forest growth and increased dieback on southern pine, or loblolly pine (*Pinus taeda*), one of the most widely used industrial timber species in the

United States. This example illustrates how climate change affects the steady-state output of a single timber stand of southern pines. Two effects are shown: a 20% increase in timber growth and a 20% increase in timber growth combined with higher dieback amounting to an increase in annual potential dieback of 3% per year. We illustrate impacts of these two changes on the steady-state forest harvest age and net present value. For the baseline, we assume the growth function for loblolly pine, in m^3 per hectare, is

$$V(a) = \exp(7.15 - 50/a), \qquad 1.$$

where a is the age of the tree. We use the Faustmann formula to determine the optimal cutting time for the tree by maximizing the following equation with respect to a and C:

$$Max \frac{P\left[(1+C)^{0.09}\right]V(a)\,(1+r)^{-a} - C}{\left[1-(1+r)^{-a}\right]}, \qquad 2.$$

where P is the stumpage price, C is the investment at planting time, and r is the interest rate. The function $(1 + C)^{0.09}$ shifts the forest yield function in response to investments made at the time of planting. Higher levels of investment will lead to higher future yields, with decreasing returns to scale. The resulting maximization provides for an optimal time to cut the trees, as well as the optimal investment at planting time. For the analysis, we assume a price of US\$100 per m^3, and interest rates are initially 5%.

Under the climate scenario that increases tree growth rates, we assume a new, climate-adjusted yield function as follows:

$$V(a) = \exp(7.33 - 50/a). \qquad 3.$$

For the dieback scenario, we follow the model by Reed (1984), who showed how forest fire risk would reduce the optimal timber rotation relative to a similar forest with no fire risk, and that the impact of fire risk on these economic decisions can be captured through an adjustment to the interest rate used to make harvesting decisions. Based on these results, we assume that the interest rate is increased to 8%. **Table 1** presents estimates of the optimal investment, rotation age, net present value (NPV) in the model for the baseline, and the two climate change conditions. As expected, the scenario that shifts growth rates not only affects the optimal rotation age but also encourages an increase in investments and causes an increase in the NPV of timber stands (assuming prices remain constant). When climate change increases dieback potential, the optimal rotation age declines to 23 years, investments decline, and the value of the stand is reduced significantly. Forests are harvested at lower rotation ages as a response that reduces the overall risk of fire affecting a stand.

These results highlight the steady-state adjustments that would occur in a single stand with climate change. One must be careful not to use these steady-state results to determine welfare effects or to infer how a forester with an existing stand will respond, as the dynamic adjustment pathway

Table 1 Results of steady-state effects of climate change on optimal rotation age (years), investments, and NPV (in USD)

Scenario	Optimal age	Investment	NPV
Base/No CC	28	$650	$8,564
CC +20% growth	28	$750	$10,464
CC +20% growth, +3% dieback	23	$350	$3,933

Abbreviations: CC, climate change; NPV, net present value.

will lead to significantly different estimates of the welfare effects (see Sohngen & Mendelsohn 1998). For example, when faced with dieback that increases over time, foresters will not adjust all standing stocks instantly, but instead will adjust them over time toward the lower rotation period. Furthermore, as stocks experience dieback, foresters will have to factor in the effects of potential salvage from these stands and the effects of both dieback and salvage on timber prices. Similarly, if growth rates are increasing, prices will adjust due to market-level effects, likely falling when growth rates are increasing and causing the NPV effects to be minimized. When measuring welfare effects, it is critical to account for the dynamic implications of climate change on forest stocks and markets together. Forests are stock resources, and as stocks are affected by climate change, a complex dynamic adjustment will occur as behavior adapts both to climate impacts and the resulting market price changes.

When considering the dynamic adjustments a landowner will make as climate changes, it is useful to consider harvesting and replanting separately. From the standpoint of a forest decision maker, any changes in the harvesting decision can be made relatively close to the optimal harvesting time. That is, when considering whether and when to harvest a stand, the typical Faustmann model (e.g., Brazee & Mendelsohn 1990) results in a decision rule that relies on information related to current growth rates of the stand, the probability of dieback in the next year, and a near-term price trajectory. Climate change obviously alters this decision, but making the decision to harvest requires information about factors influencing the stand around the time of harvest (e.g., in the current year and over the following year). It does not in principle require large amounts of information about the long-term future. This stands in sharp contrast to the planting decision.

Landowners making decisions about what to replant after they have harvested stands must factor in long-term considerations about tree growing conditions and the likely paths of future input and output prices. The decision over what to plant and how much effort to put into planting clearly requires more information about the future than the harvesting decision (or at least information further into the future). Under climate change, however, the future becomes more uncertain because forests will be susceptible to different types of disturbances, different growing conditions, and different future prices. It is not enough to know the growth rate of an individual species that has historically grown on a given site; it is also important to understand the growth rate of alternative species that could grow on a site if, as is often expected with climate change, conditions change. The model in Sohngen & Mendelsohn (1998) optimally switches species planted on a given site when growing conditions change to favor a new species type, and in their model this is controlled by the outputs from the dynamic vegetation model. Guo & Costello (2013) develop a model that illustrates the threshold conditions when a landowner would make the decision to switch from one species to another under climate change, and they show that this decision is central to the valuation of information about future climate change and its role in facilitating adaptation.

The study by Guo & Costello (2013) illustrates the important distinction between adaptations that occur on what they call the intensive and extensive margins. The intensive margin in their approach relates to shifts in harvesting forests in response to climate change, and the extensive margin relates to shifts in the types of trees planted. Their results suggest that the value of adaptation is significantly more important for the longer-term decisions associated with the extensive margin than with intensive margin decisions to shift harvesting practices. This result is consistent with the sensitivity analysis in Sohngen & Mendelsohn (1998), which found that mistakes made in terms of replanting species after harvest could be costly.

The replanting decision in regions that are managed is clearly an important decision, but the extensive margin in forestry extends to regions and areas with extremely low levels of infrastructure and overall management. Sohngen et al. (2001) and Tian et al. (2016) consider the effects of climate change on the intensive and extensive margins using a global dynamic optimization approach, incorporating a broader range of intensively managed species and extensive forests. For instance, they include fast-growing plantation species that have already been moved from place to place to take advantage of local climatic conditions, as well as old growth forests in regions that are economically inaccessible. Compared to natural forests, the fast-growing plantations are incredibly valuable in timber markets, and they have rotation ages from 10 to 20 years. As a result, they have played an increasingly important role in timber markets in recent years, producing up to 40% of the world's timber. Economic studies suggest that they will become even more important in the future as an adaptive response to climate change. Because they have relatively short rotations, land managers can assess their competitive potential much more rapidly than for longer rotation species.

Sohngen et al. (2001) and Tian et al. (2016) also model prices endogenously such that if supply is increasing globally, prices will decline globally and vice versa. The role of prices turns out to be important because climate change alters the global balance of timber harvesting and the future price path by increasing overall timber supply and decreasing prices. The change in prices influences the efficiency of adaptation actions on both the intensive and extensive margins, such that actions that may have been efficient to undertake under prices consistent with a no climate change world are no longer efficient because prices are lower. The lower prices likely to occur with climate change have their biggest potential effect at the extensive margin and, in particular, at the extensive margin in inaccessible old growth regions. Lower prices make it less valuable to develop infrastructure to access forests in inaccessible regions (e.g., boreal areas of the United States, Canada, and Russia, as well as the tropics, although access in the tropics is usually driven by different markets such as agricultural expansion), such that less timber is produced from inaccessible old growth forests. This result means that most adaptation that occurs in old growth and inaccessible areas will occur naturally (i.e., without human intervention unless it is for a nonmarket purpose). As discussed below, this can have important implications not only for carbon markets but also for the global carbon cycle.

Other approaches have been used to model climate change in forestry. Joyce et al. (1995), for example, use a static simulation model to examine the implications of changes in net primary productivity (NPP) due to climate change. The ecosystem models they use indicate that NPP increases by up to 30% in US timber species, and as a result, timber growth rates would increase, and timber output would increase as well, by up to 22%. Perez-Garcia et al. (2002) use a similar economic model, at global scale, and find that timber supply would likely expand due to climate change by 1–3% globally. Neither of these approaches accounts for changes in investments or stock-dynamic effects that would influence both optimal investments in forests and optimal timber harvesting behavior. Hanewinkel et al. (2013) also use a static simulation approach to assess European forests and find large losses in producer surplus. This is not surprising given that their approach does not account for adaptation on the intensive or extensive margin.

More recently, Hashida & Lewis (2019) have presented an empirical approach to analyze adaptation of forests to climate change. Using the US Forest Service Forest Inventory and Analysis (FIA) plot-based data from the Pacific Northwest region of the United States, they analyze the decision to harvest and replant forests using a nested logit model. This novel approach focuses on the replanting decision that landowners have made and uses their current decisions under a range of climate conditions to project future decisions based on future climate conditions. The results suggest that foresters likely will make a significant shift away from the commercially dominant species in the region, Douglas fir, toward hardwoods over the next 50–100 years as climate changes. This study illustrates the important role that climate has already played in determining forest productivity and forest management and provides important insights for future research.

CLIMATE CHANGE, FORESTS, AND MITIGATION

Forests are a large source of both emissions of carbon due to deforestation and harvesting (e.g., DeFries et al. 2002, Houghton 2003, Houghton et al. 2012) and sequestration of carbon through forest regrowth (e.g., Kauppi et al. 2006, Pan et al. 2011). As noted in **Figure 1**, the net effect of both these processes has resulted in forests being a net sink over the last 100–120 years. But this work has not focused on explaining how the sink could have arisen (Ciais et al. 2014). Mendelsohn & Sohngen (2019) develop an economic analysis of historical carbon from forest land management and change, and their results suggest that forest management, in addition to carbon fertilization, played an important role in the emergence of the large carbon sink in forests over the last century.

Looking forward, forest carbon is expected to be a large source of future potential mitigation either through sequestration in forested ecosystems, as a substitute through the production of bioenergy, or as a source of material for electricity production with carbon capture and storage (IPCC 2018). It is not difficult to find an economic explanation for why the potential for forests to be used as a mitigation source is found to be so large: Carbon prices can substantially increase the value of forest land. Consider the following example that illustrates the effect of a carbon rental policy on the NPV of the same southern pine forest stand discussed above. To include carbon prices, the formula in Equation 5 below, derived from Sohngen & Mendelsohn (2003), is used to calculate the NPV of bare forest land. Carbon pricing changes the optimal age for harvesting and it changes the NPV of the timber stock. For this analysis, it is assumed that the carbon price is \$30/ton CO_2, which is slightly lower than the social cost of carbon calculated in Nordhaus (2017). When calculating the NPV, it is assumed that the land is bare in the initial time period, establishment costs occur first, and the benefits of carbon rents and timber harvests occur over time. Although foresters will also adjust management inputs when carbon is priced, for simplicity, initial investments (planting costs) are assumed fixed at the levels shown in **Table 1** for this carbon example. The results show a large potential benefit associated with storing carbon in forests, with the value of carbon at \$30/ton CO_2 nearly doubling the value of the stand (**Table 2**). The results for less-valuable hardwood species would result in even larger differences between the combined value of timber and carbon and that of timber alone, given that hardwoods typically have greater carbon density than southern pine, accumulate it relatively rapidly, and have lower timber value.

Many studies have emerged addressing the economics of mitigation using a range of different modeling approaches, from empirical analyses to natural resource economics-based studies. Two of the most influential pieces, Plantinga et al. (1999) and Stavins (1999), use empirical methods to estimate the opportunity cost of land associated with shifting agricultural land into forests. These studies fill an important gap in the carbon sequestration literature by developing methods to calculate marginal costs of carbon sequestration (**Figure 3**). Sedjo (1989) points out that opportunity costs of land would be an important consideration, but does not attempt to estimate these costs.

Table 2 Effect of carbon prices on optimal rotation age (years) and NPV (in USD) of timber stands under the carbon rental formula

Scenario	Timber only, no carbon value		Timber + carbon rental, carbon price = \$30/ton CO_2	
	Optimal age	NPV	Optimal age	NPV
Base/No CC	28	\$8,564	37	\$15,846
CC +20% growth	28	\$10,464	37	\$19,310
CC +20% growth, +3% dieback	23	\$3,933	33	\$8,160

Abbreviations: CC, climate change; NPV, net present value.

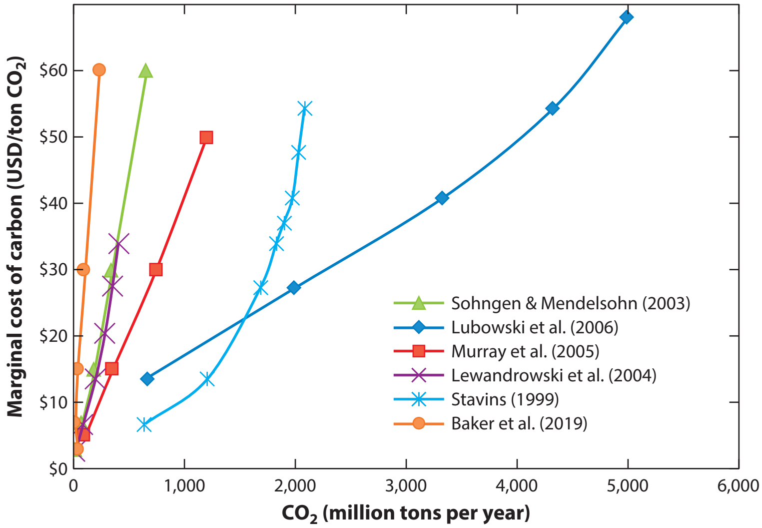

Figure 3

Marginal cost functions for carbon sequestration in the United States. Notes: Lewandrowski et al. (2004), Lubowski et al. (2006), and Stavins (1999) include only afforestation. Baker et al. (2019), Murray et al. (2005), and Sohngen & Mendelsohn (2003) account for land-use change, forest protection, enhanced reforestation, and forest management, including changes in rotation ages.

Plantinga et al. and Stavins show how the opportunity costs could be estimated and how these estimates could be linked to calculations of carbon sequestration to develop a marginal cost function for carbon sequestration. The modeling approach employed by the authors is further advanced by Lubowski et al. (2006), who develop a national-level land-use model for the conterminous United States based on disaggregated data. That model was used by the authors to determine the marginal costs of forest carbon sequestration both nationally and regionally.

The approaches in these studies established methods to determine the marginal costs of afforestation or the expansion of forests onto agricultural land. Coming out of the Kyoto Protocol in 1997, afforestation was considered as one of the most important potential methods to offset industrial carbon emissions. Within the forestry community, however, it was widely recognized that there were other opportunities to sequester carbon in forests. These other options—forest management and avoided deforestation—were gaining traction in the policy community. Economic analysis of these alternatives began in the 1990s with the work of Hoen & Solberg (1994), who were the first to show how to estimate the costs of changing forest management practices to increase carbon sequestration, especially in intensively managed forests, and Van Kooten et al. (1995), who illustrated the relationship between the age of timber harvest and the price, or marginal cost, of carbon sequestration.

Several other policy issues emerged from the debates over the treatment of forest carbon sequestration in the Kyoto Protocol, namely issues of additionality, leakage, and permanence. The most widely studied issue in the economics literature has been leakage. Large-scale planting of forests, as envisioned by Stavins (1999), could certainly increase carbon on the lands where forests were planted, but economists pointed out that not all land would be included under the policy, and markets would be heavily distorted as a result. The resulting changes in input and output prices would change the value of timber stands, and thus alter decisions on those stands and cause leakage, or the loss of forests, and forgone forest carbon sequestration elsewhere. Stavins (1999), for instance, assumes timber would be harvested on newly established forests, but does not account for the resulting price changes and thus underestimates true costs. Alig et al. (1998) develop the first estimates of leakage from tree planting programs, employing a dynamic forest sector modeling approach to assess how a large-scale tree planting program in the United States would influence net carbon storage across the entire country, accounting for full sectoral adjustment across space and time. Murray et al. (2004) use the same approach to assess leakage from different types of forest carbon sequestration projects in the United States, and Sohngen & Brown (2004) use a similar modeling approach to calculate leakage in a developing tropical country (Bolivia). These studies suggest that leakage could range from 10% to 100% depending on how the policy was implemented.

Dynamic optimization approaches to model the forest sector and forest carbon sequestration, as used by Alig et al. (1998), emerged in the late 1990s and early 2000s. Adams et al. (1999) present the first dynamic analysis of climate mitigation policy using a forest sector model. They calculate the marginal costs of carbon sequestration by constraining their model to sequester different levels of carbon, and they use the shadow prices on the carbon constraints to value the carbon. Importantly, their model allows a range of activities to enhance overall carbon storage, including increasing the area in forests, increasing forest management (as suggested by Hoen & Solberg 1994), and changing rotation ages (as suggested by Van Kooten et al. 1995). One of the benefits of such sectoral approaches is that they incorporate multiple sequestration options and thus capture the interactions across various approaches for sequestering carbon. The resulting marginal cost functions reflect the lowest potential costs under optimal policy conditions. For instance, the marginal costs of afforestation will be lower if individuals who plant forests are paid efficiently for the carbon they actually store, which will be a function of the intensity of management they choose.

A number of improvements have been realized recently in estimates of the marginal costs of carbon sequestration, such as inclusion of more activities aside from afforestation; accounting for leakage, additionality, and permanence; market studies that captured price responses; and linkages to international markets. Because these additional components, as well as the marginal user costs associated with shifting timber harvests and management over time, were included in marginal cost estimates, the estimated costs were found to be higher than earlier studies (see the trend in marginal costs over time shown in **Figure 3**). For instance, the studies in Baker et al. (2019), Murray et al. (2005), and Sohngen & Mendelsohn (2003) that use intertemporal optimization approaches suggest substantially higher costs than the results in Lubowski et al. (2006) and Stavins (1999).

One of the factors that originally encouraged the United States to sign the Kyoto Protocol was the likelihood that the treaty would include carbon trading with other countries and forest-based offsets. Under the Clinton administration, the United States fully intended to meet a large share of carbon emission reduction commitments through the purchasing of commitments in developing countries, and the administration expected that these offsets would be relatively cheap. However, it was not entirely obvious how cheap such abatement would be, as no large-scale global analysis evaluating various sequestration options had been undertaken. Policy makers knew that there was a trade-off between emissions reductions from industrial sources and emissions reductions from forests, but it was not clear what the efficient allocation of effort should be.

Sohngen & Mendelsohn (2003) integrate a dynamic forestry model with the DICE model (e.g., Nordhaus 2017) to assess the role that forests could efficiently play in overall climate mitigation policy. Their results suggest that forestry should be—on efficiency grounds—a large share of initial abatement activity, amounting to more than 65% of abatement in 2030. This outcome occurs because some forestry mitigation activities, namely avoided deforestation and

Table 3 Proportion of total mitigation at three time periods under two climate policy scenarios using an integrated assessment model.[a] Adapted from Sohngen (2009, table 4)

	2030	2050	2100
	Optimal		
Cumulative (Gt CO_2)	225	515	1,616
%Forest	65	52	30
%Energy	35	48	70
	2°C		
Cumulative (Gt CO_2)	238	575	2,410
%Forest	63	50	34
%Energy	37	50	66

[a]The optimal scenario is an optimal economic pathway and the 2°C scenario mitigates carbon such that global temperatures remain below 2°C above the preindustrial global average.

shifts in forest management, are relatively low cost in comparison to abatement in the energy sector. Over time, new forestry sector options become higher in cost compared to options in the energy sector, and an increasing share of the mitigation burden shifts to the energy sector (**Table 3**). Their analysis shows that over the entire century, forests efficiently provide 30–35% of the total mitigation effort, with around two-thirds of the abatement effort occurring in the tropics through a mix of reduced deforestation and afforestation and about one-third occurring in the temperate and boreal regions through afforestation, forest management, and protection of old-growth forests. The approach in Sohngen & Mendelsohn (2003) challenges the widely held idea that forestry is a low-cost and short-term solution to the climate change problem by showing that efforts to speed up forest sequestration could increase costs significantly, and efficient mitigation effort would occur across the entire century.

Policy attention shifted from afforestation to reduced deforestation with the 2007 UNFCCC Conference of the Parties in Bali. While the Coalition for Rainforest Nations pushed the agenda for reducing deforestation internationally, the *Stern Review* (Stern 2007) elevated the Reduced Emissions from Deforestation and Forest Degradation (REDD) agenda because it suggested that the costs of avoiding climate change by reducing deforestation were relatively low. Given the scale of emissions from deforestation, 10–15% of total emissions each year, there was great hope that efforts to reduce it could have an impact, but there was little information on the costs. Kindermann et al. (2008) provide one of the first comparisons of cost estimates using different models and different approaches. They compare the costs of avoided deforestation with static simulation and spatially explicit models with dynamic optimization approaches. The modeling results provide useful information to the policy community to evaluate how REDD activities could fit into efficiency considerations of climate mitigation. Busch & Engelmann (2017) have provided the first new approach that is not model based to estimate the marginal costs of avoided deforestation. They exploit recent advances in globally consistent spatial data sets on deforestation to conduct empirical analysis on the costs of avoiding deforestation in tropical countries. It is important to note that another recent study that has achieved significant discussion in public policy, Griscom et al. (2017), does not add new economic estimates, but uses earlier marginal cost estimates and applies those across a broader set of activities.

An important debate and discussion in recent years have been about the question of carbon neutrality in biomass energy production using forest inputs. This has become important in two areas. The first is the market for biofuels due to requirements in the Energy Independence and Security Act of 2007, which mandated production of cellulosic biofuels. The second is in the context of the emerging markets for electricity produced with forest biomass. Some US states and countries in the European Union have incentivized the use of wood-based biomass energy because they believed it to be carbon neutral. However, several influential studies have called into question whether wood-based biomass energy actually is carbon neutral (e.g., Searchinger et al. 2009, Walker et al. 2010). A large amount of economic research has now investigated whether forest-based biomass is carbon neutral and is reviewed by Khanna et al. (2017). The Khanna et al. study illustrates how the determination of carbon neutrality depends on the scale of the analysis and the inputs and behavioral assumptions of the models that are used in the analysis. Dynamic approaches based on forests managed as a renewable natural resource tend to suggest that forest-based biomass is carbon neutral (see Daigneault et al. 2012, Latta et al. 2013), whereas noneconomic approaches and static economic approaches result in a wider range of potential outcomes. There are a number of reasons for this, but one of the most important is that dynamic approaches that assume there will be increasing demand for biomass energy in the future increase the demand for wood products and provide incentives for increased forest management (e.g., Favero & Mendelsohn 2014). This increase in management ultimately leads to an expanding stock of forests, and hence, increased carbon on the landscape. Static simulation approaches, in contrast, do not have mechanisms to translate increased demand into increased forest management.

The debate over carbon neutrality is a subset of the broader debate over the role of forests and forest management in the future global carbon cycle. The recent IPCC report on 1.5°C temperature change (IPCC 2018) relies heavily on forests as a source of avoided emissions (reduced deforestation), carbon sequestration through afforestation and forest management, and biomass energy production with carbon capture and storage to achieve negative emissions. Given trends in emissions from industrial sources, which are not declining, so-called carbon dioxide removal (CDR) options have become a critical element of climate policy that attempts to maintain global temperature levels below 1.5 to 2°C above preindustrial levels (e.g., Favero & Mendelsohn 2014). While many different approaches have been taken, this has meant that large-scale integrated assessment models, which embed many different climate-related processes alongside economic decision-making models, have had to incorporate forests and forest economics into their modeling systems (e.g., Roe et al. 2019). The integrated assessment models have made a wide variety of assumptions about the role of forest management, which have influenced the approaches they have taken to model forests. This area of research remains a critical area for continued development given the importance of integrated assessment models for global climate policy analysis.

One of the interesting economic questions that has arisen when considering the role of forests in climate mitigation is whether forest-based carbon sequestration, i.e., the storage of carbon in standing forest stocks, is a substitute or complement to forest-based biomass energy. Clearly, the standing stock of forests is valuable not only as a potential future source of timber or biomass energy but also as a stock of carbon sequestered from the atmosphere while it remains standing. Policy makers have asked whether programs to incentivize forest carbon sequestration are efficient if that carbon ultimately is used to produce biomass electricity. The efficiency of various policy approaches that encourage one or the other hinges in part on whether the two options are complements or substitutes. Favero et al. (2017) and Baker et al. (2019) both show that there is a complex intertemporal interaction between the two options, with both options initially being complements but acting more like substitutes in the long run once low-cost mitigation options have been exploited. That is, in the presence of demand for biomass energy, the marginal costs for carbon sequestration in forests are lower than if the biomass energy demand is not available. There are two reasons for this. First, forests provide carbon benefits while they are growing, and they provide biomass market benefits only when they are harvested. Planting forests for biomass energy essentially provides carbon storage benefits for "free." Second, the higher wood product prices that accompany biomass energy policies lower the marginal costs of carbon sequestration by increasing the value of timber in forests.

Of course, policy makers are also interested in distributional questions, such as how one credits carbon sequestration in forests or carbon use as biomass energy. Searchinger et al. (2009) have argued that forest carbon should be taxed if it is used as biomass energy, but this is a specific distributional assumption that does not account for whether and how the forest is included in sequestration policies. Forest carbon sequestration policies can credit the storage of carbon in forests in different ways. Van Kooten et al. (1995), for instance, illustrate that annual additions to forest carbon could be credited using the carbon price, or social cost of carbon, while emissions to the atmosphere when forests are harvested are debited. This approach correctly accounts for the net exchange of carbon between forests and the atmosphere over time. An alternative distributional assumption, used in Sohngen & Mendelsohn (2003), rents forest carbon stocks while they are standing and pays the carbon price for any permanent storage that occurs when forests are harvested. As shown in Favero et al. (2020), these approaches are efficiently equivalent, although they lead to a different set of payments to landowners.

These two approaches are perhaps best compared using their mathematical representations in the Faustmann formula. The present value of a stand managed with a carbon subsidy and tax suggested in Van Kooten et al. (1995) is given as

$$PV = Max \frac{P_S V(T)\, e^{-rT} - C + \int_0^T P^C \alpha \dot{V}(a)\, e^{-ra} da - P^C\,(1-\beta)\, V(T)\, e^{-rT}}{(1-e^{-rT})}. \quad 4.$$

The present value of a stand managed with a carbon rent and payment for permanent storage is

$$PV = Max \frac{P_S V(T)\, e^{-rT} - C + \int_0^T R^C \alpha V(a)\, e^{-ra} da + P^C \beta V(T)\, e^{-rT}}{(1-e^{-rT})}. \quad 5.$$

In the equations above, P_S is the stumpage price, $V(a)$ is the forest growth function, $\dot{V}(a)$ is the annual growth of forests, r is the interest rate, α converts forest volume into carbon, and β converts m^3 of wood harvested to the tons of carbon stored permanently in wood products or carbon capture and storage (e.g., β is tons C stored permanently per m^3 of wood volume harvested). The carbon price, P^C, is the social cost of carbon, and the carbon rent is the value of holding one ton of carbon in forest stocks for a year: $R^C = P_t^C - P_{t+1}^C/(1+r)$. If a large portion of wood is used for biomass energy and subsequently stored underground in carbon capture and storage, the term β becomes large.

If there is a sequestration program in place, one need not tax emissions from forests when carbon is released as long as the carbon has only been rented. That is, policy makers can efficiently choose not to tax emissions at harvest time as long as they have not overpaid for the carbon while it is stored in forests. If there is a sequestration and biomass energy program in place that uses forest biomass at harvest time, the same results hold, i.e., one need not tax emissions as long as the storage of carbon has been rented, even if a large amount of wood is used for biomass energy. If a large amount of wood is used for biomass energy and is stored underground in carbon capture and storage, the term in Equations 4 and 5 that accounts for permanent sequestration of carbon from the atmosphere becomes large (see Favero et al. 2020 for a full discussion).

Land-based climate mitigation policies have remained a critical component of most global pathways to reduce carbon concentrations in the atmosphere (IPCC 2018), yet they have proposed to shift an extraordinary amount of land from other uses back to forests (e.g., Griscom et al.

2017, Roe et al. 2019). Such a large change in the way land will be used in the future will undoubtedly have large influences on the distribution of income and spending globally. Relatively few studies have yet addressed this issue, as most work has focused on the efficiency of overall climate mitigation effort. The studies that have begun to address this question point out that the distributional questions of large-scale mitigation efforts in forestry (and agriculture) are large (Golub et al. 2013, Meyfroidt et al. 2013).

FUTURE DIRECTIONS FOR RESEARCH INTO CLIMATE IMPACTS ON FORESTS

Although significant progress has been made in understanding the implications of climate change in forestry markets, there are numerous avenues for improved and new analysis. One important way is developing a better understanding about how climate change and climate mitigation interact. Most studies that have examined the policy efforts to influence carbon stocks have not considered the effect of climate change on those carbon stocks. If climate change affects forest growth or disturbance rates or patterns, however, the efficiency of climate mitigation efforts would change.

Some studies have partially addressed this issue. For instance, Tian et al. (2016) show that climate change generally enhances the size of the global forest carbon sink by up to 26 Pg C, and they show that mitigation efforts to hold warming below 4.5 watts per m^2 would reduce the sink capacity of forests to about half of that. The mitigation efforts, however, are assumed to occur entirely in the industrial sector. Similarly, Tian et al. (2018) find that the US forest carbon sink, however, may be slightly at risk due to climate change, with the future sink capacity diminished modestly in the next 50–100 years. Neither of these studies considered mitigation in the forestry sector as they examined the effects of climate change and thus cannot be used to comment on whether climate change increases or reduces marginal costs of carbon sequestration in forests.

Another area ripe for analysis is assessment of uncertainty in the context of climate change. There is a robust literature on the role of uncertainty in forestry management decision making. For example, the study by Reed (1984), which presents a model for incorporating forest fires into the Faustmann model, illustrates how uncertainty about forest fires can be treated in harvesting decisions. That study showed that the uncertainty of forest fires can essentially be treated in a deterministic way as a factor that influences the net discount rate that forest landowners observe. Sohngen et al. (2001) and Sohngen & Mendelsohn (1998) adopt Reed's approach given that the changes in forest fires and dieback found in the DGVMs that they use were relatively modest. They did not face climate scenarios with large-scale, nonlinear dieback events that could lead to the loss of entire ecosystems in short periods of time. If future studies find that such events are more likely, then economists likely will need to adopt new approaches to model uncertainty in forestry models.

Other economic approaches may provide opportunities for economic modelers to assess the efficiency of adaptation to climate change, especially when it involves uncertainty about the future effects of climate change on forests. For instance, a number of recent studies have exploited numerical simulation approaches to study the effect of disturbance on a range of forest management decisions, including planting, thinning, and final harvesting (Amacher et al. 2005, Daigneault et al. 2010). These approaches should be extended to more species types and more regions, and they need to be integrated with the results from DGVMs to provide better guidance to landowners and land managers about the scale of adjustments that may be necessary in management as forest disturbances shift. Although a large number of studies have emerged to consider the economic efficiency of managing forests at risk from forest fires, fewer studies have examined the role of management in response to other risks, such as hurricanes (e.g., Haight et al. 1995). Given the potential for hurricane risk and intensity to change with climate change (IPCC 2014), it may be as important for modelers to address this issue, in addition to fires, in the future.

Most of the analyses to date have considered climate impacts in accessible regions, that is, regions with access to roads and infrastructure, and they have assumed that some management is already occurring in forests. Some of the biggest concerns about large-scale increases in disturbance in forests, however, exist for forests in boreal and tropical places (Settele et al. 2014, Taylor et al. 2017, Turetsky et al. 2011). To a large degree, forests in both of these regions are characterized by little infrastructure and little existing management. Both of these regions also contain large carbon stocks, either above or below ground, which could be at risk of being emitted into the atmosphere. Very little research has been conducted on the efficiency of options to manage either carbon or timber stocks in regions that are far from markets, with high costs of access and management. Given that carbon emissions from these stocks are likely more strongly affected by disturbances than by human management, determining whether different management responses are efficient is critical given the global carbon implications. Additional research needs to be conducted into the efficiency of managing these stocks considering the full range of benefits maintaining or managing these stocks may provide.

When studying the relationship between climate and forests in inaccessible boreal and tropical regions, economists need to develop analyses at different scales. At the aggregate level, models need to address the overarching questions about whether and when large-scale new investments in infrastructure are needed to manage the risks of fire to carbon stocks. This requires developing integrated ecological and economic assessment tools that model fire risks, fire management, and adaptation activities simultaneously across space and time. For example, DGVMs (e.g., Kim et al. 2017, Stocker et al. 2013), operated independently of economic models such as that used by Tian et al. (2016), should be integrated. Integrated analysis can provide insights into the scale of investments that may be necessary to manage resources in remote places, and they can provide some spatial insights into which regions may be most cost-effective for investments.

Locally, however, economists must also consider the incentives that could be used to motivate individuals who have control over the land to shift their management activities in response to externalities (i.e., the value of carbon). This may be most important in the tropics, where land ownership appears to be less clearly defined in some cases, or at least less protected. Fortunately, a robust literature has emerged to evaluate policies or actions that have been undertaken to reduce deforestation in extensive zones of the tropics where there is an active frontier of deforestation (e.g., Alix-Garcia et al. 2008, Andam et al. 2008, Blackman 2015, Fortmann et al. 2017, Sills et al. 2015). Unfortunately, most of these studies have assumed that the primary threat to forests is deforestation due to land-use change. Few of these studies have considered threats posed by climate change, such as increases in forest fires or other disturbances. Multiple options for managing forests in tropical regions have been suggested, including development of protected areas, payments for ecosystem services programs, or common property resource systems, and the efficiency of all of these has been assessed by economists in various places. However, very little research has considered how the efficiency of these approaches will change if disturbance patterns are shifting, if large-scale dieback events occur over large areas, or even if NPP increases. Models have begun to emerge to examine adaptation of species that face discontinuities in their habitat, such as may occur under large-scale dieback events (e.g., Kling et al. 2016), but these models have been applied to locations with critical infrastructure available, property rights, and other factors that would contribute to efficient outcomes. More work like that of Kling et al. (2016) is needed in boreal and tropical locations where there is significantly less infrastructure in place.

CONCLUSION

This review has assessed the literature on forests and climate change. It started with an assessment of economic literature that has examined how climate change affects forests and how economists have analyzed these effects. These analyses have largely focused on timber outputs; however, other ecosystem outputs, such as carbon and biodiversity, are likely more valuable now as forest resources. The review then focuses on the economics of forests in climate mitigation, considering both carbon sequestration and biomass energy. Finally, the review provides some suggestions for future analysis.

Current economic analysis of climate change impacts has focused largely on the effects of climate change on timber and forest management. A number of studies have developed integrated assessment approaches that link DGVMs to economic models. Because many of the DGVMs suggest that NPP in forested ecosystems will increase in the future, despite the likelihood of increased fire activity, economic models have largely found that timber output will increase and timber prices will decline. Studies that have modeled the movement of species across space have found that if foresters can efficiently adapt and shift species types as climate change occurs, the impacts of climate change will be minimal or could be positive. As Guo & Costello (2013) point out, however, there is significant value at stake in making these decisions correctly.

One important factor affecting forest management and investments is forest disturbance. There is a rich and vibrant literature on forest fires and the types of adaptation or change in management expected when forests are susceptible to forest fires and to changes in forest fire regimes under climate change. This literature, however, focuses largely on modest changes in forest fire regimes. Little research has been conducted into potentially large-scale shifts in forest fire regimes and the implications for forest management and investments. Furthermore, most studies have examined the role of forest fires in the context of timber market outputs. While timber outputs are an important ecosystem service from forests, a more valuable ecosystem service globally is undoubtedly the world's forest carbon stock. The world's forest stock critically interacts with the atmosphere and can affect overall damages from climate change (i.e., the social cost of carbon), so an important area for research advancement is for economists to better understand the role of forest management in the context of potential nonlinear disturbance events in forestry.

The second section of the review considers the role of carbon sequestration in climate mitigation. A number of excellent economic studies have developed approaches to model and estimate the costs of carbon sequestration through afforestation, forest management, and reduced deforestation. These studies have played a critical role in climate policy analysis, and in particular, in the development of policies to regulate the global carbon budget. The role of forests in climate change mitigation appears likely to expand in the future, given the importance of forests in the scenarios the IPCC has proposed to maintain temperatures below 1.5°C warming. As discussed above, there is a considerable role for economists to continue working with integrated assessment modelers to make sure that economic approaches are included in the integrated assessment models.

When considering the value of the world's carbon currently sequestered in forests, it is clear that a wider range of analyses must be undertaken. A large share of this carbon is contained in boreal and tropical regions that are outside the scope of intensive forest management. Many studies have now been conducted in tropical regions to assess whether various policies have worked to slow deforestation, but few of these studies have considered climate perturbations. That is, the disturbances are entirely a function of human encroachment, but a defining feature of the future tropical forest may in fact be that disturbances are directly caused by climate change. It is not obvious that the same policy approaches will be relevant in that context. While boreal forests have perhaps better-defined property rights, it is equally important to develop policy approaches focused on preserving carbon and timber in these regions as well.

Over the last century, forests have become an important carbon sink, with management and carbon fertilization offsetting nearly all of the carbon emitted due to deforestation and conversion of land into agricultural uses (e.g., Mendelsohn & Sohngen 2019). Society has already scoped out an equally important and likely more ambitious role for forests in the future (IPCC 2018). Given this, economists are needed to help better understand the efficiency of efforts society may undertake either to expand forests, to protect them from losses, to manage them more intensively, or to convert them into wood products, including biomass energy. Much has been learned so far, but a number of critical information gaps persist, representing many important opportunities for economists to advance knowledge in the future.

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Volume 12, 2020

Contents

Development Economics

Methodological Approaches

Errata

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