EPA Public Access

Author manuscript

Land Econ. Author manuscript; available in PMC 2020 April 10.

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Published in final edited form as:

Land Econ. 2018 February 1; 94: 97–113. doi:10.3368/le.94.1.97.

Will U.S. Forests Continue to Be a Carbon Sink?

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Abstract

This paper develops structural dynamic methods to project future carbon fluxes in forests. These methods account for land management changes on both the intensive and extensive margins, both of which are critical components of future carbon fluxes. When implemented, the model suggests that U.S. forests remain a carbon sink through most of the coming century, sequestering 128 Tg C y^{-1} . Constraining forestland to its current boundaries and constraining management to current levels reduce average sequestration by 25 to 28 Tg C y^{-1} . An increase in demand leads to increased management and greater sequestration in forests. The results are robust to climate change. (JEL Q23, Q54)

1. Introduction and Background

Over the past century, forests in the Northern Hemisphere have become a large carbon sink, sequestering up to 2.4 Pg (1 Pg = 10^{15} g) of CO₂ y^{-1} in recent years (Intergovernmental Panel on Climate Change 2013; Pan et al. 2011). Most of this sequestration has occurred as forests have reverted from agriculture to forestlands and forests have aged (Mather 1992; Kauppi et al., 2006; Birdsey, Pregitzer, and Lucier 2006). Looking forward, however, there is concern that the accumulation of carbon in this land-based sink may slow, and recent literature indicates that this slowdown is already occurring (Nabuurs et al. 2013; Coulston, Wear, and Vose 2015). One recent study suggests that carbon sequestration rates in the United States could slow up to 45% over the next 25 years, even reverting from a net sink to a source of emissions in some regions (Wear and Coulston 2015). Other research shows that the future forest carbon flux in the United States is highly uncertain and could vary greatly with assumptions of future economic and physical conditions (Nepal et al. 2012).

With current action in the international community to address global climate change, there is increasing value in projections of greenhouse gas emissions from forestry and land use. The

United Nations Framework Convention on Climate Change Conference of the Parties 21 resulted in a global climate agreement among 195 countries with a goal of limiting the level of temperature increase to 2 °C, and this agreement was ratified in November 2016. This ambitious target is supported by country- or region-level nationally determined contributions (NDCs) from 176 parties (including a single NDC from the European Union) that establish greenhouse gas emissions reduction targets and, in some cases, anticipated mitigation actions. In preparing NDCs, many parties used a combination of emissions inventories and future projections to establish reference emissions levels and future mitigation targets. The United States is one of several countries that incorporated emissions and sequestration projections from land use, land use change, and forestry (LULUCF) activities into NDC targets.

In the *Second Biennial Report* (U.S. Department of State 2016), the United States reports “high” and “low” sequestration estimates to acknowledge the high uncertainty related to LULUCF emissions projection. This uncertainty is driven by several factors, including assumptions regarding macroeconomic growth and future demand for forest products, climate change and its potential impact on forest ecosystems, and different methods used to project emissions from the U.S. land use sectors. The gap between these two scenarios (117 Tg C y⁻¹) represents more than 6% of total observed U.S. emissions in 2005 and a significant portion of the projected emissions reduction in the U.S. NDC. This uncertainty range illustrates the relative importance of LULUCF activities for projecting baseline anthropogenic emissions and evaluating potential emissions reduction opportunities in the land use sectors.

Despite the important policy implications of understanding future carbon fluxes, few economic analyses have focused on how market factors may affect carbon flux in the future. Two general modeling approaches are relevant for addressing the question: static reduced form models based in econometrics, and structural dynamic approaches. Stavins (1999), Plantinga, Mauldin, and Miller (1999), and Lubowski, Plantinga, and Stavins (2006) used reduced form econometric approaches that model the movement of land into and out of forests. These reduced form approaches do not directly address forest management, that is, the management of carbon stocks in existing forests. As with these earlier studies, Wear and Coulston (2015) also use a reduced form econometric approach, but they model forest management and land use. Their results show that the U.S. forest sink declines over time as forests age in the United States and because less land will be devoted to forests in the future.

However, Wear and Coulston (2015) do not allow for price endogenous forest management or investment. In this manuscript, we argue that this may be an important omission, given that managers of forest resources do respond to market conditions. In the United States for example, there are now more than 25 million ha of planted forests, and globally, the area of planted forests is around 280 million ha (FAO 2015; Keenan et al. 2015). Management inputs in the United States exceed \$140 per ha, on average, on managed timberlands in the United States (Sedjo and Sohngen 2015). Given the long time-frame of forest investments, little of this would be happening if landowners did not expect a reasonable return on their investment. The models by Adams et al. (1999), Sohngen and Mendelsohn (2003), Kim,

McCarl, and Murray (2008), and Latta et al. (2013) use structural dynamic approaches that allow price endogenous land use and management choices.

We argue that developing a projection of future carbon sequestration requires the application of a structural dynamic approach to account both for land use and the management of the stock. First, future carbon sequestration depends on management, including regeneration efforts or within-rotation management activities, such as thinning and fertilizing. In the United States, forests have been planted at commercial scale for over a century, but large increases in planting occurred in the 1950s and afterward, and fertilizing occurs on a significant portion of industrially managed land (Rogers and Munn 2003). European forests, in contrast, have been managed for much longer, with planting and regeneration programs stretching back several centuries. In China, statistics suggest that planting began in earnest in the 1960s and 1970s and has continued with significant planting programs ever since (Richardson 1990; FAO 2015). Most recently, many subtropical countries have increased planting of fast-growing plantation trees (Sedjo 1984; Sedjo and Lyon 1990). The most recent Global Forest Resources Assessment (FAO 2015) notes the importance of these management efforts globally, suggesting they are playing a role in global carbon storage.

Second, and perhaps most importantly, land use plays an important role in future carbon sequestration projections. Extensive margin expansion that increases forest area, including afforestation of lands previously in agricultural uses, can result in increased total carbon storage. Throughout much of the developed world, forest area has increased over the past century as agricultural uses have declined (Houghton 2003; Oswalt et al. 2014; FAO 2015; Houghton et al. 2012). Although some of this conversion from agriculture back to forestry was simply related to a reduction in land values, improvements in forest management have increased the value of forestland and encouraged afforestation in more productive regions like the U.S. South. The trend in land use has been in the other direction in tropical regions, as large areas of land have shifted from forests to agricultural uses (Houghton 2003).

Third, another important aspect to consider is intensive margin expansion, such as the conversion of natural forests to managed forests and vice versa. As timber management has intensified in regions like the U.S. South, forests in less productive regions like the Northeast and Midwest have become less intensively managed and effectively set aside from intensive management. As these forests have aged, they have accumulated a significant carbon stock, and they have become a large part of the historical accumulation of carbon identified by Pan et al. (2011). While it is tempting to model this process as exogenous, as do Wear and Coulston (2015), carbon stocks are an outcome of market conditions and endogenous land management investments. Management of forest resources in the future will have important implications for future carbon sequestration. If passively managed, aging stands will accumulate less carbon over time (lower sequestration per year than younger stands), and forest sequestration rates will decline unless offset by carbon accumulation in younger and more intensively managed stands elsewhere. Timber harvesting also depends on prices, so the decision to harvest at all in passively managed forests must be determined endogenously with prices.

Finally, projecting forest carbon accumulation in regions with active timber markets, such as the United States, will depend not only on domestic markets, ecological conditions, and policy, but also on ecological conditions and decisions made in other regions of the world. Climate change, for instance, will affect land productivity across the globe, and it is imperative to model its impacts with global models (Sohngen, Mendelsohn, and Sedjo 2001; Perez-Garcia et al. 2002). Economic conditions elsewhere can also have important impacts domestically. For instance, if land rents are lower in subtropical and tropical regions, then timber investments in the United States may decline, leading to reduced harvests, less extensive margin expansion, and lower management intensity. Ignoring these global market interactions and land management alternatives could over- or understate the resulting carbon sequestration outcomes in the United States.

The only way to account for these many structural dynamic factors is by directly modeling the dynamics of forest carbon sequestration within the context of a global market model. In this paper, we show how carbon sequestration in forests will respond to current and anticipated market conditions using a dynamic optimization approach. In our model, land use and forest management decisions are made endogenously with prices. We start by presenting an analytical model of a forest resource management system for a single region to illustrate the link between management decisions and aggregate carbon outcomes. We then implement the approach numerically using a global (multiregion) forest sector model to account for the feedback effects between investments in forest resources made in all regions of world, timber prices, and projected carbon stocks. The presentation of results focuses on future carbon flux projections for the United States. To illustrate the contributions of land use and forest management to carbon sequestration, we conduct sensitivity analysis with the model to assess how sensitive future carbon sequestration in the United States would be to different assumptions about management or land use. Furthermore, because future climate conditions are uncertain, we integrate results from a dynamic global vegetation model into our global forest sector model, and assess the sensitivity of our results to future climate conditions.

2. Analytical Model

This section presents a dynamic model of an isolated forest resource system to illustrate the implications of dynamic forest management with endogenous prices on forest carbon flux. Additional derivations and first-order conditions from this analytical model are provided in Appendix A. The purpose of this section is to establish and illustrate the economic response foresters will make to market conditions (e.g., demand perturbations and price changes), and how subsequent management responses influence forest carbon. This analytical model establishes a theoretical linkage between forest management choices at the intensive and extensive margin and the resulting forest carbon flux. The links are then tested using a detailed dynamic economic optimization model of the global forest sector.

In both a single region (analytical) model and the more detailed global (numerical) model, the annual amount of carbon sequestered in forests in period t , c_t^s , is a function of the annual change in the stock of forests (s_t):

$$c_t^s = J(s_{t+1} - s_t). \quad [1]$$

The change in the stock of forests, in turn, is a function of the growth of existing trees (g_t) minus removals (q_t) from harvesting:

$$s_{t+1} - s_t = -q_t + g_t(X_t, Z_t). \quad [2]$$

The amount of growth is a function of the forest area by age class, $\mathbf{X}_t$, and the management intensity of the stock by age class, $\mathbf{Z}_t$. Note that $\mathbf{X}_t$ and $\mathbf{Z}_t$ are vectors of forest hectares of $x_{a,t}$, or management intensity of $z_{a,t}$ in various age classes (a). Management intensity is determined at the time the stand is planted (i.e., $t - a$ years ago), and each age class has a specific management intensity that follows the age class through time. An increase in management will increase the future volume of harvest. Given that this framework is a forward-looking model, locking in a management profile at the time of planting does not imply zero management after the initial period; instead, it means only that all management is planned at the time the stand is established. Establishment can include intensive planting with fertilizing and planned thinning operations over the life of the stand (as occurs on many industrial timberlands), or it can include natural regeneration. Intensive management, of course, will cost more than natural regeneration. Management intensity is determined endogenously and depends on costs, net returns to management (through greater harvest levels or shorter rotation time lines), and future price projections. Any change in stock will be dictated by contemporaneous or anticipated economic forces that influence each of these variables (management and harvest levels). An increase in harvesting will reduce the stock of carbon in forests commensurate with the level of biomass being removed from the system, while a net increase in growth will increase the forest carbon stock.

Because forests typically have a logistic growth function, with a period of very rapid growth followed by a period of relatively slow growth (or even no net growth if the forests are classified as old growth), then the age class of forests will also affect carbon accrual. Relatively younger forests accumulate carbon more rapidly than older forests. Thus, a price-induced shift in harvest rates that alters the age-class distribution of the system also affects the annual flux.

Harvests are determined by the demand for wood products. The inverse demand function for wood is given as

$$p_t = D(q_t, y_t), \quad [3]$$

where p_t is the delivered log price of timber and y_t is a demand shifter, representing income and population. In the case of forestry, the quantity of timber harvested is a function of the area of forests harvested and the volume of trees:

$$q_t = \sum_a V(a, z_{a,t}) h_{a,t}. \quad [4]$$

The quantity of timber harvested, q_t , is the sum of the volume of timber harvested in each age class, $V(a, z_{a,t})$, times the number of hectares harvested in each age class, $h_{a,t}$. The volume of timber is a function of age class a and the management intensity associated with that age class of trees, $z_{a,t}$.

Markets operate to maximize the present value of consumer plus producer surplus at the optimal harvest level, q_t^* , given as

$$\text{Max} \sum_0^T \rho^t \{w_t\}, \quad [5]$$

where

$$w_t = \int_0^{q_t^*} [D(q_t, y_t) - c^h(q_t)] dq_t - p^m m_t f_t - R\left(\sum_a x_{a,t}\right), \quad [6]$$

subject to various constraints outlined in equations [7] through [11]:

$$x_{a,t+1} = x_{a-1,t} - h_{a-1,t}, \text{ for } a > 1 \text{ and } t > 0 \quad [7]$$

$$X_{1,t+1} = f_t, \text{ for } t > 0, \quad [8]$$

$$z_{a,t+1} = z_{a-1,t}, \text{ for } a > 1 \text{ and } t > 0, \quad [9]$$

$$z_{1,t+1} = m_t, \text{ for } t > 0, \quad [10]$$

$$h_{a,t} \leq x_{a,t}, \text{ and } h_{a,t}, x_{a,t}, f_t > 0, m_t, z_{a,t} > 0. \quad [11]$$

In addition, initial quantities for $x_{a,1}$ and $z_{a,1}$ must be given. In the objective function, w_t represents the annual value of social surplus at period t . p^m is the cost of replanting per unit of management intensity and per hectare. $R(\cdot)$ denotes the function of land rental costs and rises with total land area devoted to forests. In the optimization above, market participants choose the number of hectares to harvest in each age class, $h_{a,t}$; the area to replant, f_t ; and the intensity of replanting, m_t . The area that is replanted could be regenerated with no management, in which case $f_t > 0$, but $m_t > 0$. This means the land is regenerated naturally with low human inputs, which is consistent with a large portion of current U.S. harvests.

Several insights emerge from the optimal conditions derived from this model (for details, please see Appendix A). For harvesting, the relevant optimal condition is

$$P_t V(a, z_{a,t}) = \rho \left[P_{t+1} V(a+1, z_{a+1,t+1}) - R' \left(\sum_a x_{a,t+1} \right) \right] \quad [12]$$

if $x_{a+1,t+1} > 0$, $h_{a,t} > 0$, and $h_{a+1,t+1} > 0$.

Equation [12] implies that forests will be harvested at the stand age when the current value of harvesting the stand is equal to the present value of waiting for one additional period to harvest the stand minus the rental cost for holding one additional hectare for one additional period. Over that one period, forests age, the volume increases, and prices may increase or decrease. One must pay land rental costs for some forests, although many forests throughout the world occur in regions where there is little competition for land, leaving rental costs at or near zero. If forests are growing particularly quickly or prices are rising rapidly, the incentives shift toward delaying harvests. However, if prices are stable or falling, and if forests are older and growing slowly, then they are more likely to be harvested. All else equal, higher rental costs will promote earlier harvesting of forests.

The optimal condition for management intensity can also be derived:

$$p^m f_{t-1} = \lim_{n \rightarrow \infty} \sum_{b=1}^n \rho^b P_{t+b} V'(b+1, z_{b+1,t+b}) h_{b+1,t+b}. \quad [13]$$

This optimal condition illustrates that the investment in regeneration management at the time of planting is increased to the point where the marginal costs of a unit of m_t (the left-hand side of equation [13]) equal the present value of the impact of that extra unit of management intensity on future harvests. The variable m_t is the choice variable, which is chosen at the time the forest is planted. This choice sticks with the forest until it is harvested. $V'(b+1, z_{b+1,t+b})$ is the derivative of the yield function with respect to m_b and the stock variable $z_{a,b}$ keeps track of the input m_t and assigns it to the appropriate hectares when harvested.

The other important choice variable is the decision on area regenerated at time t , namely, f_t . The optimal condition for regeneration can

be derived as

$$p^m m_{t-1} = \rho^n \lambda_{n+1,t+n} - \sum_{b=1}^n \rho^{b-1} R' \left(\sum_a x_{a,t+b} \right) \forall n > 0 \quad (14)$$

if $x_{n+1,t+n} > 0$.

From equation [A3] in Appendix A, $\lambda_{a,t}$ represents the shadow value of an additional hectare of trees of age class a at the beginning of year t . The optimal condition for regeneration illustrates that the regeneration area at a certain period, f_b , is increased to the

point where the marginal costs of adding a unit of f_t equal the present value of the benefits of holding an additional unit of forest stocks in the future period, minus the sum of the present value of the marginal increase in land rental costs in each future period.

In a dynamic model, carbon sequestration is structurally dependent on important economic decisions that influence harvests, land use, and investments in timber resources. These decisions in turn are made endogenously with current and future prices as forest management and land use are adjusted to maximize the net economic value of the resource. For example, if future prices are expected to be higher due to anticipated increased demand for timber resources, then one would expect current investments in timber resources to increase as well. These additional investments could cause carbon sequestration to expand. Alternatively, climate change could cause forest yield growth to expand or contract (depending on forest conditions, location, etc.), suggesting direct changes in carbon fluxes associated with forest growth and indirect effects through price changes. It is important to carefully model this system with dynamic analysis to develop projections of future carbon sequestration. Appendix A provides additional details of our single-region analytical model, including derivation of relevant first-order conditions.

3. Numerical Model Description and Scenario Design

The analytical model presented in the previous section illustrates how carbon stocks and fluxes depend on investments in forests through management and land use with a single region and species. For example, equations [1] and [2] show that forest carbon projections are a function of forest stocks, which are determined endogenously with prices, forest resource management, and forestland area. Reduced form approaches that rely on exogenous prices or exogenous management assumptions will ignore the interaction between prices, management, and land use, leading to less precise carbon flux estimates.

This section presents a numerical simulation model to illustrate the importance of investments in forest management and land on carbon flux. Specifically, we utilize a dynamic economic optimization model of the global forest sector. The same first-order conditions shown above will hold for this global model with multiple regions and separate initial forest stocks and growth functions, as annual outputs from each region are aggregated into a global demand function. This approach allows the simple analytical framework shown in the previous section to be expanded to a multiregion model representing a heterogeneous set of forest types and management techniques (see Sohngen, Mendelsohn, and Sedjo 1999). For the numerical example, we use the global timber model (Sohngen Mendelsohn, and Sedjo 1999; Daigneault, Sohngen, and Sedjo 2008), which follows the mathematical enumeration in the previous section, but is extended to represent forests from all regions of the world. The baseline GAMS code for the model, including the input parameter data sets, is provided in Appendix D.

There are several additional differences between the global model used for the numerical analysis and the analytical approach above. First, the numerical simulation model breaks the harvesting of timber into two outputs, sawtimber and pulpwood, as forests can be managed differently depending on the final product market the material is intended to fill. Second, we

model multiple timber types. These different timber types have different yields and costs. The demands for sawtimber or pulpwood are global in nature, and each timber type feeds into the global demand functions. Third, we incorporated upward-sloping marginal cost functions for accessing forests that currently are economically inaccessible. This forestland is economically inaccessible for several reasons, including location (distance to markets), high nonmarket value to private or public landowners, or limited value due to low stocking levels. The upward-sloping cost functions limit access so that if scarcity increases and prices rise, more of this land will be accessed, but if prices are stable or falling, less or none is accessed.

Fourth, upward-sloping rental functions are included. The upward-sloping rental functions control the amount of land in each forest type. If prices for timber are increasing and the rental functions are stable, then more land will be planted to forests than will be harvested, and the forest type will expand. Importantly, the rental functions are chosen exogenously based on exogenous projections of land use for the region, but the resulting land area is determined endogenously by the model. If they are shifting inward, it suggests that the rental costs for maintaining forests in the specific type are increasing. Thus, if the rental functions are shifting inward over time, then the forest type may be declining in area. Fifth, the model is global and covers all major forest production regions in the world. The model therefore accounts for trade flows between regions and heterogeneity in forest systems (and hence, options and costs for managing forests). Appendix B describes the data used in this analysis.

For the numerical analysis, key baseline input assumptions such as income, population growth, and land rents for each region are calibrated to a number of sources. Specifically, we assumed that global gross domestic product per capita increases at an average rate of 2.1% per year for the next 180 years. This trajectory follows a recent Annual Energy Outlook (AEO) report for the next 40 years (U.S. Energy Information Administration 2014). We assumed that demand for pulp follows this global projection, given anticipated growth in woody biomass for energy generation (U.S. Energy Information Administration 2014) and growing markets such as corrugated cardboard, which are supplanting other traditional forest product uses of pulpwood such as newsprint and writing paper. The simulation horizon runs well beyond the period of interest for our analysis (100 years), so we impose the assumption that the economic growth rate slows to zero in the year 200 to ensure convergence to an approximate steady state in the terminal period. The terminal condition is imposed well beyond the simulation horizon of interest such that it has little effect on the reported results of this analysis.

The model was solved for future harvest, investment, forestland area, and timber prices. Changes in forest stocks are monitored over time and used to calculate carbon stocks and fluxes. Forest stocks include above- and belowground stocks in live and deadwood components, as well as slash. Because the model monitors timber harvests, fluxes into long-term wood product storage pools are also measured and included in the calculations. To assess the implications of management and land use on U.S. carbon sequestration, we selectively fixed management, Z_t , and/or land use, X_t , and evaluated the resulting impacts on emissions projections, forest management, and markets.

To test how management restrictions effect carbon outcomes under different environmental conditions (i.e., climate change), we develop the alternative scenarios relative to multiple baselines representing the impacts of climate change on forests. The business as usual baseline assumes a continuation of current forest yields, while the climate change impacts are based on projections from the MC1/MC2 dynamic global vegetation model (Gonzalez et al., 2010; Kim et al. 2017; Tian et al. 2016). The MC1/MC2 model was simulated across a set of results from three climate models (CSIRO, Hadley, and MIROC) under two possible future emission paths, the A1B and A2 climate scenarios (Nakicenovic et al. 2000), as well as one more recent climate scenario described by Monier et al. (2013). As shown by Sohngen, Mendelsohn, and Sedjo (2001) and Tian et al. (2016), we have linked specific forest types in each of the 16 regions of the global timber model to specific vegetation types in the MC2 model that are colocated within the 16 regions. We adjust annual growth using the projected change in total aboveground carbon projected by the MC1/ MC2 model for the corresponding vegetation type. The MC1/MC2 projections are for the period 2010–2110, so we assume that the effect in 2110 remains in effect from 2110 to the end of our economic simulation (2210).

In addition to considering alternative climate scenarios, we also explore a scenario that makes a stronger assumption about future economic growth, allowing us to evaluate how expected demand growth in forest product and/or biomass energy markets can influence model projections. The five scenarios we examine are as follows (all scenarios, including the baseline, are run with and without assumed climate change impacts):

Baseline is evaluated with and without climate change impacts on forest yield growth.

Scenario 1 (“Management 2010”) locks timber management at the initial level for the entire time horizon (i.e., $Z_t = Z_1$). This scenario assumes that foresters do not respond to price incentives, and they spend the same amount on timberland management in the future as they do today.

Scenario 2 fixes land use at the baseline level (i.e., $X_t = X_1$). This means that the total amount of land in forests remains the same over time, although foresters can adjust harvesting behavior.

Scenario 3 holds both management and forestland area at their initial levels throughout the simulation horizon.

Scenario 4 (“Management = 0”) assumes that management is turned off entirely. Under the preceding scenarios, management is fixed, but even fixing management at current levels implies significantly more management than historically. Under this scenario, forests revert to no management whatsoever. Scenario 4 addresses this issue by holding land use in the United States at the initial level and setting management to 0 (i.e., $Z_t = 0$).

Scenario 5 allows land use and management to adjust, but it includes a stronger increase in timber demand. Many current studies suggest that additional forest biomass demand (e.g., growth in traditional forest product demand or increased utilization forest biomass for energy generation) will lead to a reduction in forest carbon because harvests will increase

significantly (Searchinger et al. 2009). This scenario tests that hypothesis directly by increasing demand for wood significantly over time.

4. Baseline Results

In the baseline, sawtimber prices increase by 0.6% per year, on average, with pulp prices rising by 0.5% per year. Pulpwood is less scarce, given that more types of wood can be used for pulp, so prices rise less rapidly. Nonetheless, this anticipated rate of increase in prices is slower than the rate of increase in prices that occurred over the last century in the United States (Haynes et al. 2007).

Global timber output expands by around 55% over the next century. We have assumed that the demand for sawtimber and pulpwood increases proportionally over time, so the trends of output are similar. The amount of wood sourced from less accessible (higher-cost) forests falls from around 14% of total global harvest today to around 7% by the middle of the century. For the United States, the decrease is even more dramatic, falling from around 20% of total harvest being derived from less accessible forests currently to around 5% by the middle of the century. In contrast, the total global harvest derived from plantations is 27% initially, rising to around 36% globally by the middle of the century. For the United States, total harvests from plantations are currently calculated to be 49%, rising to over 70% by midcentury.

Another way to evaluate the influence of management intensity in U.S. forests is to consider expenditures on management. The average expenditure per hectare in the United States for lands planted initially is \$140 per hectare. The average expenditure per hectare in the United States rises by around 1.2% per year over the century to \$220 per hectare by 2055 and over \$420 per hectare by 2115. Management increases are even greater over time in some other regions, with Brazil, for example, experiencing a more than 2% per year increase in management expenses per hectare over the century. Importantly, in a dynamic model with a long time horizon, in this case 200 years, management intensity is projected to still be increasing late in the century in the United States and elsewhere due to continued increases in demand in the distant future.

Globally, total carbon storage is increasing, although it is increasing at a decreasing rate. Moreover, the trends of temperate and tropical forests differ substantially. Temperate forests remain a relatively strong sink over the next 20 to 30 years, but their capacity as a sink slows down as forests age and accumulate less additional carbon on an annual basis. Tropical forests, while currently a sink, become a source in the long run due to our projection of continued land use change and conversion of forests to agricultural uses. While forests in the tropics remain a critical source of *total* carbon storage over the long term, our projections show that net annual flux shifts from sink to source due to continued deforestation. Note that our carbon flux estimates are net changes, including the net effects of deforestation and reforestation in the tropics.

The United States is projected to remain a relatively strong sink over the entire century. One reason for the maintenance of the sink in the United States is the continued increase in

management over the century, which results from the continuing increase in demand for wood products. We decomposed the U.S. sink into managed forests, inaccessible forests, and remote inaccessible forests (Figure 1). Initially, intensively managed forests are a net source of carbon, but they convert to a relatively strong sink as management inputs continue to grow. Unmanaged forests are the bulk of the current U.S. carbon sink, but this sink declines over time given that forests are aging and there are few to no management inputs in that region. Remote forests also are currently a sink, but that sink declines over time without management inputs.

5. Scenario Results

In Scenario 1, forest management is fixed at its initial condition (i.e., $Z_t = Z_1$). Carbon sequestration rates in the United States do slow over time under this scenario, but they remain fairly close to the baseline level for the first several decades (Figure 2). Because management expenses on a per hectare basis are the same in all periods as they were projected to be in the first period in the baseline case, the initial stock of timber is fixed by historical management. Given the long time it takes to adjust management in forests, it makes sense that it takes many years for a scenario with fixed management to have an impact on carbon stocks.

Fixing land use (i.e., Scenario 2 sets $X_t = X_1$) has a more immediate and stronger impact. It turns out that new forests are an important component of near-term carbon sequestration. Newly established forests can sequester carbon relatively quickly. Thus, over the next 30 years, if the area of forests is fixed, sequestration rates decrease by 13%. Over 100 years, if no new land is added to forests, sequestration rates decline by around 20%. If neither land nor management can be changed over the next century (Scenario 3), the effects on sequestration rates are nearly additive, with a 14% reduction in sequestration in the next 30 years and a 30% reduction over 100 years.

To further illustrate the important role of management, Scenario 4 completely erases management; that is, forest management expenditures are set to \$0 per ha. These levels of timber management are consistent with management conducted in the 1800s and early 1900s. When we impose this limitation on the numerical model, sequestration rates in the United States fall dramatically. Forest carbon sequestration converges toward zero, but even with no management whatsoever sequestration rates do not become zero and the United States does not revert from sink to source in our simulations.

While fixing management inputs and land use have a clear impact on carbon, they have smaller impacts on timber outputs in the United States, particularly in the near term (Figure 3). Carbon is a flow output, derived from all hectares. A reduction in management, therefore, will alter the flux of carbon relatively sooner given that it will reduce carbon fluxes on younger hectares. Harvested timber, however, is derived only from hectares that are nearing merchantable timber harvesting ages. Thus, most timber that will be harvested in the next 20 to 50 years is already established. A reduction in management, therefore, will reduce outputs but only in the longer run.

The scenarios thus far have focused on supply shocks, though it is also useful to consider how carbon fluxes may adjust to a demand shock. For instance, if biomass energy demand increases in the United States or around the world, the demand for woody materials could increase. Similarly, timber demand estimates suggest that wood demand is largely homothetic, such that demand increases proportionally to income. If incomes rise more rapidly in the future, we may expect a stronger increase in the demand for wood.

The demand scenario (Scenario 5) doubles the global demand for wood over time. This means that demand increases at 2.9% per year, rather than 1.1% per year in the baseline. To test for the effects of changes in land use, we also include a scenario in which demand doubles, but land is fixed at the baseline level. This means that land use changes over time following the initial baseline projection.

A strong increase in demand causes prices and timber output to increase (Figure 4). By the end of the century, prices increase by 135%, while global output increases 70%. There are many marginal adjustments affecting timber harvests in response to higher projected demand. In forests where Faustmann-type rotational forestry occurs, foresters respond to the demand shock by reducing timber harvests initially to increase future supplies (Faustmann 1849/1995). When forests are managed in Faustmann-type rotations, timber supply can be expanded by increasing the rotation age and moving toward maximum sustainable yield. The only way to increase the rotation age in these stocks is to reduce harvests initially and allow some forests to age. Alternatively, in regions where harvesting inaccessible forests is more important, the marginal costs of access dictate that higher prices will lead to increased timber harvesting. Thus, in the tropics or the boreal regions where a large share of timber is derived from inaccessible types of forests, outputs are likely to increase initially in response to the demand shock.

There also is a long-term management response. Higher future prices will lead individual landowners to invest more in forest resources. These increased investments will also enhance output in the long run. The resulting adjustment of the market to higher future demand for timber increases the strength of the sink capacity in forests. By shifting forests to older age classes and reducing harvests initially, carbon stocks increase and carbon storage in forests increases. By increasing the age of timber over time and increasing investments in forests, this increase in sequestration strengthens over time. The increase in timber harvesting also leads to more storage of carbon in wood products. There is some additional harvesting of wood in inaccessible regions and some additional deforestation in the tropics due to higher demand, but these changes are modest compared with the overall increase in management.

The results could be sensitive to many of the parameters used in the model. Through sensitivity analysis, we determined that the forest yield function parameters and land supply elasticity parameters have the most important implications for carbon flux. To consider uncertainty in these two sets of parameters, we conduct a Monte Carlo analysis on these parameters, as described in Appendix C. The Monte Carlo analysis reproduces the general shape and magnitude of the deterministic U.S. carbon flux projection in the baseline. Over a 100-year period, the 95% confidence interval on carbon flux is $\pm 13\%$ of the mean annual flux, and the minimum and maximum range is $\pm 17\%$. In comparison, assuming that there are

no changes in forest management in the future (Scenario 1) leads to a 34% reduction in carbon flux by the end of 100 years, and assuming there is no change in land use (Scenario 2—a perfectly inelastic land supply function) leads to a 24% reduction in carbon flux by the end of 100 years. These results suggest that while it is important to resolve uncertainty in parameters, it is perhaps more important to account for changes in forest management when projecting carbon fluxes.

A different type of sensitivity analysis considers the role of climate change. For this, we replicate all scenarios with climate change impacts derived from the MC1 and MC2 models. The goal of the climate change analysis for this paper is to assess whether climate change alters the important role that management will play in maintaining the sink capacity of U.S. forests in the future. To accomplish this goal, we compare our baseline results to the same set of scenarios run for each of seven different climate change scenarios. Thus, we produce seven new baseline scenarios with climate change, and then conduct the same perturbations (e.g., management restrictions) for each of these scenarios. Across these seven climate change scenarios, the MC1/MC2 model projects that average aboveground carbon in the United States increases by 5% by 2060 and 8% by 2110, on average. This amounts to an increase in sequestration of 2 Tg C y^{-1} between 2020 and 2050 due to climate change, and 9 Tg C y^{-1} between 2050 and 2100 in the United States. Globally, aboveground carbon increases 9% and 13% over the same time periods, respectively. The maximum change for the United States in the seven scenarios is a 24% increase by 2060 and 47% increase in aboveground carbon by 2110, while the minimum change is a 5% and 10% decrease in aboveground carbon by 2060 and 2110, respectively. Despite the reduction in growth projected under some of the scenarios, we still find that forests remain a sink over the entire century.

From the perspective of our analysis, the more important results to consider are whether the changes in carbon due to our assumptions about management differ under climate change compared to the no climate change baseline. Under these sensitivity scenarios, the net effect of restricting management options turns out to be similar with and without climate change (Table 1). Restricting forest management options has a similar net effect on total forest carbon and is not significantly affected by assumed structural shifts in forest productivity in our climate change scenarios. This provides further evidence that forest management is a key determinant of terrestrial carbon outcomes, regardless of assumed future environmental conditions.

6. Discussion and Conclusion

This paper develops a structural model of the world's forest carbon sink. Forest carbon is shown to be a function of the area of land in forests and forest management, both of which affect forest structure and age. These components are dynamic in nature and adjust over time in response to market forces. Analytical results show how forest management, and consequently forest carbon flux, respond to market prices and land rents. Rising prices will induce forest managers to hold trees for longer periods, effectively increasing the stock of carbon in forests and increasing the sink capacity. While this seems surprising, given that younger stands sequester carbon more rapidly than older stands, harvesting also entails

emissions that can be avoided by holding onto trees for longer periods between harvesting. Analytical results also show that forest management inputs are a function of future price expectations. If prices are expected to rise, then management inputs increase, and vice versa. From a pure timber market perspective, management inputs increase future timber harvests at the time of harvest, but they also increase the sink capacity of forests across the entire time period when forests are growing.

To illustrate the importance of forest management and land use on forest carbon sinks, we developed a numerical simulation model of the world's forests. This model optimizes welfare in timber markets, the key driver of forest management globally. The simulations were conducted for 200 years in decadal time steps. An important recent paper by Wear and Coulston (2015) suggests that the sink capacity of U.S. forests will decline in the future largely due to slowing land use change. We tested the influence of land use change and management in our structural model by fixing these decisions in alternative future scenarios.

Our model finds that the U.S. carbon sink will remain strong for the coming century. This contrasts with the carbon sink projected for other regions of the world, where the sink capacity falls over time. An important reason for the strength of this sink capacity in the United States is forest management. The model projects that forest management increases by over 1% per year in the United States, with a greater proportion of timber harvested from intensively managed plantations than extensively managed forests. This continued shift toward intensively managed forests contributes significantly to the U.S. forest carbon sink. These more intensively managed forests become the primary source of additional forest carbon sequestration in the United States in the middle and latter parts of the century.

Fixing land use or management has a noticeable impact on our results. Over the next 30 years, fixing land use reduces carbon sequestration by around 20%, or around 28 Tg C y⁻¹. In contrast, in the study by Wear and Coulston (2015), fixing land use leads to a 50 Tg C y⁻¹ loss in the sink capacity. Fixing management has a smaller effect in the near term but has similar long-term consequences as fixing land use. Even the scenario that fixes land use and management causes only a 36 Tg C y⁻¹ change in the sink.

This analysis establishes the importance of modeling the dynamics of forest management when projecting future forest carbon sinks. Results of this analysis are consistent across different baseline assumptions, including how forest yields might evolve over time with and without the influence of climate change. Static and reduced form approaches do not adequately account for many adjustments landowners will make in response to price incentives. This means that calculations of future fluxes derived from static models likely over- or understate potential future fluxes.

Although our modeling approach illustrates the importance of market prices and forest management in maintaining forest carbon sinks, our results rest in part on a strong assumption about property rights. The ability of managers to respond to higher prices by increasing management is most feasible on privately held land. Property rights, however, are very uncertain in many regions of the world, and in particular for forests, which limits the ability of foresters to make long-term investments. Our results for the United States, thus,

may not be applicable in all regions of the world. That is, higher prices due to higher demand will increase investments in many regions, but some forest management types in some regions will experience reduced carbon fluxes with higher prices because there is very little economic incentive to manage these forests. This outcome indicates the importance of strengthening property rights on forests throughout the world, whether those rights are held by communities, governments, or individuals.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This paper was supported by the U.S. Environmental Protection Agency (EPA) (Contract EP-BPA-12-H-0023, Call Order #EP-B15H-0143). The views and opinions expressed in this paper are those of the authors alone and do not necessarily state or reflect those of the EPA, and no official endorsement should be inferred.

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Figure 1.
Baseline Annual Carbon Sequestration Rate in the United States by Management Intensity and Accessibility Categories over Time (Tg C y⁻¹)

Figure 2.
U.S. Annual Sequestration over Time for the Baseline, Restricted Management, and High-Demand Scenarios (No Climate Change)

Figure 3.
U.S. Timber Production over Time for Three Scenarios (million m³ y⁻¹)

Figure 4.
Global Timber Prices (*above*) and U.S. Timber Harvests (*below*) under Baseline and Doubled Demand Scenarios

Table 1**Net Change in Projected Carbon Stocks across Management Scenarios**

	Baseline	No Land Use Change	2010 Management	2010 Management/No Land Use Change	Management = 0/No Land Use Change	High Demand
<i>Without Climate Change Impacts</i>						
Aboveground Tg C in 2050	24,654	24,088	24,570	24,082	23,182	25,732
% difference from baseline		-2.3	-0.3	-2.3	-6.0	4.4
Aboveground Tg C in 2100	27,803	25,982	27,518	25,726	24,235	31,952
% difference from baseline		-6.6	-1.0	-7.5	-12.8	14.9
<i>With Climate Change Impacts (Average, Minimum, and Maximum of Scenarios)</i>						
Aboveground Tg C in 2050	24,727 (24,274, 25,221)	24,248 (23,709, 24,800)	24,638 (24,118, 25,182)	24,152 (23,575, 24,756)	23,439 (22,802, 23,937)	25,704 (25,334, 26,202)
% difference from baseline		-1.9 (-1.7, -2.3)	-0.4 (-0.2, -0.6)	-2.3 (-1.8, -2.9)	-5.2 (-5.1, -6.1)	4 (3.9, 4.4)
Aboveground Tg C in 2100	28,317 (27,065, 29,327)	26,638 (25,243, 27,393)	28,044 (26,659, 29,160)	26,336 (24,874, 27,187)	25,084 (23,691, 25,874)	32,211 (30,768, 33,789)
% difference from baseline		-5.9 (-6.6, -6.7)	-1 (-0.6, -1.5)	-7 (-7.3, -8.1)	-11.4 (-11.8, -12.5)	13.8 (15.2, 13.7)

Note: Includes the baseline case without climate change and the seven climate change scenarios examined. The climate change results are the average across the seven scenarios. The minimum and maximum changes are shown in parentheses. All carbon calculations are Tg C.