Three Essays on the Economics of Carbon Sequestration, Timber Production and Land Use

DISSERTATION

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By

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Abstract

My dissertation develops a wide range of quantitative tools to examine the carbon policies for wood biomass production, explore the potential policy instruments to create incentives for carbon sequestration and investigate the implications of increasing industrial plantations for timber markets.

The first chapter examines the greenhouse gas (GHG) effects of wood biofuel policies and the implications of potential carbon policies with biomass production. Previous literature suggests that an increase in wood biomass demand will cause more carbon emissions, and they suggest emissions from wood based biomass should be taxed. These studies, however, are static, and they ignore forest growth and sequestration. This paper develops a forward looking dynamic general equilibrium model with a dynamic forestry sector. By taking into account the dynamic land use adjustment in the forest sector, we show that the optimal strategy is to subsidize carbon growth in forests and to tax carbon emissions. Proposed strategies that would only tax carbon emissions from the forest sector including biomass energy production without compensating forest sequestration actually causes more net carbon emissions than if forest based bioenergy is simply treated as carbon neutral and ignored. This study makes two major contributions to the economics literature. It is the first study that develops a dynamic general equilibrium model with a dynamic forest sector. Second, the study illustrates a critical problem with several prominent studies that address biofuel policy.
The economic potential of carbon sequestration in forests is widely acknowledged but there is no consensus on the policy instrument that should be adopted to promote it. The second chapter focuses on the comparison of efficiency of different forest carbon policies recommended by past studies. We employ an optimal control model of timber management to examine the effects of different policies numerically, taking into account market effects and intertemporal adjustments. We find that the optimal policies are the ones which pay by explicitly tracking carbon in and out of forests. A ‘per hectare’ land subsidy could be 5 to more than 10 times more costly than a ‘per ton’ carbon tax & subsidy or carbon subsidy policy depending on the carbon prices. A carbon tax on forest emissions without compensating the sequestration leads to net carbon emissions and is thus the least efficient policy choice.

The third chapter examines the implications of wood production in the emerging regions on timber output in the United States, and specifically in the Southern U.S. A key component of the work involves updating GTM with new information on yields from emerging region plantations and more detailed representation of the Southern US. The preliminary results show that technological change in timber plantations could have very important influences on timber markets, nationally and globally.
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Chapter 1: The Greenhouse Gas Effects of Wood Bioenergy using A Dynamic General Equilibrium Model

Introduction

Many countries are promoting the production and use of bioenergy for reducing greenhouse gas (GHG) emissions and increasing their energy independence. For example, in 2007, the United States passed the Energy Independence and Security Act which requires a minimum of 36 billion gallons of biofuel production by 2022, a substantial increase from the roughly 15 billion gallons used today. The law requires that most of this increase be derived from cellulosic material, such as forests or cornstalks. A more immediate use of cellulosic material for energy other than transportation fuels, however, is the use of wood biofuels for producing electricity. Wood already supplies about 25% of renewable energy in the United States according to the Energy Information Administration (2013), with most of this used for electricity generation.

There is a significant debate over whether or not wood used for energy is carbon neutral. Although timber is renewable, it requires many years to mature depending on the species and where it is grown. In the US we have been harvesting much less wood than we are growing over the past 30 years, so there are large stocks of wood available for harvesting (Smith et al., 2007). This has created significant confusion in the literature, with some authors suggesting that emissions from wood based biofuels should be treated
differently than emissions from non-wood based biofuels (e.g. Searchinger et al., 2009). Similarly life cycle analyses (LCA) have concluded that carbon emissions from wood-based biofuel products should be taxed (e.g., Manomet Center for Conservation Sciences 2010). Both these studies suggest that the burning of long established forests causes large releases of carbon, and as a result, the authors suggest that the policy remedy is to tax carbon emissions generated by wood-based biofuels.

These studies, however, ignore forest management and the associated carbon sequestration with forest growth. Any policy that affects timber prices will affect landowner behavior. Landowners can change forestland area and management practices, such as harvest ages, thinning and fertilizing. Because forests absorb carbon while growing, these changes in forest management will alter the amount of carbon sequestered in forests. From the perspective of the carbon cycle, taxing only the emissions from burning wood without also subsidizing the accumulation of wood as forests grows, as suggested in Searchinger et al. (2009), leads to inefficient economic outcomes. In other words, while the tax could result in reduction in emissions, it will also reduce the rate of carbon sequestration by discouraging landowners from intensifying management, regenerating trees and expanding forestland. Furthermore, an inappropriate tax on woody biomass will alter the relative prices between wood based biofuels and other energy sources. An increase in woody biofuel prices will reduce their use and increase emissions elsewhere.

The purpose of this study is to illustrate the inefficiency created in a general equilibrium model of a policy that taxes only wood-based biofuels without considering
the potential carbon gains. The study begin by developing a simple optimal control model of carbon mitigation and abatement in the energy and forest sectors to derive the optimal carbon policies. We assume in the study that the carbon policy options are limited to directly pricing carbons by a carbon tax or subsidy, while we acknowledge that there might be other policy alternatives depending on the technology available (e.g. Favero and Mendelsohn 2014 proposes an indirect subsidy on wood biomass if Carbon Capture and Storage is cost effective). We show theoretically that an optimal carbon policy with wood-based biomass is the one that compensates carbon accumulation from forest growth while taxing on emissions from the forest sector including biofuel emissions. We then show how deviations from this optimal policy cause inefficient outcomes. In particular, we illustrate how the proposal to only tax carbon, without also recognizing the benefits of forest sequestration, will have large ramifications on forest management, forest land areas and timber harvests.

To quantify the implications of these different carbon policies, we develop a dynamic general equilibrium model with a dynamic forest sector for the United States. The resulting numerical simulation model optimizes dynamic decisions in all the sectors including the forest sector. The energy sector uses biofuel and fossil fuel to generate energy for firms and households. The forest sector produces wood which can be used for energy as well as for traditional wood uses. The forest sector is land-based with a detailed representation of age class distribution and yield information of the United States.

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1 The carbon subsidy and tax policy was proposed by van Kooten et al., (1995). An efficiently equivalent proposal is to rent carbon sequestered in forests and to pay for carbon that is permanently stored in marketed wood products, as done in Sohngen and Mendelsohn (2003).
forest inventory. The forest model takes into account management in forestry and adjusts forest stocks optimally over time, following the model described in Sohngen and Mendelsohn (2003, 2007).

To solve the model, we use a technique which decomposes the problem into two parts and solve the two parts iteratively. The model is decomposed into a mixed complimentary problem (MCP) to solve the general equilibrium model and a nonlinear optimization problem to solve the forest sector model (see Böhringer and Rutherford 2009). A demand approximation for timber goods and wood biomass is derived from the MCP problem to represent the general equilibrium demand. The demand structure is then imported into the forest sector to solve new outputs and prices of timber and wood biomass, reflecting the explicit technology and management in the forest sector. Newly generated outputs and prices are then imported to the MCP model to derive a new demand structure and so forth. A solution of the iterative algorithm is obtained when the convergence reaches contain tolerance.

There are important advances represented in our approach. The study is the first to develop a dynamic general equilibrium model with a dynamic forest sector. The development of a dynamic analysis rather than static analysis turns out to be critical in this case because we are modeling forests, where any changes in harvesting or management has implications for the future. Projections from static models cannot capture the user costs. Dynamic land use modeling has long been established in partial equilibrium models (see Sedjo and Lyon 1990, Sohngen and Mendelsohn 2003, Beach and McCarl, 2010), but those models fail to capture the interaction between the forest
sector and the rest of the economy with policy interactions. Previous general equilibrium models have attempted to incorporate the forest sector but they have not comprehensively represented the critical dynamics of forestry. Wise et al. (2009), Reilly et al. (2007), Ahammad and Mi (2005) and Sands and Kim (2009) use recursive dynamic CGE models, but the models, with multiple time steps, are essentially static and thus have no forward looking behavior. As to the forest sector, they usually model managed forests as agriculture crops and ignores the effects on optimal rotation, harvesting, regrowth and management. Other studies (Golub et al., 2008 and Hertel et al., 2009) create links between CGE models and dynamic forest sector models via price or quantity paths; however, the links are largely intended for initial calibration and the CGE models are not fully dynamic, so the two types of model cannot be fully integrated.

Also importantly, in climate policy analysis, the recursive dynamic methods mentioned above have been widely applied by Integrated Assessment Modeling (IAM) teams to project land use changes in climate policy analysis (for example Sands and Leimbach (2003); Wise et al., 2009; Reilly et al., 2007; Schlosser et al., 2007; Lauri et al., 2013). Because the IAM community has not been able to integrate forward looking behaviors in the forest sector, their policy-relevance of assessments is limited. This modeling framework and the solution algorithm represented here can be expanded to a multi-region general equilibrium model focusing on climate policy and land use issues and can also be widely used by the IAM community in climate policy analysis.

Besides a methodology contribution, this study addresses the critical limitation in the US regulation of GHG emissions from burning wood-based biofuel. On January 12,
2011, USEPA announced a series of steps to address the treatment of biogenic $CO_2$ emissions from stationary sources, including a detailed accounting framework for biogenetic $CO_2$ emissions (EPA, 2011). The EPA accounting framework treats wood-based biofuel as a source of carbon emission to the atmosphere. Our results, however, suggest that if tax and subsidy policy cannot be implemented, a preferred alternative is to treat bioenergy emissions as carbon neutral.

The paper is organized as follows. Section 2 is a simple analytical model of carbon mitigation in which we derive the optimal carbon policies for biomass emissions and carbon sequestration. In Section 3, we develop a general equilibrium model with a dynamic land-based forest sector and describe the methods to solve the model. In Section 4, we calibrate the model to the US economy, energy markets, forest inventories and land use data. In Section 5, simulations are conducted for various biofuel and carbon policy scenarios. Specifically, three scenarios are examined and compared: carbon tax excluding biofuel (Scenario 1), carbon tax to all emissions including biofuel emissions (Scenario 2) and carbon tax to all and carbon subsidy to sequestration (Scenario 3). Section 6 concludes the study.

An analytical model of carbon mitigation

An optimal control model of carbon mitigation and sequestration with biomass emissions

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2 The EPA accounting framework for biogenetic $CO_2$ emissions nets out average forest growth within a similar region when calculating the biogenetic accounting factor. While this is an improvement over the Searchinger et al (2009) suggestion, it does not fully account for the incentive effects of the policy on future net carbon emissions from land use.
We start with a dynamic model of carbon mitigation with emissions from biomass. The model minimizes the present value of the costs of carbon emissions. The costs are composed by the abatement costs and climate damages caused by the accumulation of carbon. Carbon emissions from fossil fuel and biofuel combustion accumulate in the atmosphere causing damage on society. The stock of carbon in the atmosphere decays at a constant rate, \( \lambda \). The economic value of damages associated with any given concentration of carbon in the atmosphere, \( X(t) \), equals to \( D(X(t), t) \). The baseline emission from fossil fuels is given as \( E_f(t) \) and the baseline emission from biomass is given as \( E_b(t) \). In the baseline, \( E_f(t) \) and \( E_b(t) \) are the business as usual emission pathways. The choices in the model are the abatement for fossil fuel and biomass emissions as well as carbon sequestration. The abatement for fossil fuel is denoted as \( A_f(t) \) and the cost associated with the abatement is \( C_e(A_f(t)) \).

Forests sequester carbon through biological growth and they release carbon with harvests for timber, bioenergy or land use change. Changes in carbon flows are determined by three forestry actions: the area forestland, \( l(t) \); the age trees are harvested, \( h(t) \); and management intensity, \( m(t) \). The three actions affect both carbon sequestration and carbon emissions from biomass simultaneously but in different ways. Adding forestland can include either planting new forests on old agriculture land or reducing deforestation on lands projected to be converted to agriculture. The additional forestland will result in additional carbon sequestration and additional future carbon emissions from harvests for biomass. Changing management intensity changes the carbon density of forests. Extending harvest age increases carbon storage by reducing harvests initially,
and increasing the size of trees in a stand over the long-run. The amount of carbon sequestered above the baseline forest stock is $S(I(t), h(t), m(t), t)$. Carbon abatement through biomass energy production and land use change is given as $A_b(I(t), h(t), m(t), t)$, and the cost function for biomass abatement is $C_b(A_b(I(t), h(t), m(t), t))$.

The social planner’s problem can be written as

$$\min_{A_f(t), I(t), h(t), m(t)} \int_0^{\infty} e^{-rt} \left[ C_e(A_f(t)) + C_b(A_b(I(t), h(t), m(t), t)) + D(X(t), t) \right] dt$$

subject to

$$\dot{X} = E_f(t) + E_b(t) - A_f(t) - A_b(I(t), h(t), m(t), t) - S(I(t), h(t), m(t), t) - \lambda X(t)$$

Solving the optimal control problem, we have the following condition characterizing the optimal solution:

$$C_e A_f = \mu(t) = \frac{D_x + \dot{\mu}}{r + \lambda}$$

$$C_e A_f = \frac{C_b A_b I}{A_b + S_I} = \frac{C_b A_b h}{A_b + S_h} = \frac{C_b A_b m}{A_b + S_m}$$

$\mu(t)$ represents the shadow value of an additional ton of carbon removed from the atmospheric carbon stock at time $t$. The first equation above shows that the marginal costs of an additional ton of abatement of energy should be equated to the shadow value, $\mu(t)$, of an additional ton of abatement as well as the present value of the stream of damages this additional ton causes. The second equation shows that the marginal cost of
abatement of fossil fuels equals the marginal costs for an additional ton of carbon savings in forests by the three choices in the forest sector separately: l (forestland), h (harvest ages) and m (management intensity). Their marginal costs are calculated as the costs with one unit of change in these actions divided by the carbon savings caused by this unit of change. As each of these choices with forests affect forest sequestration as well as abatement of emissions from burning wood for energy at the same time, the carbon savings are sum of changes in carbon abatement from biomass (A_b) and the changes in carbon sequestration (S).

These two conditions have important implications for carbon policies in forest sector. On one hand, as with energy abatement, carbon sequestration should reflect the incentive to reduce the social damages of carbon accumulation in the atmosphere. On the other hand, unlike a carbon policy that targets only the traditional, non-biofuel energy sector, a carbon tax that targets biofuel emissions will also affect carbon offsets because the taxes will alter forest management incentives. Since both carbon abatement through biomass energy and carbon sequestration directly affect the social cost of mitigation, both must be considered when developing policy.

Forest firms perspective and optimal carbon policy in forest sector

This section shows how policies in forestry should be developed to provide economic incentives to achieve the socially optimal level of biomass abatement and carbon mitigation. From van Kooten et al. (1995), we know that the optimal forestry carbon incentive is a subsidy for forest growth and a tax for emission at harvest. The optimal level of subsidy and tax is determined by solving the problem of forest firms as
following. Assume that forest firms are subjected to a constant tax ($\eta$) on per ton of carbon emitted from forest and a constant carbon subsidy ($\theta$) to per ton of carbon sequestered by forests. The problem of forest firms is formed as:

$$\min_{l(t),h(t),m(t)} \int_{0}^{\infty} e^{-rt}\left[ C_b\left(A_b(l(t), h(t), m(t), t)\right) + \eta(t)(E_b(t) - A_b(l(t), h(t), m(t), t)) - \theta(t)S(l(t), h(t), m(t), t)\right] dt$$

Solving the problem, we have the following conditions characterizing the optimal solution for the forest firm:

$$C_{bA_b}A_{b1} - \eta(t)A_{b1} - \theta(t)S_1 = 0$$

$$C_{bA_b}A_{bh} - \eta(t)A_{bh} - \theta(t)S_h = 0$$

and

$$C_{bA_b}A_{bm} - \eta(t)A_{bm} - \theta(t)S_m = 0$$

The three equations show separately that the marginal cost of increasing forestland, lengthening rotations and increasing management intensity should all be equated to the sum of additional revenues of the carbon tax and subsidy due to the changes of carbon sequestration and carbon emissions from biomass.

The optimal carbon policy is a combination of the carbon taxes and subsidies with which the optimal paths of carbon emissions and sequestration coincide with the social optimal paths of carbon emissions and sequestration.

From 2.1, we know that
Combining this equation with the optimality conditions of forest firms, we have

\[
C_{e\lambda(t)} = \mu(t) = \frac{D_x + \mu_t}{r + \lambda} = \frac{C_{ba\lambda} A_{b\lambda}}{A_{b\lambda} + S_{\lambda}}
\]

We can get similar conditions for \( h(t) \) and \( m(t) \), which are:

\[
\left( C_{e\lambda(t)} - \eta(t) \right) A_{b\lambda} = \left( \theta(t) - C_{e\lambda(t)} \right) S_{\lambda}
\]

\[
\left( C_{e\lambda(t)} - \eta(t) \right) A_{b\lambda} = \left( \theta(t) - C_{e\lambda(t)} \right) S_{\lambda}
\]

\[
\left( C_{e\lambda(t)} - \eta(t) \right) A_{b\lambda} = \left( \theta(t) - C_{e\lambda(t)} \right) S_{\lambda}
\]

As we mentioned in 2.1, \( A_{b\lambda} \), \( l(t) \), \( h(t) \), \( m(t) \), and \( S(l(t), a(t), m(t), t) \) are two different functions as carbon sequestration and carbon emissions from harvests are two independent processes. So \( A_{b\lambda} \) does not necessarily equal \( S_{\lambda} \) for all periods. Therefore, the necessary and sufficient condition to satisfy the above conditions is:

\[
C_{e\lambda(t)} = \eta(t) = \theta(t)
\]

This condition shows that the optimal carbon policy is such that the carbon taxes on emissions from biofuel as well as the subsidy on carbon sequestration should all be set equal to the present value of the stream of social damages and rising damages that an additional ton of carbon causes. Deviations from this condition will result in deviations of forest firms’ behavior from the optimal carbon results in the forest sector and thus higher social cost of climate mitigation. Specifically, a tax on carbon emissions from biomass in the absence of any compensation for carbon sequestration is inefficient in part
because it alters management practices and discourages forest sequestration activities. It is also inefficient because it results in an incorrect set of relative carbon prices in the two important carbon abating sectors, forests and energy. Carbon sequestration, just like energy abatement, should be appropriately incorporated into the carbon policies with biomass emissions.

A general equilibrium model with a dynamic forest sector

This section of the paper presents a dynamic CGE-forest model with forward looking behaviors, and it presents an algorithm for solving the resulting intertemporal problem. The model is based on a stylized neoclassical general equilibrium model for a single country, although in principle the analysis can be extended to as many countries as necessary, given the appropriate forestry data. The first part of this section describes the assumptions about the technology and investment for the CGE model, and the second part focuses on the specification of the forest sector. The last part presents the algorithm for numerically solving the problem.
The specifications of the CGE model and rational expectations

Consumption

The representative consumer maximizes expected utility of the intertemporal sequence of aggregated consumption goods, $C_t$:

$$\max \int_{t=1}^{\infty} \frac{1}{(1 + \rho)^{1+t}} \cdot \frac{1}{1 - \sigma} C_t^{1-\sigma}$$

This is a discrete homogenous utility function with a constant elasticity of intertemporal substitution, $\sigma$. The consumption is discounted by the consumer’s constant rate of time preference $\rho$. The aggregate consumption is generated by a Cobb-Douglas aggregation of goods from a general production sector $X_{c,t}$ with a specific expenditure
share of $\alpha_t^h$ and energy goods from the energy sector $E_{c,t}$ with an expenditure share of $\alpha_2^h$. So the aggregation for final consumption $C_t$ is

$$C_t = X_{c,t}^{\alpha_1^h} E_{c,t}^{\alpha_2^h}$$

The consumer owns the wealth of the economy and rents capital to producers in each period. The accumulation of wealth in each period depends on the consumer’s income and expected return from investments. Income consists of capital payments, labor payments, payments for timber goods, and payments of wood bioenergy. The income will be treated as either consumption or savings to investment goods, the price of which is specified as $P^K$. The consumer’s budget constraint at each period is written as:

$$r_t K_t + P^L_t L_t + P^T_t T_t + P^B_t Bio_t = P^C_t C_t + P^K_t [K_{t+1} - (1 - \delta)K_t]$$

Solving the dynamic optimization problem, we have the intertemporal condition (Euler Equation), which characterizes the rate of consumption growth in response to changes in the price of investment goods and the interest rate $r_t$.

$$\frac{P^{C_{t+1}} C_{t+1}^\sigma}{P^C_t C_t^\sigma} = \frac{P^K_{t+1} (1 - \delta) + r_t}{(1 + \rho) P^K_t}$$

A larger interest rate or future price of investment good makes current consumption more expensive and thus the consumption will grow faster over time and vice-versa. The interest rate equals the returns of capitals in the production sector. The price of investment goods, as we will discuss in the investment part, is determined by the prices of final goods in each specific production sector.
In order to link the forestry sector to the other production sectors, we introduce timber products as an intermediate input in the final goods production sectors. Timber products are treated as a substitute for other inputs into production, including capital, labor and energy. For the purpose of this analysis, we have one general production sector producing a single final good in the model. The production function for general sector is a nested Constant Elasticity of Substitution function (CES). The first layer is an aggregation of capital, labor and energy input through a Cobb-Douglas function. The second layer is a CES function which aggregates timber and non-timber inputs. The Cobb-Douglas production function for first nest is specified as:

\[ Q_{1,t} = AK_{t}L_{t}^{\alpha}E_{p,t}^{\beta} \]

The CES function producing final goods is specified as:

\[ X_{t} = \left[ r_{t}Q_{1,t}^{\rho} + (1 - r_{t})T_{1,t}^{\rho} \right]^{1/\rho} \]

where the elasticity of substitution between non-timber input \( Q_{1,t} \) and timber input \( T_{1,t} \) is specified as \( \frac{1}{1-\rho} \).

The dynamic decisions of the firms are to choose the paths of labor, energy and timber inputs. Capital and investment decisions are made by the households. Because we assume that firms are competitive and their dividends in each period are zero, the firm's optimization problem can be written as:

\[ \text{Max}_{\{L_{t},T_{t}\}} \left[ r_{t}Q_{1,t}^{\rho} + (1 - r_{t})T_{1,t}^{\rho} \right]^{1/\rho} - r_{t}K_{t} - P_{t}^{L}L_{t} - P_{t}^{E}E_{p,t} \]
Solving the optimization problem above, we have the conditions for choosing paths for the production factors: the prices of inputs equal their marginal productivity to the final goods. As we assume a Cobb-Douglas production function for the non-timber inputs, the share of these three factors is constant relative to each other while the share of timber input could vary over time.

\[[L_t]: \quad p^L_t = \frac{p^x_t X_t r_t \alpha Q_{1,t}^\rho}{[r_t Q_{1,t}^\rho + (1 - r_t) T_{1,t}^\rho]} L_t \]

\[[K_t]: \quad i r^K_t = \frac{p^x_t X_t r_t \beta Q_{1,t}^\rho}{[r_t Q_{1,t}^\rho + (1 - r_t) T_{1,t}^\rho]} K_t \]

\[[E_{p,t}]: \quad p^E_t = \frac{p^x_t X_t r_t \gamma Q_{1,t}^\rho}{[r_t Q_{1,t}^\rho + (1 - r_t) T_{1,t}^\rho]} E_{p,t} \]

\[[T_t]: \quad p^T_t = \frac{p^x_t X_t (1 - r_t) \gamma T_t^\rho - 1}{[r_t Q_{1,t}^\rho + (1 - r_t) T_{1,t}^\rho]} \]

**Energy Sector**

The energy sector produces homogenous energy goods using inputs from traditional fuels (fossil fuel) and biofuels from the forest sector. The energy goods are consumed by the production sector and households for private use. The CES production function of energy goods is specified as:

\[ E_t = \left[ r^E_t \text{Fuel}_t^\rho + (1 - r^E_t) \text{Bio}_t^\rho \right]^{1/\rho^E} \]
We assume the price of fossil fuel is exogenously determined by fuel suppliers so the costs are not explicitly modeled here. The dynamic decisions of the energy sector are to choose the paths of fossil fuel, biofuel such that the price of each input equals its marginal product of energy goods. The optimality condition for the two inputs over time is thus derived as:

\[
\frac{p_t^F \text{Fuel}_t^{1-\rho^E}}{p_t^B \text{Bio}_t^{1-\rho^E}} = \frac{r_t^E}{1 - r_t^E}
\]

*Specifications with the dynamics and land use in the forest sector*

The forest sector produces wood for bioenergy as well as for traditional timber uses. The sector is endowed with forest inventory in the initial period, which is specified by forest productivity classes, ages, yield information and carbon. The same logs can be used to produce two types of products, traditional timber and bioenergy. Bioenergy can be made from a wider variety of logs, pieces of logs, or the remains of logs after they are used for traditional timber products, and thus is in greater supply. The forest firms face timber prices as well as bioenergy prices and make decisions with harvests, management and land changes. The objective of forest firms is to maximize the net present value of net profits in timber markets as well as the energy markets. Net profits are defined as the difference between revenue of timber and biofuel products and the costs of management, harvesting and land rental associated with holding forests. Nonmarket timber value is not considered here.

The forest owner’s problem is:
\[
\max \int_{t=1}^{\infty} \left( \prod_{t=1}^{\infty} \frac{1}{1 + r_t} \right) \left( P^T_t \cdot T(H_t, V_a) + P^{Bio}_t \cdot \text{Bio}(H_t, V_a) - R(S_t) - \text{Cost}^P_t - \text{Cost}^M_t \right)
\]

\( P^T_t \) is timber price which is determined by its productivity in general sectors and its production costs in the forest sector. \( H_t \) is the area that has been harvested. \( V_a \) is the yield function where \( a \) is the age of the tree. \( Q(H_t, V_a) \) is the total quantity harvested. \( S_t \) is the total size of forests and we differentiate the forestland by age classes using the yield function. \( R(S_t) \) represents land cost, which is a constant elasticity increasing function of \( S_t \). It is the opportunity cost associated with holding land in timber rather than transforming it to other uses. \( \text{Cost}^M_t \) is cost of management.

The initial age class distribution of forestland and the yield functions are exogenous. The form of yield function used in this analysis is:

\[ V_{a,t} = h \cdot \exp (\delta - \pi/a). \]

The term "h" is the stocking density, which can be adjusted depending on the intensity of management, \( m_{t0} \); “a” represents age of trees and the others are all parameters determined by specific species.

The costs of holding timberland are rental costs of maintaining land in timber rather than other uses, such as agriculture. The costs of managing timber include costs of harvesting, accessing timber and transporting timber as well as costs of replanting timber. Those costs are different for different land classes and different timber types. Since most of the biofuel is derived from residues or lost cost woods, the management costs for biofuel use are much lower than that for timber products.
An iterative way of solving the CGE model

An intuitive way to solve the dynamic model is to solve all the intertemporal optimization conditions as a system of equations. Under static expectations, there is no difficulty in solving the problem, but when the forward looking behaviors are introduced, it becomes very difficult to solve the system simultaneously. First, while the model is decadal, the harvesting and replanting decisions depend on long-term expectations of future prices which are also endogenous in the model. Second, the output of the forest sector is a function not only of the type of land but also the distribution of age classes. Timber yields are nonlinear, and this nonlinearity adds complexity in the model solution. We resolve this difficulty by using an iterative method. We separate the CGE model into a forest sector model and a new CGE model. We first take a guess of the timber supply path ($T_t$) and biofuel supply path ($Bio_t$) and assume the timber supply is fixed at $Q_t$ in the new CGE model; we solve the model without any intervention of dynamics of forest sector. The solved optimal timber price path should satisfy the following optimality conditions:

$$p^T_t = \frac{px_t X_t (1 - r_t) Y T_t r_t - 1}{r_t Q_t r_t + (1 - r_t) T_t r_t - 1}$$

The solved optimal biofuel price path should satisfy the following optimality conditions (see Section 3.1.3):

$$p^E_t = \frac{p^E Fuel_t (1 - r_t) Y t - 1}{r E_t r_t}$$
We also know that \( Q_{t,i} = A_i K_{t,i}^{\alpha_i} L_{t,i}^{\beta_i} T_{t,i}^{\gamma_i} \). Combining this with the three optimality conditions, we can derive a downward sloping timber demand function:

\[
Q_t = \sum_i (D_t \cdot P_t^T - \frac{1}{\alpha_i + \beta_i}) \quad \text{where} \quad D_t = \left( c_i \cdot P_t A_i K_{t,i}^{\alpha_i} L_{t,i}^{\beta_i} \right)^{\frac{1}{\alpha_i + \beta_i}}
\]

The \( D_t \) in the function captures all the information determining the demand for timber products in the general sectors. Higher final goods price, higher capital level and labor supply will all shift the demand function outward and vice-versa.

We then introduce the demand function as a constraint into the forest sector and solve the forest owner’s problem as a dynamic nonlinear programming problem (See Sedjo and Sohngen 1998). The intertemporal decisions of harvesting and replanting and the optimal path of quantity being harvested (\( Q_t^N \)) are generated. This is the closing for the first iteration.

In the second iteration, we set the \( Q_t \) equals to \( Q_t^N \) and repeat the first step. We then use the new results from the CGE model to update \( D_t \) and resolve the forest sector model. The iteration will continue until the timber price paths generated from two parts converge. We find that the convergence is accelerated with an improved starting guess.

Description of calibration data and scenarios

The simulation model uses data from three sources. The calibration with the economy and general production sectors relies on the 2013 National Income and Product Accounts (NIPAs) from U.S. Bureau of Economic Analysis (BEA). We use 2010 as the base year to calibrate the size of initial capital, investment, labor share, real interest rate and gross
domestic output. We assume an exogenous population growth of 1% per year and 10% per decade. The rate of depreciation is calibrated based on the investment, capital and real interest rate. A social accounting matrix showing the initial values for each sector and households are shown in Table 1.

<table>
<thead>
<tr>
<th>Unit: Billion US dollars/year</th>
<th>General Firms</th>
<th>Energy Sector</th>
<th>Forest Sector</th>
<th>Households</th>
<th>Fuel Supplier</th>
<th>Total(Received)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Firms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>Energy Sector</td>
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<td>271.58</td>
<td></td>
<td></td>
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<td>1213.87</td>
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<tr>
<td>Forest Sector</td>
<td>58.56</td>
<td>2.88</td>
<td></td>
<td></td>
<td></td>
<td>61.44</td>
</tr>
<tr>
<td>Households</td>
<td>10680.6</td>
<td>61.44</td>
<td>1210.99</td>
<td></td>
<td></td>
<td>11953</td>
</tr>
<tr>
<td>Fuel Supplier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1210.99</td>
<td>1210.99</td>
</tr>
<tr>
<td><strong>Total(Expended)</strong></td>
<td>11681.4</td>
<td>1213.87</td>
<td>61.44</td>
<td>11953</td>
<td></td>
<td>24909.7</td>
</tr>
</tbody>
</table>

Table 1 Social Accounting Matrix

The data associated with energy production are from the Energy Information Administration Annual Energy Outlook (AEO) 2013 ‘Reference Case’ for domestic energy consumption and renewable energy production. The elasticity of substitution between fossil fuel and biofuel is 3.95 (Hertel, Tyner and Birur 2008). For the supply of fossil fuel, we assume a fixed price which is 10 million dollars per trillion Btu.

Because the AEO Outlook does not explicitly list the demand for wood-based biofuel in energy generation, we assembled the demand by using the demand of cellulose in the
electricity generation for the BAU case. For this paper we assume that 1 cubic meter of timber produces approximately 850 kWh. This is based on the assumption that 1 cubic meter of timber produces 8.8 MMBtu of energy. The demand of wood for bioenergy starts from 44 million cubic meters in 2010 and steadily increases to about 80 million cubic meters in 2100.

The forestry model tracks the age class, growing stock volume and harvest of 26 land classes of US. The initial forest area and inventories in the model are obtained from the database of Forest Inventory Forest Inventory and Analysis, USDA Forest Service. The marginal cost functions for land supply are calibrated based on the initial forest area and inventories. The marginal benefits for expanding a new hectare of forests are the present value of future timber harvests from the new established hectare. We assume the price elasticity is 0.25 for land supply, which means land is responsive to demand increase from either timber market or the bioenergy market.

The substitution between timber input ($T_t$) and nontimber input ($Q_{1,t}$) is determined together with the price elasticity of demand in timber demand function. The literature in forest economics gives a wide range of estimates for the price elasticity of timber demand, from -0.14 to -1.33 among studies of different regions, scales, time ranges and timber types (see Haynes et al. 1981, Newman 1987, Simangunsong and Buongiorno 2001, Uusivuori and Kuuluvainen 2001, Turner and Buongiorno 2004). We choose an price elasticity of -1.0 which is at the high end of the range because we are doing a long term analysis and long term elasticity tends to be larger than short run ones. .
For this analysis, we calculate total ecosystem carbon in aboveground and belowground plant material, and soil carbon. We also tracked carbon stored in timber products and decay starting from being harvested. In addition, we also calculate the reductions in emissions from combustion of fossil fuel due to the displacement of wood bioenergy and how much more emissions occur with the use of wood bioenergy. The problem is solved by GAMS and we do the simulation in decadal time steps. We run it for 15 time steps. A structure of the model is displayed in Fig. 1.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario 1</strong></td>
<td><strong>C Tax Excl Bio</strong></td>
</tr>
<tr>
<td></td>
<td>• No tax to carbon emissions from the forest sector</td>
</tr>
<tr>
<td></td>
<td>• No subsidy to carbon sequestration in the forest sector</td>
</tr>
<tr>
<td><strong>Scenario 2</strong></td>
<td><strong>C Tax All</strong></td>
</tr>
<tr>
<td></td>
<td>• Carbon tax to emissions from the forest sector at $30/ tCO₂</td>
</tr>
<tr>
<td></td>
<td>• No subsidy to carbon sequestration in the forest sector</td>
</tr>
<tr>
<td><strong>Scenario 3</strong></td>
<td><strong>C Tax All&amp;Subsidy</strong></td>
</tr>
<tr>
<td></td>
<td>• Carbon tax to emissions from the forest sector at $30/ tCO₂</td>
</tr>
<tr>
<td></td>
<td>• Carbon subsidy to sequestration in the forest sector at $30/tCO₂</td>
</tr>
</tbody>
</table>

Table 2 Description of Scenarios

**Simulation results**

For this analysis, we compare the results for 3 scenarios: carbon tax excluding biofuel (Scenario 1), carbon tax to all emissions including biofuel emissions (Scenario 2) and carbon tax to all and carbon subsidy to sequestration (Scenario 3). The scenarios have the same assumptions of technology change, population growth and productivity etc. except that they are different from each other in the exogenous carbon policies in the forest.
sector. We assume a constant carbon price at $30 per ton of CO₂ over time. The specific assumptions of each scenario are described below (Table 2).

The scenarios

Scenario 1: Carbon tax excluding biofuel

This scenario assumes that a tax is imposed on carbon emissions from fossil fuels. Wood can be used to produce energy, but carbon emissions from wood biofuel and other wood uses are not taxed. There is also no compensation for carbon sequestration that occurs with forest growth. The tax is collected from fossil fuel producers according to the total amount of carbon emissions from the use of fossil fuel. The tax revenue is redistributed to the consumer as transfers. This scenario is consistent with the present situation in US, where woody bioenergy is treated as carbon netural and is thus excluded from a carbon tax; meanwhile, there is no state-wide policy with forest sequestration.

Scenario 2: Carbon tax to biofuel and forest products

This scenario assumes that a tax is imposed to carbon emissions from both fossil fuel and wood biofuel combustion as well to emissions from harvesting non-biofuel timber goods in the forest sector. There is no compensation for carbon sequestration in forest growth. This scenario reflects the policy recommendations from the studies which suggest a carbon tax on woody biofuel emissions (e.g. Searchinger et al., 2009). Woody bioenergy is treated as a net source of carbon emissions to the atmosphere. The carbon taxes on biofuel and fossil fuel are collected from forest firms and energy firms separately based on the total amount of carbon emissions from each types of fuel. The tax revenue is redistributed to the consumer as transfers.
Scenario 3: Carbon tax to all and carbon subsidy to sequestration

This scenario is the same as Scenario 2 except that a subsidy at the same carbon price is included on each equivalent ton of CO₂ sequestered by forests. This scenario is consistent with our first best carbon policy scenario (Section 2.2). By introducing the carbon subsidy, carbon sequestration is equally compensated as carbon abatement in the energy sector. As we do not have a specified government sector specified here, the carbon subsidy is deducted from households’ income. Carbon sequestration is calculated from the volume of growth of forests multiplied by a carbon conversion factor.

Results

Scenario 1 is constructed as the baseline where there is no climate policy in the biofuel market or the forest sector. The projection shows that the area of US forestland remains stable in the long run, with a small expansion of 10 million hectares from 2010 to 2010 (Fig. 2). This masks the slow expansion in plantations in recent decades. Similarly, the timber output also increases over the projection period, with an average increase rate of 1% per decade (Fig. 3). Notably, the projected output of wood biomass increases from 44 million m³ in 2010 to the level of around 60 to 70 million m³ by 2030 (Fig. 2). The increase in biomass outputs, fed by the forest sector, mimics the bigger role of woody bioenergy in the energy sector in the future. The price of wood biomass stays at around $53 per m³, which is equivalent to $5.7 per million Btu.
Figure 2 Forest Area
The effects of a carbon tax in the forest sector

**Scenario 2 (Carbon tax to biofuel and forest products)** is constructed to show the separate effects of a carbon tax in the forest sector under the situation where there is already a carbon tax to fossil fuel. The effects of **Scenario 2** are labeled as lines with diamond arrows through Fig. 2 to Fig. 5. We first focus on the changes in output and land uses. The carbon tax to forestry reduces both outputs and area of forests. The reduction is especially substantial with timber outputs (Fig. 3). This is evident by comparing the timber outputs under **Scenario 1** and **2**: the timber output decreases by 13% after the inclusion of the tax. The strong effects on timber output as well as on biofuel are the results of two factors: (1) the inclusion of tax reduces the revenue of per hectare of forest and thus the total area (Fig. 2); (2) it shifts up the per unit production cost; as a result, the per hectare output also reduces.
We next focus on the carbon stocks in the forest sector. Fig. 5 reports the results of the aggregate forest carbon stocks under the scenarios. The level of carbon stocks is lowered by 1%-2% after inclusion of the tax. Here the carbon stocks effect is partly driven by the reductions of total forestland. However, it also directly related with the carbon dynamics on the forestland. The forest carbon consists of carbon stocks from four pools: the growing stocks, the harvest and logging slash, forest soil and timber products. To effectively compare the effects on different carbon pools, we calculated the differences in the carbon accumulation of each pool between Scenario 1 (without carbon tax on timber and biofuel) and Scenario 2. The differences are shown in Fig. 6.
The effects on growing stocks carbon pool are positive in the first 4 decades and then negative in the long future. This is the joint results of changes in harvests, regrowth and tree growth. As noted earlier, the tax on biofuel and timber products reduces the forest land area, which indicates the decrease in rates of regrowth. Additionally, the tax delays the harvest to elder age classes and this is a further decrease in total rate of growths. In general, the tax reduces both the rate of harvest and the rate of growths and the total effects on growing stocks carbon are determined by the competition of the two pools. In the short term, the effect on harvest is stronger than that on the growth; in the longer term, the effect on growths is stronger.
The negative effect on harvest leads to negative effect on timber products carbon. The gaps between the two scenarios as the differences in harvests accumulate over time. Similarly, the effect on the harvest and logging slash mirrors the effects on harvest because the slash is byproducts of timber products. As expected, the effect on slash is also negative. For soil carbon, we assume there is no change unless there is land use change (Johnson and Curtis, 2010). The effect on soil carbon is negative initially as the forests are converted to agriculture land. However, the effect on soil is far smaller than the effects on the other carbon pools.

Figure 5 Forest carbon stock
An important advance of general equilibrium modeling is that the policy impacts can be captured outside the forest sector. We can investigate the general equilibrium effects on social carbon emissions which include not only carbon changes in the forest sector but also emissions from energy use such that any impact in the other sectors due to a policy shock in the forest sector can be captured. To show this, we plot the social net carbon emissions of US under all the scenarios in Table 3. The social net carbon emissions are calculated as the carbon emissions from combustion of fossil fuel and biofuel plus the forest carbon stock changes each period. The inclusion of carbon tax in the forest sector

\[\text{Figure 6 Effects of forest carbon tax on different forest carbon pools}\]

\[3\text{ The values displayed here are calculated as the level under Scenario 2 minus that under Scenario 1, so negative values means that there is less carbon stocks in the pool under Scenario 2, and positive values means that there is less.}\]
leads to a higher net emission level of US over all the projection periods (Table 3). In total, the carbon tax in the forest sector causes additional 950 million metric tons of carbon emissions from 2010 to 2060, which is equivalent to 10.2% of current annual net emissions. For exposition, we have not plotted the paths of the two scenarios because it is hard to visualize the differences relative to the scales of rising trend of total carbon emissions.

The comparison between Scenario 1 and 2 have several important implications. First, the impacts of the carbon tax differ among forest management activities. There are negative effects on land areas whereas the effects on harvest ages are positive i.e. the harvest ages are delayed to elder ages. And the percentages of changes are also very different. For example, percentage changes of forest area are much smaller than that of timber output as land change is generally price inelastic than timber output changes. Second, short term effects are different from long run effects. Land use changes and harvest adjustments happen mostly during the short run while carbon stock impact emerges from zero and gradually grow over time. This reflects the fact that forest area and harvest can respond to carbon policy instantly while the carbon stocks cannot because it takes time to accumulate carbon through growth as well as to release carbon from timber products and slash. Third, due to the complexity in the impacts on forest management, the effects among different carbon pools are also very different. Lower harvest rate leads to lower output but not necessarily more carbon stocks. Rather, the negative effects on harvest causes lower rate of carbon accumulation in timber products.
as well as in logging slash. Together with the lower rate of growth in general, the carbon tax in the forest sector leads to the opposite effects of what intended.

The social optimal policy

As noted in section 2, the social optimal carbon policy is to tax to carbon emissions in all sectors, and to subsidize carbon sequestration. Therefore, we construct Scenario 3 to show the effects of the social optimal policy. Again, the effects of Scenario 2 are labeled as lines with dot arrows through Fig. 2 to Fig. 5. As the inclusion of subsidy substantially raises the income from per hectare forests, total forest area expands about additional 60 million hectares by 2020 and maintains about this level throughout our projection. As expected, the subsidy with the land expansion has driven up the harvest of timber and biofuel; yet, the changes are dominated by the negative effects of the carbon tax to forest sector on outputs. As a result, under the tax and subsidy, the output of timber and biofuel is higher than Scenario 2 but lower than Scenario 1. A side effect is thus less emission from timber and biofuel use.

Fig. 5 shows the effects on forest carbon stocks. The positive effect on forestland and the negative effect on output lead to substantial increase in forest carbon stocks: the forest sector is projected to capture an additional of 38 billion tons \(CO_2\) by 2060, which is equivalent to 21% of the sum of current forest standing stock and soil carbon stock. Note that, the increase is accumulated gradually over time. Table 3 shows the effects on net carbon emissions of US, which are the emissions from energy use, including the use of fossil fuel and biofuel, minus the amount of carbon sequestration in the forest sector. The
total net emissions shift downward from the level under Scenario 1 by 342 million tons of CO$_2$ per year on average between 2010 and 2060.

<table>
<thead>
<tr>
<th>Year</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
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<tr>
<td>2010</td>
<td>9380.8</td>
<td>9.9</td>
<td>-333.5</td>
</tr>
<tr>
<td>2020</td>
<td>9633.8</td>
<td>23.4</td>
<td>-449.6</td>
</tr>
<tr>
<td>2030</td>
<td>10033.1</td>
<td>15.9</td>
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</tr>
<tr>
<td>2040</td>
<td>10562.7</td>
<td>1.0</td>
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</tr>
<tr>
<td>2050</td>
<td>11078.6</td>
<td>12.5</td>
<td>-344.5</td>
</tr>
<tr>
<td>2060</td>
<td>11588.2</td>
<td>33.0</td>
<td>-96.7</td>
</tr>
</tbody>
</table>

Table 3 Annual Net Emissions of US

**Conclusion**

This paper develops a dynamic general equilibrium model with a dynamic forest sector to examine carbon policies with wood-based bioenergy in US. Existing studies (e.g., Searchinger et al., 2009) suggest that an increase in the use of woody biomass for energy will result in a significant debt in the GHG accounting. These authors suggest that emissions from burning wood should be taxed. Unfortunately, these studies ignore both forest growth and the general equilibrium implications of their policy proposals. This study develops a dynamic general equilibrium analysis of the US economy with a dynamic forestry sector to illustrate how to efficiently provide incentives for climate mitigation in traditional energy, biomass energy, and the forestry sector. Forward looking behaviors are incorporated to all sectors and land uses to account for the dynamic adjustments in the forest sector.

The paper first presents a theoretical dynamic model to illustrate dynamically optimal carbon incentives across sectors. This model illustrates that the marginal cost of carbon
abatement in the energy sector should be set equal to the marginal cost of carbon abatement in the biomass energy sector, and both of these should be set equal to the marginal cost of carbon sequestration in forestry. All three of these, of course, should also be set equal to the marginal damages of an additional ton of carbon in the atmosphere. We then illustrate how these incentives should be implemented in the forestry sector which removes carbon from the atmosphere via forest growth and which emits carbon into the atmosphere via harvesting and potentially combustion in the energy sector. Specifically, we illustrate that the carbon tax and subsidy approach in van Kooten et al. (1995) is the appropriate way to implement this policy. The paper then develops a dynamic general equilibrium model with a dynamic forestry sector. We illustrate how to solve this model numerically using data for the United States.

Our policy analysis considers three alternative ways to implement climate policies: These are a carbon tax on both traditional energy and bioenergy, a carbon tax only on traditional energy (excluding a tax on bioenergy), and a carbon tax on both types of energy combined with a subsidy for forest growth. The first approach is that suggested by papers such as Searchinger et al. (2009), and the last approach is the dynamically optimal way to implement policy in this sector. The results illustrate that the largest net emissions occur in the scenario which taxes both types of energy but does not have a countervailing subsidy for forest growth. The smallest net emissions occur under the optimal scenario. The policy that treats bioenergy as carbon neutral (the carbon tax on only traditional energy) interestingly has lower net emissions than the policy that taxes both sectors equally.
These results illustrate the inefficiency in current policy suggestions for bioenergy. The suggestion of Searchinger et al. (2009) to simply tax the bioenergy sector without considering forest growth is actually worse for the environment than treating biofuels as carbon neutral and ignoring them. The reason for this is that the tax on forestry outputs provides disincentive to investment and the resulting reductions in investments lead to net carbon emissions. Searchinger et al. (2009) actually ignored investments by the forestry sector and the influence of policies on those investments.

The proper policy is to tax emission and subsidize growth. Of course, there are limitations to this policy as well, given that it would require an entirely new set of land use policies for the US. There has been significant discussion of these potential policies in recent years, and it’s not obvious that policy makers are ready to embrace this type of dramatic change across the entire country. Furthermore, the tax and subsidy policy has large distributional consequences. Taxes on emissions from the forest sector would tax current carbon stored in trees, which creates a large debit for existing forest landowners. Over the long-run these debits are re-paid via subsidies for forest growth, but the policy changes the value of land for existing landowners. An alternative suggested by Sohngen and Mendelsohn (2003) is a carbon rental subsidy combined with a payment for permanent storage in wood products. This approach is efficiently equivalent to the tax and subsidy, but has different distributional consequences which could be more attractive to existing forestland owners. Of course, if society decides not to implement a nationwide land use policy, the net best alternative is to treat forest based bioenergy as carbon neutral and leave it out of policy altogether.
Chapter 2: Efficiency of Forest Carbon Policies on the Intensive Margin and Extensive Margin

Introduction

Because trees absorb carbon dioxide while growing, using forests to sequester carbon is recognized as a potential option for mitigating greenhouse gas (GHG) effects. It is estimated that forests could be efficient in contributing as much as one-third of total global carbon abatement (Sohngen and Mendelsohn 2003). With forests, many countries can meet relatively stringent emission targets at lower costs by storing additional carbon in forests. Beyond their use as an efficient component of global climate policy, forests play an important role in the emerging regional and voluntary markets that have cropped up in the absence of an international regime for climate change. Many of these markets offer a possibility to finance forest carbon credits, most recently from reducing emissions from deforestation and forest degradation.

Although the economic potential of forest sequestration is widely acknowledged (Stavins and Jaffe, 1999; Plantinga et al., 1999; Sohngen and Mendelsohn, 2003; Richards and Stokes, 2004), there is no consensus on how to accomplish forest carbon sequestration. Different studies recommend different schemes that have varying levels of efficiency. Sohngen and Mendelsohn (2003) propose a carbon rental system with a payment for carbon permanently stored in wood products. Van kooten et al. (1995)
suggest a carbon subsidy for growth and tax for net emissions at harvest time. Both
approaches focus explicitly on measuring the carbon that is sequestered or emitted,
whereas there are other approaches being proposed which deviate from accurate
measurements of carbon to different extents. Searchinger et al. (2009) , for example,
consider a form of carbon tax to deter land use change and GHG emissions due to
expansion of wood-based biofuel production. Similarly, other approaches recommend a
variety of subsidy schemes based on various discounting factors in order to account for
problems like permanence, additionality , and leakage (see Dutschke 2001, 2002;
Colombia Ministry of the Environment 2000; Blanco and Forner 2000; Chomitz 2000;
and Kim et al 2008). Some approaches do not consider the level of carbon stored in
forests (Stavins and Jaffe, 1999; Plantinga et al., 1999). These approaches provide a
payment for land use change and vary the payment based on land opportunity costs.
Although these approaches can sequester carbon, they are unlikely to be efficient.

The literature in environmental regulation has long established that the way to
achieve efficient levels of pollution involves charging per unit of pollution based on
damages caused by that unit (Helfand et al 2003). By the same logic, the efficient carbon
policies are those paying forest owners per ton of carbon sequestered, which are the
carbon rental (C Rental) approach in Sohngen and Mendelsohn (2003) and the carbon tax
and subsidy (C Tax & Subsidy) approach in van Kooten et al. (1995). Any proposal that
incorporates forests into carbon markets using alternative methods will be more costly,
and it is important to understand the resulting cost differences due to policy choice. This
paper develops a framework to compare and measure the differences in efficiency of
alternative forest carbon policies, taking into account forest management practices and market effects in a dynamic context.

Carbon sequestration can be achieved through either increasing forestland (the extensive margin) or increasing carbon stocks on per unit of land (the intensive margin) by changing management practices including changing harvest ages, thinning, and fertilization, among other practices. The impacts of changes at extensive and intensive margins are not mutually exclusive. Instead, forestland owners react to carbon policies at both margins simultaneously and the reaction at each margin could be different across the policies. Because these reactions all lead to changes in carbon consequences, it is important to consider effects on both margins when valuing the efficiencies of carbon polices. Few studies examining policy options comprehensively account for different management practices. Parks and Hardie (1995) compare the effectiveness of programs based on per-ton of carbon and per-acre of land for converting marginal agriculture lands into forests; but they ignore the role of management. Antle et al (2003) show that ‘per ton’ carbon policies are less costly than ‘per hectare’ carbon policies, particularly in the presence of heterogeneous croplands. We extend the approach suggested by Antle et al. (2003) and examine differences in costs among per ton and per hectare policies with a stock resource that is managed dynamically. For example, we focus on forests, where the decision over the age of harvesting the trees has important implications for carbon storage, and we model harvest age as a continuous choice which can vary among tree classes and over time. In this way, we can better capture adjustments on the intensive margin of forest management in response to carbon policies.
Another contribution of this study is that we include policy-induced market effects. The market effects are derived from the systematic changes of in aggregate timber supply at the aggregate level due to carbon policies. Though forests can produce timber and carbon services on the same site, providing additional carbon sequestration will not necessarily lower the level of timber supply per acre. On one hand, at the extensive margin, forestland could either expand or contract, depending on the carbon policies; and on the other, at the intensive margin, even if there is no land use change, increasing carbon stocks in existing forests could lead to higher or lower timber supply, depending on the age of forests (Sohngen 2007). These market effects will indirectly affect timber price and thus the efficiency of policies. If, as many authors assume (e.g. van Kooten, 1995), timber prices are held constant and carbon benefits/debits have no effects on timber market, the net losses or gains in timber markets are not reflected.

This study also provides an application of dynamic models into the design of policies in forestry. Forest management is a long term behavior in which the current stocks and decisions not only rely on but also have consequences to future timber prices and carbon polices. The literature in policy design for environment regulations suggests that the intertemporal nature of environmental and resource externalities affect the choice of optimal policy (See Farzin 1996, Benchekroun and Van Long 1998, Chakravorty et al 2006). Furthermore, a number of studies focusing on optimal policy design have taken into account the stock effects of various pollutants or renewable resources in a dynamic context. Issues examined include nonpoint-source pollution (for example see Xepapadeas 1992), carbon dioxide emissions (Farzin and Tahvone 1996, Jaffe and Stavins 1995),
nonrenewable resources (Rubio and Escriche 2001, Strand 2010) and fishing regulations (Hansen et al 2008). Though the methods of dynamic modeling in forestry have been established (Lyon and Sedjo 1998; Sohngen and Mendelsohn, 1998), policy studies in forestry, including carbon policies, however, are either static (Parks and Hardie 1995) or steady state analysis (van Kooten 1995, Koskela, and Ollikainen 2001, Kim et al 2008). This study demonstrates a dynamic framework examining policy instruments in the forest sector.

Our results demonstrates the importance of focusing on dynamic adjustments at management (i.e the intensive margins) for designing sequestration policies. First, we find that a ‘per hectare’ policy could be 5 to 10 time more costly than a ‘per ton’ policy depending on the carbon prices and land use conditions because ‘per hectare’ policy could not effectively create incentive to sequester more carbon at the intensive margin. Second, a particular concern is raised with respect to the policy which taxes on emissions from the forests without subsiding sequestration because we find it leads to net carbon emissions on per unit of lands in addition to contraction of forestland area.

The simulation part develops a dynamic model of timber markets. A timber market is modeled specifically to capture the market derived effects of different policies, both in the short run and in the long term. We focus on choices of harvest ages and land use, which are two major land owners’ decisions affecting the carbon stocks at the intensive margin and extensive margin separately. Five policy instruments are examined: a subsidy to carbon sequestration, a tax to carbon emissions, Carbon Tax & Subsidy, C Rental and a ‘per hectare’ forestland subsidy. We compute the carbon supply and costs under these
policies in a one region, multi age class context for regularly managed southern pine. Particularly, we highlight the aggregate effects on forest carbon stocks due to extensive and intensive margin adjustment. The reasons we focus on southern pine are: these forests play an important role in storing carbon, greater than other regions of US; a significant amount of similar forests are found in developed countries where economic incentives can be implemented.

The numerical model

In this section, we present an optimal control timber markets model, initially developed in Sohngen and Sedjo 1998. Timber prices are endogenously determined by the supply and an exogenous demand function. As we model the full dynamic adjustment to the policy in harvests and replants for every age classes, the optimal control model captures the intertemporal effects both in the near term and long run.

The objective of this model posits that a social planner attempts to maximize the net present value of net surplus in timber markets. We introduce carbon market to the model. As a result, the net surplus is defined as the area between a timber demand curve and the cost of land rent plus the carbon benefit. Modifying Sohngen and Sedjo 1998, the social planner’s problem is thus

\[
\max_{H(t),G(t)} \int_0^\infty e^{-rt} \left\{ \int_0^{Q(t)} D \left( Q(H(t), V(a)) \right) dQ - bG(t) - R(t)X(t) \right\} + f_c \left( H(t), X(t) \right)
\]
\[ \bar{X} = -H(t) + G(t) \]  

\( H(t) > 0; G(t) > 0; X(0) \text{ is given} \)

\( D(\cdot) \) is a downward sloping demand function given the stumpage quantity per period. \( Q(\cdot) \) is the total quantity harvested generated by the demand function. \( H(t) \) represents a vector of \( h(a,t) \), hectares harvested at each age \( a \); and \( V(a) \) is the timber yield function, where \( a \) is the age of timber harvested. \( G(t) \) is the replant hectares and \( bG(t) \) represents the regeneration cost where \( b \) is a constant. \( X(t) \) is a vector of \( x(a,t) \), the forest land hectares at each age \( a \). \( R(t) \) represents land rent or the opportunity cost of maintaining land as forest rather than allowing it for alternatives uses. \( R(t) \) increases with \( X(t) \) at an increasing rate. \( f_c(\cdot) \) represents the carbon benefit associated with carbon sequestration, where \( c \) represents carbon. \( r \) is the interest rate which should reflect the risk with carbon uptake service (e.g., fire risk, slower than expected tree growth, etc). The state variable here is \( t \). The choice variables are \( H(t) \) and \( G(t) \). The state variable will vary over time according to Eq 32 where \( \bar{X} \) is the vector of changes in forest stocks between current period and the next period. Different from the traditional timber models where the size of land is fixed, Eq 32 allows for the flexibility in replanted hectares. So there is the

\[ ^4 \text{all the variables represent the marginal change between the current period and the next period} \]
possibility that some harvested land may not be replanted, and also the possibility that additional land will be transformed into forest.

*Intertemporal analysis*

The baseline case for this study is the amount of net carbon offsets in the forest when carbon policy is absent. The policy scenarios examined in this part are shown in Table 4. The Carbon Subsidy scenario only subsidizes carbon updates by measuring growths, while the Carbon Tax scenario only taxes on emissions upon harvests and burning wood for energy. The Land Subsidy scenario gives a subsidy to each unit of forested land at a rate equaling to the carbon offsets value per unit of land in the baseline case. Besides the three instruments, there are two more scenarios: Carbon Tax & Subsidy system and Carbon rental system. The two systems, unlike the other three choices, create carbon incentives by explicitly measuring the carbon that is sequestered or emitted. The Carbon Tax & Subsidy system, proposed by van Kooten et al 1995, is combination of the carbon tax policy and the carbon subsidy policy. Carbon sequestered each year through forest growth is paid the current carbon price while carbon emissions are taxed at the current carbon price upon harvest. The Carbon Rental system (Sohngen and Mendelsohn, 2003) propose another approach to solve the impermanence of forest service by treating the carbon service as temporary. Under the carbon rental system, forest owners are compensated by annual rents for providing annual carbon storage services; at harvest, landowners are paid the carbon price for carbon stored permanently in wood products.
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Descriptions</th>
<th>( p_c \delta ) ( X(a) \cdot V(a) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1 Carbon Subsidy (Subsidy)</td>
<td>Carbon uptakes are subsided at the current carbon price. No tax on emissions.</td>
<td>-( p_c \delta (1 - \sigma)Q(H(t),V(a)) )</td>
</tr>
<tr>
<td>Scenario 2 Carbon Tax (Tax)</td>
<td>Per unit tax on on carbon emissions released upon harvest but no carbon subsidy.</td>
<td>( p_c \delta ) ( X(a) \cdot V(a) )</td>
</tr>
<tr>
<td>Scenario 3 Carbon Tax&amp;Subsidy (Tax&amp;Subsidy)</td>
<td>Carbon emissions are taxed upon harvest and carbon uptakes are subsided at the current carbon price.</td>
<td>-( p_c \delta (1 - \sigma)Q(H(t),V(a)) )</td>
</tr>
<tr>
<td>Scenario 4 Carbon Rental (C Rental)</td>
<td>Annual rents are given for providing annual carbon storage services; also, landowners are paid at the carbon price for carbon stored permanently in wood products.</td>
<td>( r_c \delta ) ( X(t) \cdot V(a) ) +( p_c \delta \sigma Q(H(t),V(a)) )</td>
</tr>
<tr>
<td>Scenario 5 Land Subsidy(Land)</td>
<td>The carbon payments are given by the total forest area.</td>
<td>( l \sum_a x(t, a) )</td>
</tr>
</tbody>
</table>

Table 4 Descriptions of Scenarios

\(^5 p_c^c\) is the social cost of per unit of additional carbon emissions i.e the current carbon price.
\(^6 \dot{V}(a)\) is the growth rate per ha for age class \( a \).
\(^7 \delta\) is the carbon conversion rate for wood products.
\(^8 \sigma\) is the proportion of permanently stored carbon in wood products.
\(^9 r_c^c = p_c^c \left( r - \frac{dp_c^c}{dt} \right)\).
\(^{10} l\) is the subsidy rate per hectare. \( x(a, t)\) is the forest area for age class \( a \).
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield function</td>
<td>( \ln(V(a)) = 7.82 - 52.9/a )</td>
<td>Sohngen and Sedjo, 1998</td>
</tr>
<tr>
<td>Pickling rate</td>
<td>0.35</td>
<td>Daigneault et al. 2010</td>
</tr>
<tr>
<td>Carbon price</td>
<td>The optimal carbon tax scenario</td>
<td>DICE-2010 Model</td>
</tr>
<tr>
<td>Interest rate</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Carbon conversion rate</td>
<td>0.20 tC/m³</td>
<td>eg. van Kooten et al 1995</td>
</tr>
<tr>
<td>Price elasticity for wood products</td>
<td>-0.5</td>
<td>Simangunsong and Buongiorno 2001</td>
</tr>
<tr>
<td>Land supply elasticity</td>
<td>0.33</td>
<td>Lubowski et al., 2006</td>
</tr>
</tbody>
</table>

Table 5 Key Parameters and Sources
A detailed description of the parameters and initial conditions of this analysis are given in Table 5. The initial forest stocks are calibrated for an evenly distributed multi-age class forest land. The forest is homogeneous with a yield function applied to each hectare (ha). The amount of carbon captured is a fixed percentage of the forest volumes. It is assumed that a fixed percentage of carbon (pickling rate) in the wood harvest is stored in the wood permanently. The carbon prices here are estimated from the optimal carbon tax scenario of DICE-2010 Model (Nordhaus 2010), which represent the social optimal marginal cost of an additional ton of CO₂ emissions to the atmosphere. The increase path of carbon price is displayed in Fig. 8. The projection uses the carbon price in 2010 as the starting level and the price rises to as high as $700 per ton C until 2110. The discount rate is assumed to be 0.95, implying a real interest rate of 5%. The carbon conversion rate applied here is 0.20 tC/m³ for standing volume and for harvested wood as well.
The social planner faces a calibrated constant elasticity timber demand function which remains unchanged over time. Forest area is adjusted via harvests and regenerations according to a constant elasticity increasing land supply function, so land will be more expensive to rent if new land is introduced to forest production. The prices, inventories and harvests in the baseline all start from a steady state where they are stable over the projection. The forestland stays in 9.84 million hectares with 28 even distributed age class. The optimal harvest age in the baseline is thus chosen as 28 and the replant area equals to the harvest area. The equilibrium timber price stabilizes at $58/m^3 over time. We use the baseline as reference and compare the effects of each policy scenarios over the baseline results. The equilibrium results for various policy scenarios are shown from Fig. 9 to Fig. 14, with each scenario labeled differently.
i. Scenario 1: Carbon Subsidy

In this scenario, we assume that a subsidy is given to per unit of carbon sequestration according the growths of forest inventories at the carbon prices. No tax is imposed on harvests. The subsidy has positive effects on harvest ages. The harvest ages are initially 28. As the carbon price increases over time, the average harvest ages gradually rise to 40 till 2055 and continue rising to higher levels as the farmers foresee the carbon policy and the coming carbon price path.

Figure 8 Paths of Average Harvest Age

Fig. 10 shows the schedules for forest areas. The forest area enlarges gradually over time. The changes in forest inventories lead to changes in outputs, prices and carbon services. The effects on outputs are also positive. As the timber resources become less scarce, the paths of timber prices are thereby lower. The effects on outputs are results of two factors: (1) the average outputs on per hectare of forests decreases as the harvest ages
moves beyond the maximum mean annual increment ages (Buongiorno and Gilless, 2003); (2) the total area of forests increases. The latter dominates the former so we observe the total outputs are higher than that in the Baseline case.

Figure 9 Path of Forest Area

Our principle interest is how the carbon policies affect the carbon contents in the forest sector. Fig. 13 shows the schedules of effects on carbon offsets. The carbon gains are calculated as the differences in net carbon sequestration every year between each scenario and the Baseline. The net carbon sequestration captures the carbon uptakes due to growths as well as the carbon emissions due to harvests. The carbon subsidy has positive effects on net carbon sequestrations. The effects enlarge as the carbon price rises over time. Similarly, the effects on carbon stocks are results of two factors: (1) the average carbon gains on per hectare of forests increases (Fig. 14) as the harvest ages become older (2) the total area of forests increases. In sum, both factors lead to positive
carbon gains.

Figure 10 Paths of Timber Prices

ii. Scenario 2: Carbon Tax

Here, only a carbon tax is imposed on per unit of carbon emissions upon harvest. No subsidy is given to sequestration at all. We first focus on the effects on harvest ages. The schedule of average harvest age for each year is all below that in the baseline case. This is surprising at first glance because in a Faustmann model, a harvest tax is expected to delay the harvest age (Koskelaa and Ollikainenb, 2001). Note that the Faustmann model is based on the assumption of fixed timber price and the inclusion of carbon prices is essentially equivalent to a decrease in timber price. Here we assume the timber price is determined by the timber market. The inclusion of the carbon tax shifts up the supply curve of wood products because it increases the cost of production. So the equilibrium timber price is higher than the baseline case (Fig. 11). Accordingly, the higher timber prices push the harvest ages downward.
The effects on forest area are as expected. Total forest area shrinks further and further as the carbon price rises (Fig. 10). In other words, more trees are harvested than replanted every year. The changes in harvests and replants bring in changes in inventories as well as carbon services. Beyond the decrease in total forest area, less carbon is being sequestered on each unit of land on average (Fig. 14). In general, the Carbon Tax scenario leads to more net carbon emissions than the baseline case.
The rationale to promote a carbon tax here is to reduce net carbon emissions from the forest sector by creating disincentive on emissions associated with harvests or other uses of wood (Searchinger et al 2009). However, the taxes also reduces the rate of carbon sequestration by two means: (1) the tax drives more forest land into alternative uses, which reduces forest inventories as a whole; (2) the market induced effects on timber price push down harvest age thereby result in negative effects on carbon sequestration on the intensive margin. As a result, the total rate of net carbon sequestration decreases because of the tax.

Figure 12 Path of Total Carbon offsets
iii. Scenario 3: Tax & Subsidy and Scenario 4: C Rental

Both these two scenarios pay for carbon sequestrations by explicitly tracking the carbon flows in and out of forests. The differences between them are only in their accounting methods: the Tax & Subsidy scenario directly trade carbon credits while the Carbon Rental scenario rent the emission credits. As a result, though the actual payments would be different, the two scenarios should create the same marginal incentives in managing forests and sequestrating carbon. The simulation results turn out to be consistent. The two scenarios have identical effects on all management practices. As expected, the carbon subsidy has positive effects on both harvest ages and forest area (Fig. 9 and 10). Yet, their harvest age effects are larger than that of the Carbon Subsidy scenario while the forest area effects are smaller. This is not unreasonable because from Error! Reference source not found., we know that, without considering the timber market effect, a carbon tax delays harvest age and squeezes forest area. So combining the carbon tax with subsidy should strengthen the harvest age effects and weaken the forest area effects.
Figure 13 Path of per ha Carbon Offsets

In general, their trend in the carbon offset effects is similar with the Carbon Subsidy scenario. As expected, more carbon is sequestered than in the Baseline (Fig. 13) and the effects enlarge over time. Yet, we observe that their effects on carbon gains are smaller than the Carbon Subsidy scenario before 2031, but larger from 2031 to the end of the simulation, with the differences continuing expanding. We know from above that Tax & Subsidy and Carbon Rental policy, compared with the Carbon Subsidy one, has stronger impacts on the intensive margin but smaller impacts on the extensive margin. Because land adjustments are usually accomplished faster than the carbon accumulation on the site, the impacts on extensive margin dominate in the near term while in the longer term, the impacts on the intensive margin dominate the other. Consequently, compared with the Carbon Subsidy scenario, these two scenarios sequester less carbon in the near term and more carbon the longer term.
iv. Scenario 5: Land Subsidy

Different from the scenarios examined above, this scenario compensates carbon sequestration by the area of forest regardless of the management with the stands. The rate of subsidy equals to the current average value of carbon sequestration on per hectare of forests in the baseline case. The rationale is to boost carbon sequestration by introducing more land into forests or avoiding deforestation. The advantage of this approach is its low measurement costs. The most important effects here on management practices are the positive effects on forest area (Fig 4). The total forest area enlarges over time. How about the effects on harvest ages? Results from Faustmann model states that a lump-sum transfers by forestland (e.g a lump-sum tax illustrated by Koskelaa and Ollikainenb 2010) have no incentive on the harvest ages as it does not create any incentive to management on the stands. Yet, we find here that the per hectare policy causes changes on the average harvest age in the short term, although the changes are minor (the harvest age reduces by about 1 year). The short run changes can be explained by inventory adjustments (Fig. 9) and they are much smaller compared with the scales of effects under other scenarios. In general, the land subsidy does not create significant effects on harvest ages.

The carbon effects are positive and significant. Again, the effects are increasing over time. However, the carbon gains from land subsidy are much smaller than the Tax & Subsidy and the Carbon Rental scenario. The carbon gains are less than 10% of the level under the Tax & Subsidy Scenario and around 15% of the level under the Carbon Subsidy scenario. The gaps cannot be fully explained by their land expansion schedules.
as the rates of land expansion of the other scenarios are only around twice of that of the Land Subsidy one. This indicates that most of the differences in total carbon offsets stem from their variances on the intensive margins. We know that Land Subsidy has little economic incentives on the intensive margins, thereby it losses the large potential to promote carbon sequestration by changing management practices compared with those ‘per ton’ policies. As a result, the effectiveness of land subsidy is largely diminished. We will further demonstrate the efficiency losses from land subsidy by comparing different marginal cost curves.

*The cost of carbon sequestration*

We now apply the same numerical analysis framework above to an analysis of the costs of carbon sequestration. Here, we compare the marginal cost curves among different policies. The marginal cost for per ton carbon sequestered for each type of policy is presented in Fig. 15. For each policy, we run the multi-simulations by varying the carbon prices. We first compute an implicit cost which equals the social welfare losses of the timber sector at each simulation. The implicit cost is then matched with its levels of carbon gains given the carbon prices. Finally, the marginal cost per ton is found by linking each increment of the implicit costs with the additional carbon sequestration this specific increment triggers.
First of all, the Carbon Tax scenario has its plotted marginal costs and coordinated carbon supplies negative while all the other scenarios have both values to be positive. The negative marginal costs of carbon sequestration can be interpreted as positive marginal costs of carbon emissions. From the numerical analysis above, we know that the per ton carbon tax creates net carbon emissions instead of sequestrations. Beyond that, it also reduces the social welfare as it brings distortion to the timber market. Specifically, the bigger the carbon loss is, the bigger the social welfare losses are with the forest sector. So the society, if relying on taxing on emissions from harvests, pays extra costs of social welfare for the additional emissions from the forest sector.
Figure 15 Marginal Cost Curves-Deforestation

For the other scenarios which create positive carbon offsets, the lowest marginal cost occurs with the Tax & Subsidy and the Carbon Rental policy. As noted earlier, these two policies are the only policies which pay by explicitly measuring carbon flows, so they are the most efficient policies in promoting carbon sequestration here. The Carbon Subsidy policy provides a relative inefficiency, with a marginal cost curve next higher to the two optimal policies. The marginal cost of the Land Subsidy policy is substantially higher than both the two optimal ones and the carbon subsidy one. In addition, the cost curve rises much faster and gradually diverges with the other three curves as the carbon quantity increases. For the Land Subsidy scenario, for example, at $112/MtC (equivalent to $30/ Mt CO₂), its carbon supply equals to 10.1% of that under the Tax&Subsidy policy.
scenario and 14.1% under the Carbon Subsidy scenario; at $224/MtC (equivalent to $60/ Mt CO₂), its carbon supply equals to only 6.3% of that under the Tax & Subsidy scenario and 9.1% under the Carbon Subsidy scenario.

Figure 16 Marginal Cost Curves - Inelastic land supply

One concern with the result is its initial state of land uses. So far we have assumed an afforestation situation where the total size of forestland is stable without carbon polices and could potentially increase as much as possible if there is a carbon incentive. For robustness, we examine the costs of carbon sequestration under two other land use situations. Fig. 16 presents the results under a deforestation situation where the forest area decreases in absent of carbon policies. This mimics the cases where forests are currently being converted to agriculture or other land uses due to high opportunity costs.
of forestland. Fig. 17 shows the results of the case where we increase the elasticity of land supply to reflect a high land competition case. The results are consistent with the previous findings. In both cases, the marginal cost curve of the Land Subsidy is higher than that of Tax & Subsidy and diverges at high carbon quantity. The cost curve of Carbon Subsidy locates between Tax & Subsidy and the Land Subsidy while it almost overlaps with the curve of Tax & Subsidy in the case of land boundary. In general, the results here reflect that the ‘per hectare’ policy (Land Subsidy) bears significant efficiency losses compared with the ‘per ton’ policies (Tax & Subsidy, Carbon Rental and Carbon Subsidy) at every level of payments. More importantly, the efficiency losses drastically increase with carbon quantities, with a marginal cost as high as 4.1 of that of the ‘per ton’ policies for carbon supply of 1 million MtC to 14.6 times for carbon supply of 5 million MtC.

Now we compare our results with Antle et. al. (2003). They also find that the ‘per ton’ policy is more efficient than the ‘per hectare’ policy but the two marginal cost curves there converge at high carbon quantity. This controversy can be resolved by comparing their reasons causing the efficiency differences with the reasons here. The efficiency differences in Antle et. al. (2003) are explained by spatial heterogeneity, so the differences would diminish at the point where all land participates in the carbon programs. However, the differences found here are caused by the failure of ‘per hectare’ policy to create carbon on the intensive margin. Thus, the inefficiency exists regardless of their effects on the extensive margins. Even if the same forests are enrolled, as in the case with a land boundary, the effects on the harvest ages are still dramatically different
between the two types of policy. Therefore, the findings here complement Antle et. al. (2003) in two aspects: First, the findings indicate that the policy makers or carbon contracting parties could potentially bear a significant measurement costs for the ‘per ton’ policy if there is possibility of multi-choice or multi-dimension management practices relevant to carbon sequestration. Second, the efficiency gains from ‘per ton’ policies are especially large at high carbon prices or for large scale programs.

Conclusion

The purpose of this study is to evaluate the effects of different policy instruments to promote carbon sequestrations on both intensive and extensive margins, taking into consider the policy induced market effects and intertemporal changes. The analysis considers five policy options by employing an optimal control model of timber market. We investigate the dynamics of the policy effects on forest inventory, timber market and carbon consequences for five policy options. There are a ‘per ton’ carbon tax, a ‘per ton’ carbon subsidy, a ‘per hectare’ land subsidy and two optimal policies which pays by explicitly measuring carbon in and out of forests: the Carbon Tax & Subsidy policy and the Carbon Rental policy. We find that under the same carbon price path, the two optimal policies lead to the biggest carbon sequestration of all the scenarios. Particularly, the Carbon Tax scenario here causes carbon losses at both intensive and extensive margins after considering the market effects.

We then apply the same intertemporal model to compare the marginal costs of sequestration of the five policies under different land use situations. The findings under all land use situations confirm that the most efficient systems are the two optimal
policies: the Carbon Tax & Subsidy policy and the Carbon Rental policy. The next efficient policy choice is the Carbon Subsidy, which slightly deviate from the optimal policies. The ‘per hectare’ Land Subsidy is substantially less efficient than the other three ‘per ton’ policies and the efficiency losses are especially significant at high carbon quantities. The results indicate its marginal cost ranges from 4 to more than 10 times of that for the Carbon & Tax policy. The least efficient carbon policy is the Carbon Tax policy because it leads to simultaneous losses in social welfare and forest carbon.

The study provides practical implications for carbon policy designs with the land use sectors. First, the results show that the government can achieve more carbon sequestration efficiency on both the intensive margin and the extensive margin. While the potential on the extensive margin are constricted to the regional land conditions, the potentials on the intensive margin are substantial and should not be ignored. Second, it is worthwhile to implement a ‘per ton’ policy instead of a ‘per hectare’ policy as long as the administration costs do not exceed the efficiency losses. A ‘per ton’ carbon subsidy policy may be an appropriate choice if taking into consideration of the measurement because it provides the close approximation in efficiency to the optimal policies and it avoids a measurement costs on actual emissions from harvest. Third, when designing climate policies, a recommended policy choice is to treat land use sector differently from the other emission sectors. While it is correct to directly tax on carbon emissions from energy uses, taxing on emissions from the forest sector without compensating sequestration leads to inefficiency outcomes because the carbon tax reduces the rate of
carbon sequestration as well. We’ve shown this in the first chapter with respect to the US federal regulation on wood biofuel emissions (Tian, Sohngen and Sands, 2013).
Chapter 3: Outsourcing Timber: The Role of Emerging Region Timber Plantations on Southern US Production

*Introduction*

One of the most important trends in timber markets in the past several decades has been the growth in output from the so-called “emerging” region. Countries in this emerging region include Brazil, Uruguay, Argentina, and Chile in South America, South Africa, New Zealand, and Australia, among other countries. Since the 1960s, timber output in these regions has risen far faster than output in traditional timber producing regions like the United States and Europe (United Nations Food and Agricultural Organization, 2009). To a large extent the increase in production in these regions has resulted from increases in the area of fast-growing timber plantations. These fast-growing plantations may produce 3-10 times as much timber on an annual average basis as natural forests in temperate regions, and thus provide a large, sustainable, supply of timber.

The increase in timber production from some of these emerging regions in recent years has been rather astounding (United Nations Food and Agricultural Organization, 2010). While global industrial wood output has increased 1.0% per year since 1960 (Table 6), output in South America, China, and Southeast Asia has increased at least 2.0% per year. Output in Oceania, which includes New Zealand and Australia, has
increased 2.5% per year since 1965. Meanwhile, traditional timber producing regions, like the US and Europe, have seen only modest growth in output, near the world average.

Within traditional timber producing regions, there is growing concern that competition from this emerging region, with its fast-growing timber plantations, could have important implications for existing wood markets. Real prices for wood products, according to the United Nations Food and Agricultural Organization (2010), in fact, have largely stabilized since 1980, suggesting that globally, timber supply is at least keeping up with demand. These stabilizing prices could have strong implications for the timber market and for regions with large investments in timber output.

This paper examines the implications of wood production in the emerging region on timber output in the United States, and specifically on timber output in the Southern US. For the analysis, the global timber model described in Sohngen et al. (1999), Sohngen and Sedjo (2006) and Daigneault et al. (2008) is used. The model is a dynamic optimization model that maximizes the present value of timber production in all modeled regions. The model is described more fully in Appendix C.

To conduct the analysis, the existing model is updated with new information on yields from emerging region plantations and detailed representation of the Southern US. A recent study undertaken by Cubbage et al. (2010) provides a thorough review and analysis of current productivity information in a number of important plantation species worldwide. This paper utilizes this data to update current estimates of yields for these regions and to update our assumptions about technological change in timber plantations. For the Southern US, we use the data base of the Subregional Timber Supply (SRTS)
Model. For the purpose of this analysis, the Southern US is represented by 117 different management types. Then, several scenarios are run with the global model, and the results and implications of these scenarios for global and US timber markets are examined. The specific scenarios considered are our baseline, a high technology change scenario, a high demand scenario, and a scenario that assumes faster-paced technological change outside the US than inside the US.

The next section of the paper presents general information on global trends in timber markets, including a discussion about trends in timber plantations. The following section then describes the analysis conducted with the global timber market model and the results of that analysis. The final section is the conclusion.

Global trends in plantations

World-wide, industrial wood production has increased at a pace of about 1% per year since the 1960s. The US and Europe continue to be the largest timber producers (Figure 18) with each region, producing around 400 million cubic meters (m$^3$) of industrial wood per year. Canada, Russia, and South America each produce about half as much each, or around 200 million m$^3$ per year, although output has been increasing substantially in recent years in South America (Table 6). Oceania produces just less than 200 million (m$^3$) per year but output there has been rising rapidly as well. Output in China increased through the 1990s.
Figure 17: Historical output in major timber producing regions, 1961-2008

<table>
<thead>
<tr>
<th>Region</th>
<th>Rate of Growth in Output 1965-2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>1.0%</td>
</tr>
<tr>
<td>South America</td>
<td>4.4%</td>
</tr>
<tr>
<td>Oceania</td>
<td>2.5%</td>
</tr>
<tr>
<td>China</td>
<td>2.4%</td>
</tr>
<tr>
<td>SE Asia</td>
<td>2.0%</td>
</tr>
<tr>
<td>Canada</td>
<td>1.6%</td>
</tr>
<tr>
<td>Europe</td>
<td>1.0%</td>
</tr>
<tr>
<td>US</td>
<td>0.9%</td>
</tr>
<tr>
<td>Rest of World</td>
<td>0.5%</td>
</tr>
<tr>
<td>Former Soviet Union</td>
<td>-1.1%</td>
</tr>
</tbody>
</table>

Table 6 Rate of growth in Industrial wood output by major timber producing region

A large share of the increase in output arises from timber harvested from industrial wood plantations. Industrial wood plantations are highly productive forestlands managed with fairly short-rotation species (10-45 years) that are devoted almost entirely to produce
sawtimber or pulpwood for traditional wood product uses. Around 30% of these plantations lie in developing countries, and they have become an increasingly important component of the world timber supply over time (Cubbage et al. 2010). Daigneault et al. (2008) found that these plantations supply around 13% of industrial wood currently, but that plantations could expand to 50% of total industrial wood supply by 2050.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US/Canada</td>
<td>11.0</td>
<td>10.3</td>
<td>17.1</td>
<td>18.8</td>
</tr>
<tr>
<td>Europe/Russia</td>
<td>30.0</td>
<td>22.5</td>
<td>27.6</td>
<td>25.8</td>
</tr>
<tr>
<td>Other</td>
<td>30.0</td>
<td>29.5</td>
<td>43.2</td>
<td>21.7</td>
</tr>
<tr>
<td>Total Developed</td>
<td>71.0</td>
<td>62.4</td>
<td>87.9</td>
<td>66.4</td>
</tr>
<tr>
<td>Subtropical/Tropical</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Oceania</td>
<td>0.0</td>
<td>2.4</td>
<td>3.9</td>
<td>2.8</td>
</tr>
<tr>
<td>South/Central America</td>
<td>3.0</td>
<td>8.3</td>
<td>12.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Africa</td>
<td>2.0</td>
<td>12.1</td>
<td>13.2</td>
<td>3.7</td>
</tr>
<tr>
<td>SE Asia</td>
<td>0.0</td>
<td>10.8</td>
<td>13.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Total Subtropical/Tropical</td>
<td>5.0</td>
<td>33.6</td>
<td>43.1</td>
<td>18.9</td>
</tr>
<tr>
<td>Other</td>
<td>2.0</td>
<td>6.3</td>
<td>8.3</td>
<td>4.9</td>
</tr>
<tr>
<td>Total</td>
<td>78.0</td>
<td>102.2</td>
<td>139.3</td>
<td>90.2</td>
</tr>
</tbody>
</table>

Table 7 Area of industrial wood plantations over time

The United Nations Food and Agriculture Organization (FAO) estimates that there could be as many as 140 million hectares of these fast-growing timber plantations globally, with around 43 million hectares in subtropical regions (Table 7). The area has been increasing by about 2 million hectares per year since the 1970s, using the estimates by Sedjo (1983) as the starting point. The estimate of plantations used by FAO, however, likely includes a large number of plantations that are also used for fuelwood or other
purposes. A 1999 study by the Australian Bureau of Agricultural and Resource Economics and the consulting group Jaako-Poyry found that the area of subtropical wood plantations was only about half that of the FAO estimate for the late 1990s/early 2000s (ABARE/Jaako-Poyry, 1999; see Table 7). In particular, the estimates for Africa and Southeast Asia seem are substantially lower in the ABARE/Jaako-Poyry (1999) report than in the FAO data suggests.

Estimates of timber production from emerging region industrial wood plantations are also promising. A recent review of data on plantations by Cubbage et al. (2010) suggests that yields range from 6 to over 30 m³ per hectare per year across the world (Table 8). Using their estimates, and the area estimates presented in Table 8, potential output from industrial wood plantations can be calculated. The results suggest that industrial wood plantations could produce up to 1.1 billion m³ of industrial roundwood per year, or over two thirds of the current global output. The estimate in Table 8 is an over-estimate of the output from industrial wood plantations, likely due to an over-estimate of the area of plantations actually used for industrial wood output, or an over-estimate of the average yield. The calculation, however, illustrates the point that if the world becomes truly serious about producing its industrial wood on less land, or on plantations alone, it appears perfectly plausible to produce more timber on a lot less land.

There has been substantial investment in the quality of the plantations over the years. Sedjo (2001) suggests that traditional breeding programs could achieve a 21% increase in yield in each generation of trees. Assuming 20 year rotations, this implies that traditional breeding programs can provide yield increases of about 1% per year. This estimate does
not account for gains that might arise from other types of improvements in management, such as the introduction of fertilizer programs, or management of competition species.

<table>
<thead>
<tr>
<th></th>
<th>Yields</th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Million ha’s</td>
<td>m³/ha/yr</td>
<td>Million m³/ha/yr</td>
</tr>
<tr>
<td>Developed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US/Canada</td>
<td>18.8</td>
<td>15</td>
<td>281.8</td>
</tr>
<tr>
<td>Europe/Russia</td>
<td>25.8</td>
<td>10</td>
<td>258.3</td>
</tr>
<tr>
<td>Other</td>
<td>21.7</td>
<td>9.5</td>
<td>206.6</td>
</tr>
<tr>
<td>Total Developed</td>
<td>66.4</td>
<td></td>
<td>746.6</td>
</tr>
<tr>
<td>Subtropical/Tropical</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td>2.8</td>
<td>17</td>
<td>47.1</td>
</tr>
<tr>
<td>South/Central America</td>
<td>6.7</td>
<td>25</td>
<td>168.0</td>
</tr>
<tr>
<td>Africa</td>
<td>3.7</td>
<td>14</td>
<td>51.5</td>
</tr>
<tr>
<td>SE Asia</td>
<td>5.8</td>
<td>6</td>
<td>34.6</td>
</tr>
<tr>
<td>Total Subtropical/Tropical</td>
<td>18.9</td>
<td></td>
<td>301.2</td>
</tr>
<tr>
<td>Other</td>
<td>4.9</td>
<td>5</td>
<td>24.3</td>
</tr>
<tr>
<td>Total</td>
<td>90.2</td>
<td>12</td>
<td>1,072.1</td>
</tr>
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</table>

Table 8 Potential output from timber plantations using current yield estimates from Cubbage et al. (2010)

One way to gage potential increases in timber yields in these fast-growing plantations is to compare estimates of plantation yields made at two different time periods. Fortunately, two studies are available that allow us to make this comparison. Specifically, estimates of plantation species timber yields in subtropical regions were developed for the late 1970s by Sedjo (1983). Cubbage et al. (2010) used similar methods to calculate timber yields for the same species in many of the same regions. The estimates of timber yields were made roughly 30 years apart, so represent a fairly substantial difference in time. Table 9 presents a comparison of timber yields for the same species. For the
comparison, we assess annual increment, or the average volume harvested per hectare per year.

By these estimates, the yields of highly productive timber plantations increased by 1.6 – 2.1% per year in Brazil, 1.0% per year in Chile, and 0.9-1.1% per year in the United States. These increases in yields are likely driven by three factors: First, genetic stocks are likely improving over time; second, management techniques are improving over time; and third, the sites on which stands are located may be improving over time. Surprisingly, yields are estimated to have declined slightly in New Zealand and South Africa.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rotation</td>
<td>m³/ha</td>
<td>m³/ha/yr</td>
</tr>
<tr>
<td>Brazil</td>
<td>P. taeda</td>
<td>15</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>E. grandis</td>
<td>15</td>
<td>525</td>
</tr>
<tr>
<td>Chile</td>
<td>P. radiata</td>
<td>19</td>
<td>490</td>
</tr>
<tr>
<td>New Zealand</td>
<td>P. radiata</td>
<td>28</td>
<td>480</td>
</tr>
<tr>
<td>South Africa</td>
<td>P. patula</td>
<td>30</td>
<td>526</td>
</tr>
<tr>
<td>USA</td>
<td>P. taeda</td>
<td>27</td>
<td>369</td>
</tr>
<tr>
<td></td>
<td>Ps. Menzesei</td>
<td>45</td>
<td>833</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>22.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Plantation yield estimates from two studies conducted 30 year apart
In summary, current estimates suggest that the total area of industrial wood plantations globally is around 90 million hectares, with a high estimate of 140 million hectares. The higher estimate likely includes a large number of plantations that are not intended for industrial wood production, but instead for local fuel wood needs or other purposes. The largest differences in estimates occur in tropical countries. Potential timber output from these plantations is very high. Current estimates of plantation yields by Cubbage et al. (2010) suggest that 90 million hectares of plantations globally could produce an average of 12 m³ per hectare per year. This would lead to output of nearly 1.1 billion m³ of industrial wood globally. Clearly this is substantially higher than actual output from existing plantations, but it nonetheless illustrates the potential.

Calculations of potential technological change, or annual yield improvements in plantations, range from 0 to over 2% per year. One important outcome from comparing yield growth in plantations across regions is that US yields seem to be rising more slowly than competitor countries, namely South America. Over the long-term slower technological change, of course, could have strong implications for output.

*Linking SRTS and GTM*

To have a detailed representation of the regional supply of Southern US, we updated inventory data of Southern US in GTM relying on the Subregional Timber Supply Model (SRTS). This section describes how we integrate the SRTS data into GTM. SRTS was developed by the Southern Forest Resource Assessment Consortium to project inventories, removals and price of softwood and hardwood of US south (Abt et al. 2009). The projection uses the inventory data from USDA Forest Service Forest Inventory and
Analysis (FIA) by management type. The model allows simulating the detailed impact of changes in demand and supply for subregions at the FIA survey units.

Figure 19 illustrates the data frameworks for both STRS and GTM. In STRS, the forest inventory is stocked by states, survey units, ownerships, management types, and age classes by 5 years. Three steps are taken to input the SRTS data into GTM. First, we aggregate hectares and growing stocks for different survey units and ownerships while keeping information of states and management types. Second, to represent ownerships in an alternative way, we separate the inventory into economic reserve areas and accessible regions. In GTM, accessible forests are defined as forests which are regularly managed as commercial forests while economic reserve forests are defined as lands where the marginal costs of harvesting are well above the value of the merchantable timber or land owners are not interested in harvesting the trees. We assume the trees older than the economic rotation age for each management type in SRTS to be in economic reserves and we move them into this class in GTM. Third, we calibrate the parameters for growth functions according to information on growing stock and hectares for different management types in each state. Plus, the inventory for accessible regions is adjusted when running GTM so that the harvest of base year matches the removals in STRS data.

---

11 We use the typical rotation ages for US south for each management type. The age for 30 for planted pine, 50 for natural and mixed pine, and 60 for upland and lowland hardwood.
There are 70.3 million hectares of forestland in US south, among which 49.5 million hectares is accessible forests and 20.87 million hectares is economic reserve forests. Planted pine accounts for 22.6% (11.2 million hectares) of accessible forests. Those forests are disaggregated by states and management types and there are 117 different management types in total. Each management type is characterized by area, species, age class distribution and individual yield function. Figure 20 shows the aggregate age class distribution for accessible planted pine, natural pine and upland and lowland hardwood. Note that for planted pine, the area of younger age classes are higher. This suggests there have been increasing regenerations of plantations in the last two decades. The largest
area for lowland and upland hardwood lies in the 40-60, yet their regenerations have also bound up in the last two decades.

<table>
<thead>
<tr>
<th></th>
<th>S1: Baseline Yield Increase (%/yr)</th>
<th>S2: High Yield Increase (%/yr)</th>
<th>S4: High Global Yield Increase (%/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. taeda</td>
<td>1.0%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>E. grandis</td>
<td>1.0%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Rest of South America</td>
<td>Pinus Sp.</td>
<td>0.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Eucalyptus Sp.</td>
<td>0.6%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Oceania</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pinus Sp.</td>
<td>0.6%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Eucalyptus Sp.</td>
<td>0.6%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>Pinus Sp.</td>
<td>0.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Eucalyptus Sp.</td>
<td>0.0%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>USA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. taeda</td>
<td>0.6%</td>
<td>1.5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Ps. Menzeii</td>
<td>0.6%</td>
<td>1.5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. Massoniani</td>
<td>0.6%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

Table 10 Plantation technological change: % change in annual yields assuming management is constant

**Description of scenarios**

For the analysis, four future scenarios are constructed. The baseline provides our base assumptions about future yield growth in plantations. For modeling purposes, we have used more conservative calculations than some estimates shown in the previous section. Two additional scenarios are compiled to examine alternative future timber yield projections. One of these scenarios follows the faster rates of technological change.
suggested in the previous section, and another scenario assumes that these faster rates of technological change occur outside the US, but not in the US. A fourth scenario considers the implications of much stronger future demand growth for timber. A detailed description of the scenarios is given below.

**Scenario 1 (Baseline case):**

This scenario assumes that global income per capita rises at 2.4% per year. Our income elasticity parameter is 0.87, rising modestly to 0.88 by end of the simulation. Thus, each 1% increase in income per capita increases demand by roughly 0.88%. The demand for wood in the model is the derived demand for logs delivered to the production mill. We have assumed that technology is improving for converting wood logs into end-products, which reduces the growth in demand. We thus include a factor in the model that reduces the growth in demand for wood by 0.9% per year. As a result of these assumptions, demand grows over time, but demand growth slows over time. The demand function essentially doubles in 100 years, but demand growth is relatively slow in the second half of the century.

Yields for industrial wood plantations are assumed to increase over time at rates shown in Table 10. For this baseline scenario, we choose plantation yield increases of 0.6% for all regions. These rates are lower than those found historically in Brazil and elsewhere and shown in Table 9.

**Scenario 2 (High Global Demand):**

This scenario assumes that global demand rises more quickly over time. To accomplish this, we increase the income elasticity of demand. In this scenario, income
elasticity rises to 0.93. Thus, each 1% increase in income per capita increases demand increases by roughly 0.93%. Yields for industrial wood plantations area assumed to follow their baseline level. In this new scenario, the demand function doubles by 2050 rather than by 2100 as in the baseline.

**Scenario 3 (High Plantation Yield Growth):**

For this scenario, the income and demand assumptions are the same as the baseline case; however, yields in industrial wood plantations are adjusted by increasing the rate of technological change in plantations throughout the world. Specifically, we assume that all regions with fast-growing timber plantations experience increases in the yield of these plantations at a rate of 1.5% per year.

**Scenario 4 (High Global Plantation Yield Increase/Modest US Yield Increase):**

This scenario assumes that larger investments in yield improving technologies occur outside the United States. We assume that yields for fast-growing timber plantations in the US improve at their baseline level and yields for fast-growing plantations outside the US increase at 1.5% per year. Demand follows the baseline scenario.

---

**Results and discussion**

**The Baseline**

The results of the baseline forecast are shown in Figure 21 through Figure 23. Figure 21 presents the projection of time profile of long term regional harvest volume. The projection for the world shows gradual growth in total output, at an average growth rate of 0.8% per year for the next 40 years. The entire period experiences a total output...
increase of about 38.3%. US and Canadian forests, as two traditional timber production regions maintain approximately their initial output levels throughout the forty years. The harvest level of South America, which is below US and Canada initially, gradually increases, surpasses them and increases even further by the end of the projection period. By 2020, South America is forecasted to be the largest single producing region as the intensively managed plantations expand and reach maturity. Globally, most of the increase in harvest over the projection period results from the emerging regions including South America. Due to the increasing competition from the emerging plantation regions, we find substantial structural shift of production towards high-growth, fast rotation and intensively managed industrial plantation regions and a declining role of the traditional temperate forest regions.

Figure 22 presents an index of harvest level relative to the initial harvest level in 2010 by forest type for southern US. Production stays in its initial level throughout the projection period though there are decline in the first three decades and comeback at the end. The trends of the five management types significantly deviate from each other. Hardwood production declines, both in upland and bottomland types. This results from the paucity of inventories in those forest types in 20-40 year age classes initially. . The production of natural pine even doubles at the end.

Figure 23 presents the projection of the time profile of world timber market price. The projection shows that prices are fairly stable in the next 40 years until 2050 while there are small volatilities throughout this period. This suggests that supply will keep up with demand in the future as timber is sustainably supplied.
Figure 19 Age class distribution of Southern US by management types
Figure 20 Regional output: historical trends and baseline projection
Figure 21 Baseline Projection: Southern US output by management relative to the initial level
Figure 22 Global price: historical trends and baseline projection
The high-demand scenario

The high-demand scenario posits the same conditions and assumptions as the baseline scenario except that we assume the global demand rises more quickly than in the baseline. The demand rises as two times as faster than in the baseline so that the global demand function doubles by year 2050 rather than 2100. Without any adjustment in the supply side, we expect the price should also rise more quickly overtime. Figure 24 through Figure 28 present the projected time profile of the high-demand growth scenario’s price and output. While demand is about 45.6% greater by 2050, timber prices are only about 11.6% higher than in the baseline. Because the price elasticity of the demand function is assumed to be -1, this suggests the supply of timber expands significantly under the higher demand scenario due to improvements in management and yield. As expected, the South produces more under the high global demand. The path of harvest is all above the baseline and the gap between the two is getting bigger over time. The harvest increases by about 16% over the next 40 years.
Figure 23: Timber price projections for four scenarios

Figure 24: Global output projections for four scenarios
Not surprisingly, the US South also harvest more than the baseline under the high demand. The South increases its output by 16% as it responds to the higher price and most of the increase come from expanding the area of accessible forestland. In other words, with higher timber prices, some economically infeasible land classes become feasible and are thus draw into wood production. If we look specifically into species, we find that the output of plantation and non-plantation both increase, yet non-plantation still dominates wood production of the South.
Figure 25 Timber output in the US.
Figure 26 Southern US: area of accessible forests and average annual harvest
Figure 27 Southern US: output of plantations and non-plantations
Figure 28 Historical price with projections for three scenarios
The high plantation scenario

The high plantation scenario assumes the same yield for plantation species as the baseline but further assumes the growth rate of yield would increase faster than the baseline. Specifically, we assume that all regions with fast-growing timber plantations experience increases in the yield of these plantations at a rate of 1.5% per year. Figure 24 through Figure 28 present the time profile of outputs and prices for the high plantation scenario (red). As the yield of plantations are higher, the high plantation scenario harvest more wood than that were found in the baseline. The output level is 15% higher than that of the baseline by the end of the projection period. This also results in a lowering of market price for industrial round wood. Plus, there are changes in the regional structure of the harvest. Most of the world like US as well as the emerging regions experiences higher harvest while we find the output of Canada does not rise significantly and is even lower for some intervals of the projection periods. Since there are few plantation species in Canada, this suggests that the high volume harvested from plantation displace production from non-plantation species.

The strong yield of plantation also boosts the output of Southern US rises significantly over time. The South harvests about 20% more than the baseline by the end of the projection. The increases in harvest results from not only changes in productivity per hectare but also the land use adjustment. Though the total accessible forestland is lower than the baseline, the total area of plantation expands by 1.3 million hectares (12% of total plantation in the South). This illustrates that the improvement in yields of the
planted species will drive some of the accessible non-plantation forestland to submarginal land classes. Plus, by the end of the projection, the plantation of Southern US surpasses non-plantation and becomes dominant timber producing sector of the South.

**The high global plantation scenario**

The fourth scenario posits the same assumptions as the high plantation yield scenario except that the rate of yield growth for US maintains the same as baseline. We assume that yields for fast-growing timber plantations in US improve at their baseline level and yields for fast-growing plantations outside US increase at 1.5% per year. Demand follows the baseline scenario. This scenario examines the implications if larger investments in yield improving technologies occur outside US. The time profile of price and outputs are presented in Figure 24 Though Figure 28 (purple). The trends in price and global output are close to those of the high plantation yield scenario: more harvests occur overtime and in turn there is a lowering in global market price than the baseline.

The major differences lie in the responses of US and the South as well. With larger investments in yield improving technologies outside US, the outputs of US and the South are substantially less than that of baseline. The decreases in a major part result from forestland contractions compared with baseline (Figure 26). Though there is only a modest decline in total accessible forestland of the South over time, the level is about 13% lower than that of baseline. Plantation forests and non-plantation forests both contract. The asymmetric rates of technology adoption in improving yields induce the regional shift of production. Part of the forestland in the South which is economically
accessible in the baseline is no longer economically feasible in this scenario and subsequently driven out of the accessible land class.

**The comparison of the scenarios**

While price are projected to be stable in baseline, the differences of price path in the high demand and high plantation yield scenario are relatively modest. Figure 28 shows the historical timber prices from 1910 with the forecasted prices profile. Stronger demand shifts the price path up and stronger yield growth shifts it down. Yet, the changes are all within the range of 15% up and down around the baseline price levels. Systemwide technology improvements could substantially slow down the growth of timber prices and producer should not expect dramatic changes in price even with stronger demand in the future.

Yet, structural changes among either regions or management types are abundant. The changes, in a large part, are driven by improvements in yields of industrial plantations. The emerging world displays competitive advantage in productivity and draws increasing investments on regeneration on the limited accessible forestland. This gives rise to rapid increases in plantation outputs in the emerging regions and offsets drawbacks of production in the traditional temperate regions like Canada. The results demonstrate that fast growing plantations play a major role in meeting stronger future demand and also offset the contraction in demand.

In general, these results of the various scenarios illustrate the important role that technological change can have in timber markets, and especially the role it can have on southern US markets. Big boost in harvest of the South would only come with improved
technology. On one hand, even if there is stronger global demand, the harvest increase for the South is very modest. On the other hand, as we showed above, most of the additional accessible forestland occurs not in the developed world but in the emerging regions where land are relatively cheaper. If there are strong improvements in technology, output from the South could increase by over 20%; obviously, to achieve this, continued application of these technologies in the US is required. If new technologies are applied elsewhere in the world, but not in the US, then Southern pine output in the US actually could fall relative to the baseline.

Conclusion

This study examines the role of industrial wood plantations on global and US timber markets. The study begins by examining several trends in wood markets, including the expansion of industrial wood plantations globally, and changes in output from these plantations. Data from a recent analysis of timber yields in wood product markets is then used to update data in a global timber market model. Data for Southern US is also updated with a detailed representation of the South using data from the SRTS model. This model is used to examine how some of these trends may affect wood markets in the US.

Our results show that technological change in timber plantations could have very important influences on timber markets, nationally and globally. Specifically, by examining two studies conducted at two different time periods, 30 years apart, we find that timber yields in plantations have risen anywhere from 0% per year to 2.1% per year
in some regions. The analysis suggests that yields appear to be rising faster in other regions than in the US.

The study then takes information from the recent study of timber plantations and uses the information to analyze the implications of technology change and plantation establishment in regions outside the US on US output. A global timber market model is used for this analysis, and four different scenarios are considered. The results of the scenarios show that though price will change with global demand and rate of technology adoption, the range of changes are very small (within 15%). Technological change in timber plantations can have strong effects on timber price. If technology change is robust (e.g., 1.5% per year globally), then plantations can outpace demand and lead to timber price decrease. With slower technology change, the price will maintain about the current level over time. If US lags behind its global producing competitors, its outputs will suffer in the long run. If yields of plantations in the rest of the world outpace US yields by roughly double over the next 50 years, this could depress US output by 7%-11% over the time period.
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The global timber model used in this analysis is built upon the model described in Sohngen et al. (1999), and used by Sohngen and Mendelsohn (2003), Sohngen and Sedjo (2006), and Sohngen and Mendelsohn (2007) to analyze global forestry carbon sequestration potential. The model maximizes the net present value of consumer's plus producer's surplus in timber markets. Because forestry land competes with agriculture for land, it models the interaction between the two markets via land supply functions that account for the costs of renting forestland. These land supply functions are specified for each timber supply region in the model. They either are constant or shift over time, depending on assumptions about future development of agriculture in each region.

Timber is supplied from 146 distinct timber types. The model solves explicitly for harvesting (e.g., rotation ages), management intensity (e.g., $/ha spent regenerating and managing sites), and the area of land in each timber type. For expositional purposes, the results from these many forest types are aggregated into 13 regions. The 13 regions are the United States, Canada, Central America, South America, Europe, Russia, China, Japan, Southeast Asia, Oceania, Africa, Central Asia, and Japan.

For the purposes of describing the model, each of the 146 timber types modeled can be allocated into one of three general types of forest stocks. Stocks $i$ are moderately valued forests, managed in optimal rotations, and located primarily in temperate regions.
Stocks Sj are high value timber plantations that are managed intensively. Subtropical plantations are grown in the southern United States (loblolly pine plantations), South America, southern Africa, the Iberian Peninsula, Indonesia, and Oceania (Australia and New Zealand). Stocks Sk are relatively low valued forests, managed lightly if at all, and located primarily in inaccessible regions of the boreal and tropical forests. The inaccessible forests are harvested only when timber prices exceed marginal access costs12.

Formally, the following is solved numerically:

$$\max \sum_0^\infty \rho^t \left\{ \sum_{i,j,k} \left[ Q^*(t) \left\{ \right. \right. \\
\left. \left. D(Q_t, Z_t) - C_{H^i}() - C_{H^j}() - C_{H^k}() \right\} dQ(t) - \right. \\
\left. \right. \sum_{i,j} C_{i,j}^k (G_{t}^{i,j,k}, m_t^{i,j,k}) - \sum_{j} C_{N_t}^{j} (N_t^{j}, m_t^{j}) - \sum_{i,j,k} R^{i,j,k} (X_t^{i,j,k}) + CC(t) \right\} \right\}$$

$$Q_t = \sum_{i,j,k} \left[ \sum_{a,t} H_{a,t}^{i,j,k} y_{a,t}^{i,j,k} (m_{t0}) \right]$$

In equation (1), $D(Q_t, Z_t)$ is a global demand function for industrial wood products given the quantity of wood, $Q_t$, and income, $Z_t$. The quantity of wood depends upon $H_{i,j,k}$, the area of land harvested in the timber types in i, j, or k, and $V_{a,t}^{i,j,k}(m_{t0})$, the yield function of each plot. The yield per hectare depends upon the species, the age of the tree (a), and the management intensity at the time of planting ($m_{t0}$). $CH(\bullet)$ is the cost

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12 In this study, forests in inaccessible regions are harvested when marginal access costs are less than the value of the standing stock plus the present value of maintaining and managing that land as an accessible forest in the future.
function for harvesting and transporting logs to mills from each of timber type. Marginal harvest costs for temperate and subtropical plantation forests (i and j) are constant, while marginal harvest costs for inaccessible forests rise as additional land is accessed. $C_{i,kG}(\cdot)$ is the cost function for planting land in temperate and previously inaccessible forests, and $C_{jN}(\cdot)$ is the cost function for planting forests in subtropical plantation regions. $G_{i,kt}$ is the area of land planted in types i and k, and $N_{jt}$ is the area of land planted in plantation forests. The planting cost functions are given as:

$$
C_{G}^{i,k}(\cdot) = p_{m}^{i,k} m_{i}^{i,k} G_{i}^{i,k}
$$

$$
C_{N}^{j}(\cdot) = p_{m}^{j} m_{i}^{j} N_{i}^{j} + f(N_{i}^{j}, X_{i}^{j})
$$

where $m_{i,j,kt}$ is the management intensity of those plantings purchased at price $p_{i,m}$, $p_{j,m}$, or $p_{k,m}$. $f(N_{jt}, X_{jt})$ is a function representing establishment costs for new plantations. The cost function for establishing new plantations rises as the total area of plantations expands.

The yield function has the following properties typical of ecological species: $V_{a} > 0$ and $V_{aa} < 0$. We assume that management intensity is determined at planting. The following two conditions hold for trees planted at time $t_{0}$ and harvested “a” years later $(a+t_{0}) = t_{0}$:

$$
\frac{dV_{i}(t_{a}, t_{0})}{dm_{i}(t_{0})} \geq 0 \quad \text{and} \quad \frac{d^{2}V_{i}(t_{a}, t_{0})}{dm_{i}(t_{0})^{2}} \leq 0
$$

105
The total area of land in each forest type is given as $X_{i,j,kt}$. $R_{i,j,k}(\bullet)$ is a rental function for the opportunity costs of maintaining lands in forests. Two forms of the rental function are used:

$$\begin{align*}
(5) & \quad R(X) = \alpha(t)X + \beta(t)X^2 & \text{for temperate and boreal regions} \\
& \quad R(X) = \alpha(t)X^2 + \beta(t)X^3 & \text{for tropical regions}
\end{align*}$$

The marginal cost of additional forestland in tropical forests is assumed to be non-linear to account with relatively high opportunity costs associated with shifting large areas of land out of agriculture and into forests. The parameters of the rental function are calibrated initially so that the elasticity of land supply is 0.25 initially, the reported relationship between forests and agriculture in the US (Hardie and Parks, 1997; Plantinga et al., 1999). There are no similar estimates of the elasticity of land supply for other regions of the world, although empirical work is currently being undertaken on this topic. The calibration procedure utilizes the initial land area in each forest type, $X$, and the initial rental value for the forest type, $R(X)$ and chooses the parameters $\alpha(t)$ and $\beta(t)$ so that the elasticity will be 0.25. This elasticity implies that the area of forests could increase by 0.25% if forests can pay an additional 1% rental payment per year.

The parameters $\alpha(t)$ and $\beta(t)$ are assumed to be constant over time for temperate regions. For tropical regions, they are assumed to change over time in order to simulate conversion of forestland to agriculture. The rental functions shift inward, thus raising the rental costs of maintaining forestland. The shift in the rental functions is an assumption.
in the model, and the assumptions are developed with scenario analysis. Specifically, the
scenario developed for the analysis in this paper was to simulate similar deforestation
rates as observed in the past 10 years during the first decade of the model run, and to
simulate a decline in deforestation over the rest of the century. An alternative to this
scenario analysis, of course, would be to explicitly model the agricultural sector.

The sensitivity of these assumptions about the land rental functions have been
tested elsewhere. Sohngen and Sedjo (2006) examined sensitivity around the assumed
path of deforestation in tropical regions. Not surprisingly, they found that stronger
increases in deforestation over the projection period in their analysis (100 years) raised
the costs of deforestation. The results in the analysis of this paper are consistent with the
higher marginal cost estimates in their study. Sohngen and Mendelsohn (2007) have
examined adjustments in assumptions over land supply elasticity. More elastic land
supply functions reduce the costs of carbon sequestration, including reduced emissions
from avoided deforestation, and vice-versa. Specifically, they found that cutting the
elasticity assumption in half would reduce the global quantity of carbon sequestered by
10-20%. It is not clear

The stock of land in each forest type adjusts over time according to:

\[
X_{a,t}^i = X_{a-1,t-1}^i - H_{a-1,t-1}^i + G_{a=0,t-1}^i \quad i = 1 - I
\]

\[
X_{a,t}^j = X_{a-1,t-1}^j - H_{a-1,t-1}^j + N_{a=0,t-1}^j \quad j = 1 - J
\]
\[ X_{a,j}^k = X_{a-1,j-1}^k - H_{a-1,j-1}^k + G_{a=0,j-1}^k \quad k = 1 - K \]

Stocks of inaccessible forests in Sk are treated differently depending on whether they are in tropical or temperate/boreal regions. All inaccessible forests are assumed to regenerate naturally unless they are converted to agriculture. In tropical regions, forests often are converted to agriculture when harvested, so that Gka=0 is often 0 for tropical forests in initial periods when the opportunity costs of holding land in forests are high. As land is converted to agriculture in tropical regions, rental values for remaining forestland declines, and land eventually begins regenerating in forests in those regions. This regeneration is dependent on comparing the value of land in forests versus the rental value of holding those forests. Inaccessible forests in temperate/boreal regions that are harvested are converted to accessible timber types so that Gka=0 is set to 0. The stock of inaccessible forests in Sk is therefore declining over time if these stocks are being harvested. Each inaccessible boreal timber type has a corresponding accessible timber type in Si, and forests that are harvested in inaccessible forested areas in temperate/boreal regions are converted to these accessible types. Thus, for the corresponding timber type, we set Gia=0 ≥ Hka-1. Note that the area regenerated, Gia=0, can be greater than the area of the inaccessible timber type harvested because over time, harvests and regeneration occurs in forests of the accessible type.
The term CC(t) represents carbon sequestration rental payments. Rental payments are made on the total stock of carbon in forests, thus, the form for CC(t) is given as:

\[
CC_t = CR_t \sum_{i,j,k} \gamma_{i,j,k} \sum_a \{V_{i,j,k}^a (m_{i,j,k}^a(t_0))\}X_{i,j,k}^a + \\
(7)
\]

\[
PC_t \sum_{i,j,k} \theta_{i,j,k} \sum_a \{V_{i,j,k}^a (m_{i,j,k}^a(t_0))\}H_{i,j,k}^a - E_{t_b}^h,
\]

where CR(t) is the annual rental value on a ton of carbon, PC(t) is the price of a ton of carbon, \(\gamma_{i,j,k}\) is a conversion factor to convert forest biomass into carbon, \(\theta_{i,j,k}\) is a conversion factor to convert harvested biomass into carbon stored in products, and \(E_{t_b}\) is baseline carbon sequestration. For this model, we assume that product storage in long-lived wood products is 30% of total carbon harvested (Winjum et al., 1998).

The model is programmed into GAMS and solved in 10 year time increments. Terminal conditions are imposed on the system after 150 years. These conditions were imposed far enough into the future not to affect the study results over the period of interest. For the baseline case, \(PC_{t} = 0\), there is no sequestration program, and the term \(CC_{t}\) has no effect on the model. Baseline carbon sequestration is then estimated, and used for \(E_{t_b}\) in the carbon scenarios. The sequestration program scenarios are based on the assumed prices for \(PC_{t}\).

Data on initial forest area and inventories the model is obtained from multiple sources (Table 11). For most developed countries and temperate forests, inventories are obtained
from original sources within the countries or regions because those sources often also contain age class information. For most developing countries in tropical regions, information on forest areas are obtained from the United Nations FAO (UN FAO, 2005).

<table>
<thead>
<tr>
<th>Region</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>USDA, Forest Service Forest Inventory and Analysis (USFS FIA, Various Years)</td>
</tr>
<tr>
<td>Europe</td>
<td>Kuusela (1993)</td>
</tr>
<tr>
<td>Russia</td>
<td>Russia: Forest Account (2003); Backman and Waggener (1991)</td>
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<tr>
<td>Canada</td>
<td>Lowe et al. (1994)</td>
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<tr>
<td>New Zealand</td>
<td>New Zealand Ministry of Agriculture and Forestry (MAF).</td>
</tr>
<tr>
<td>China</td>
<td>China (Ministry of Forestry, Center for Forest Inventory)</td>
</tr>
<tr>
<td>All other</td>
<td>United Nations FAO (2005)</td>
</tr>
</tbody>
</table>

Table 11 Sources of forest area and inventory data