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Abstract

This study presents a Dynamic Computable General Equilibrium model that combines economic and ecological aspects of forest biomass. A framework is introduced for modeling the growth of a biomass stock which interacts with economic sectors. Harvest of and demand for forest products and forest amenities are determined endogenously in an inter-temporally consistent way. The idea is based on a Markovian growth model of the forest. The study demonstrates an approach for incorporating non-market values of forests, such as carbon sequestration, recreation and biodiversity, into a growth model. A simulation illustrates harvest behavior when the economy is subjected to shocks.

Key words: Dynamic CGE; Markovian growth; Ecosystem modeling; Inter-temporal optimization; Infinite-horizon equilibria
JEL classification: C68; D58; Q26

1 Introduction

The use of Computable General Equilibrium (CGE) models in analyses of the forest sector has been motivated by the importance of links between the forest sector and the rest of the economy (Haynes et al. 1995). In regions where the forest sector is an important contributor to employment and gross domestic product, the effect of changes in the forest sector on the economy may be of significant interest. In, for example, Binkley et al. (1994) a CGE model was used to analyze the economic impact of reductions in the annual allowable cut in the Canadian province of British Columbia, where the forest industry is a major component of the economy. In addition, the Global Trade Assessment Project (GTAP) model has been used as part of an Asia-Pacific Economic Cooperation (APEC) study to assess the effects of the removal of specific non-tariff barriers to forest product trade on a country's gross domestic product, welfare, and trade (New Zealand Forest Research Institute 1999).

In other cases, partial equilibrium (PE) analysis has been applied. The CINTRAFOR Global Trade Model (CGTM) describes forest growth, wood supply, processing capacity and final demand. Market equilibria are solved on a period-by-period basis with inter-period changes in forest inventory as a dynamic element. The CGTM has been applied to many forest sector issues, e.g., Perez-Garcia (1994), Perez-Garcia (1995), Eastin et al. (2002). Detailed descriptions of the CGTM are presented in Kallio et al. (1987) and Cardellichio (1989). Another example of a PE model is the Global Forest Product Model (GFPM) (Buongiorno 2003), which integrates timber supply, processing industries, product demand and trade. For each year an equilibrium is computed, while year-by-year changes are simulated by recursive programming. Both CGTM and GFPM are designed as policy analysis tools, but they do not attempt to predict the feedback effects of changes in the forest sector on the rest of the economy. Nor do they attempt to optimize the forest sector over the planning horizon. Yet another example of a partial equilibrium model is the Timber Assessment Market Model (TAMM) (Adams and Haynes 1980), which focuses mostly on North America, but has been used to analyze international issues (Adams and Haynes 1996). The two main components of the TAMM are a market model and an inventory projection module. The market model covers supply and demand for wood over regions and sectors. Pulp fiber requirements and projections of forest inventory and forest growth are exogenous inputs to the model. In TAMM, the spatial equilibrium is found by "reactive programming" which makes it difficult to represent policy scenarios involving constraints on endogenous variables (Adams and Haynes 1996).

The CGE and PE models discussed incorporate similar detail regarding the supply and demand sides of the forestry sector. Another feature of these models is that they are static, or have dynamic elements that link each period's solution, such as CGTM, GFPM and TAMM, but do not satisfy optimality in an inter-temporal sense.

The Timber Supply Model (TSM) (Sedjo and Lyon 1998), on the other hand, was developed to study the transition of the world's forests from old-growth to plantation-grown industrial forests, and focuses on the issue of global timber supply. The modeling approach uses control theory to determine the inter-temporal optimal transition. The TSM is a dynamic model focusing on accurately describing the wood supply sector.

This study presents a Dynamic CGE model, suitable for policy analysis, which combines simple economic and ecological aspects of the forest biomass. Biologists point out that biological populations can seldom be accurately described by the aggregate biomass without paying attention to the internal structure, including variables such as the age-class distribution (Getz and Haight 1989). Therefore, the model presented here has a detailed age-structured representation of growth and harvest of biomass stocks, interlinked with the rest of the economy. Harvest and demand for forest products and forest amenities are determined endogenously in an inter-temporally consistent way. The general idea is Markovian growth[1]. The possible policy instruments include taxes, subsidies and tariffs. Questions regarding the value of carbon sequestration and the cost of setting aside special parts of forest land for recreation can also be addressed. Further, it is possible to impose restrictions on forest harvests, in accordance with prevailing regulations.

The paper proceed as follows. Section 2 briefly explains the ecological model of the forest. Section 3 has a presentation of the dynamic CGE model. Simulations are presented in section 4 and section 5 has concluding remarks.

[1] The Markov growth model is a well-known mathematical model for the random evolution of a memoryless system. That is, one for which the likelihood of a given future state, at any given moment, depends only on its present state, and not on any past states.

2 The Ecological model

The ecological part of the model is based on the forest growth model in Sallnäs (1990), which has been used to develop software, called EFISCEN (Schelhaas et al. 2007), by the European Forest Institute that is used for projections of forest resources. Input to EFISCEN is based on national forest inventories and input data are available for 31 European countries. The EFISCEN software generates an initial Area Distribution Vector (ADV), describing the state of the forest, and a Transition Probability Matrix (TPM), which describes the growth process of the forest. As illustrated in figure 1, the indices of the ADV can be viewed in two-dimensional space, with age and volume classes along the axes. The values of the vector represent an area measure. Briefly, the ADV divides the total area of forest into age and volume classes. In each time increment, the area compartments in the ADV move to a higher age class, and with some probability, p, the compartment moves to a higher volume class. The probability for staying in the same volume class is $1-p$. This process is governed by the TPM. The harvest can be restricted to compartments of choice, indicated by the circles, and harvested areas are transferred to the bare land compartment (BL). These two outputs, ADV and TPM, can be used in a combined economic-ecological model and thus provide for economic projections into the future. The EFISCEN model can be disaggregated to several different levels, with an ADV for each

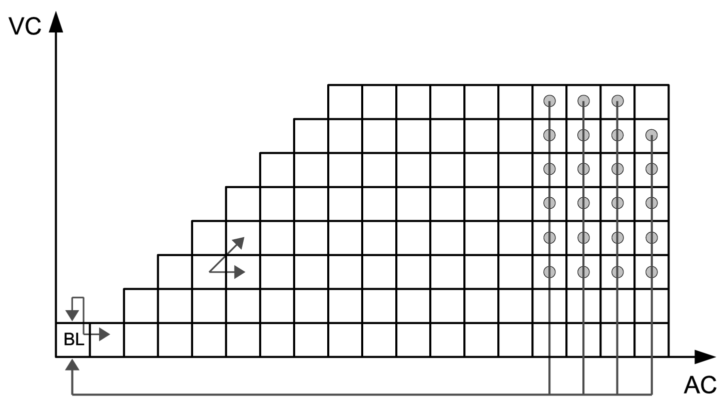

Figure 1: Illustration of the Area Distribution Vector and the Transition Probability Matrix. VC and AC represent volume and age class, respectively.

aggregate. The aggregation information provided by the EFISCEN software is:

Country

Region

Owner type (small, big)

Site productivity class

Tree type (Spruce, Pine)

In EFISCEN, an ADV describing forests in Sweden would typically consist of 10 volume classes and 36 age classes, and the time increment for each growth period would be 5 years. The EFISCEN model also supplies information for each item in the ADV. The kinds of information provided are:

Mean biomass volume per ha

Carbon content per ha

Proportions of Stem/Tops/Branches/Bark per ha

This allows for a large spectrum of analyses, but this study will focus on recreational values and carbon sequestration.

3 Formulation of the Eco-Eco-model

In this dynamic equilibrium model, we have a single infinitely-lived representative agent. The closed economy consists of a household which owns the stock of biomass. The stock of biomass is the only source of consumption, i.e., there is no production of goods in this economy. The simplicity of the economic activities is chosen in order to emphasize the dynamic biomass structure of the model. The consumption bundle consists of harvest of the biomass stock and the standing biomass stock. Consumption of the standing biomass stock is regarded as recreation. Expectations by private agents are forward-looking and rational. Hence, all agents have perfect foresight because there is no uncertainty. These assumptions imply that the optimal allocation of resources by a central planner who maximizes the utility of the representative agent is identical to the optimal allocation of resources in an undistorted decentralized economy. However, (Scarf and Hansen 1973, p. 4) states *"The determination of prices that simultaneously clear all markets cannot, in general, be formulated as a maximization problem in a useful way. Rather than being a single maximization problem, the competitive model involves the interaction and mutual consistency of a number of maximization problems separately pursued by a variety of economic agents."* This well known fact in the literature of computable general equilibrium modeling leads to an approach different from that of regular optimization. Following Mathiesen (1985), the market equilibrium in the model is defined by non-negative price-activity pairs that satisfy the following conditions:

> (i) The zero profit condition: Every activity in the economy earns non-positive profits, and activities operated at positive levels earn zero profits.
>
> (ii) The market clearance condition: Excess supply for each commodity is non-negative, and a positive price implies zero excess supply for that commodity.
>
> (iii) The income balance condition: Expenditure does not exceed income, and a positive income implies that expenditure equals income.

These conditions exhibit complementarity with the price-activity pairs. Thus, we will formulate a general equilibrium model as a square system of weak inequalities, each with an associated non-negative variable. This is referred to as a complementarity problem in mathematics, and the associated variables are referred to as complementary variables.

3.1 NLP Formulation

The Nonlinear Programing (NLP) formulation is based on an explicit representation of the utility function for the single representative household. The social planner maximizes the present value of lifetime utility for the representative household, which receives instantaneous utility from the harvest and the standing stock. The instant utility received from the standing stock could be regarded as representing some non-market value of the standing stock, for example recreational value, biodiversity value, or carbon sequestration value. These non-marketed components of the utility are modeled as functions of the standing stock. The instant utility function is assumed to be homothetic and separable in its arguments. The function maximizing lifetime utility is assumed to be additive, separable across time. The representative agent maximizes utility subject to the constraints (essentially based on empirical results from Sallnäs (1990)) on growth and harvest of the forest stock. The stock in each period equals the growth of the stock in the previous period minus the harvest in the previous period.

With vectors and vector valued functions in bold, the NLP problem is stated as:

$$\begin{aligned} max \ & \sum_{t=0}^{\infty}(\frac{1}{1+\rho})^t u(\boldsymbol{c}_t, \boldsymbol{n}_t) \\ s.t. \ & Q\boldsymbol{s}_t - (I-B)\boldsymbol{h}_t - \boldsymbol{s}_{t+1} \geq \mathbf{0}, \ \forall t, \\ & \overline{\boldsymbol{s}}_0 - \boldsymbol{s}_0 \geq \mathbf{0}, \\ & \boldsymbol{h}_t - \boldsymbol{c}_t \geq \mathbf{0}, \ \forall t, \\ & \boldsymbol{f}(\boldsymbol{s}_t) - \boldsymbol{n}_t \geq \mathbf{0}, \ \forall t, \\ & \boldsymbol{c}_t, \boldsymbol{n}_t, \boldsymbol{s}_t, \boldsymbol{h}_t \geq \mathbf{0}, \ \forall t \end{aligned}$$

where ρ is the time preference rate, $\boldsymbol{c}_t$ is the consumption vector of area harvest in period t, $\boldsymbol{n}_t$ is the "non-market quantity", which yields non-market values, such as recreation and carbon sequestration (specified later), of the standing stock in period t, $\boldsymbol{f}(\cdot)$ is an increasing general purpose function quantifying the non-market goods from the forest stock (specified later), and $U(\cdot)$ is the instantaneous utility of consumption assumed homothetic. $\boldsymbol{s}_t$ is the area distribution vector (ADV), specified above, of the forest stock in period t, I is the identity matrix, B is a matrix that projects the harvested area compartments into the bare land compartment, $\boldsymbol{h}_t$ is the vector of area harvested in period t, and Q is the Markov probability transition matrix (TPM) governing the growth of the stock. The initial forest stock in period $t=0$, $\boldsymbol{s}_0$, is specified exogenously.

The Lagrangian of the NLP is:

$$\begin{aligned} \mathcal{L} = & \sum_{t=0}^{\infty}(\frac{1}{1+\rho})^t u(\boldsymbol{c}_t, \boldsymbol{n}_t) + \\ & \boldsymbol{p}_{t+1}^{s\prime}(Q\boldsymbol{s}_t - (I-B)\boldsymbol{h}_t - \boldsymbol{s}_{t+1}) + \\ & \boldsymbol{p}_t^{c\prime}(\boldsymbol{h}_t - \boldsymbol{c}_t) + \\ & \boldsymbol{p}_t^{n\prime}(\boldsymbol{f}(\boldsymbol{s}_t) - \boldsymbol{n}_t) + \\ & \boldsymbol{p}_0^{s\prime}(\overline{\boldsymbol{s}}_0 - \boldsymbol{s}_0) \end{aligned}$$

where $\boldsymbol{p}_t^s$, $\boldsymbol{p}_t^c$, and $\boldsymbol{p}_t^n$ are the associated Lagrangian multipliers, or shadow prices, for the area distribution vector, harvest consumption vector, and "non-market quantity", respectively. A prime indicates vector transpose. The system yields the following Karush-Kuhn-Tucker (KKT) conditions:

$$\boldsymbol{p}_t^c \geq (\frac{1}{1+\rho})^t \nabla'_{\boldsymbol{c}_t} u(\boldsymbol{c}_t, \boldsymbol{n}_t) \;\perp\; \boldsymbol{c}_t \geq \mathbf{0} \tag{1}$$

$$\boldsymbol{p}_t^n \geq (\frac{1}{1+\rho})^t \nabla'_{\boldsymbol{n}_t} u(\boldsymbol{c}_t, \boldsymbol{n}_t) \;\perp\; \boldsymbol{n}_t \geq \mathbf{0} \tag{2}$$

$$\boldsymbol{p}_t^s \geq \boldsymbol{p}_{t+1}^{s\prime} Q + \nabla'_{\boldsymbol{s}_t} \boldsymbol{f}(\boldsymbol{s}_t) \boldsymbol{p}_t^n \;\perp\; \boldsymbol{s}_t \geq \mathbf{0} \tag{3}$$

$$\boldsymbol{p}_{t+1}^{s\prime}(I - B) \geq \boldsymbol{p}_t^c \;\perp\; \boldsymbol{h}_t \geq \mathbf{0} \tag{4}$$

$$\boldsymbol{h}_t \geq \boldsymbol{c}_t \;\perp\; \boldsymbol{p}_t^c \geq \mathbf{0} \tag{5}$$

$$\boldsymbol{f}(\boldsymbol{s}_t) \geq \boldsymbol{n}_t \;\perp\; \boldsymbol{p}_t^n \geq \mathbf{0} \tag{6}$$

$$Q\boldsymbol{s}_t - (I - B)\boldsymbol{h}_t \geq \boldsymbol{s}_{t+1} \;\perp\; \boldsymbol{p}_{t+1}^s \geq \mathbf{0} \tag{7}$$

$$\bar{\boldsymbol{s}}_0 \geq \boldsymbol{s}_0 \;\perp\; \boldsymbol{p}_0^s \geq \mathbf{0} \tag{8}$$

If we assume that all relevant variables, i.e., prices and quantities, have strictly positive values at equilibrium, the inequalities 1 to 8 all hold as equalities. In this situation, the economic rationale for equality to hold in 1 and 2 is that, at equilibrium levels of $\boldsymbol{c}_t$ and $\boldsymbol{n}_t$, prices of harvest and "non-market quantities" equal the discounted marginal utility of these commodities and amenities. Equality in condition 3 can be interpreted as a cost relation for a multiple output production capability. The input to this production is the current period stock of forest and the outputs are the next period stock of forest and the current period forest amenities. The cost relation at the margin of current stock indicates that the current price of each compartment equals the future price of compartments to which current compartments will grow, according to the transition probability matrix, plus the marginal value of forest amenity outputs. In short, the price of the current stock equals the marginal value of production of future stock and current amenities. Note that the price of forest stock thus contains the shadow price of the non-market amenities. Equality in condition 4 states that the harvest, in compartments where harvesting is allowed, is kept at such a level that the current price of harvesting equals the future price of those compartments minus the future price of bare land. The conditions 5 to 8 are considered self-explanatory.

3.2 MCP Formulation

The formulation of the equilibrium in Mathiesen (1985) relies on the existence of closed-form demand functions which express consumption demand as a function of market prices and income, m. The demand functions for harvest, and non-market value consumption are determined through utility maximization and are defined by:

$$\boldsymbol{D}^c(\boldsymbol{p}, m) = \underset{all\ \boldsymbol{c}_t}{argmax}(\sum_{t=0}^{\infty}(\frac{1}{1+\rho})^t u(\boldsymbol{c}_t, \boldsymbol{n}_t) | \sum_{t=0}^{\infty} \boldsymbol{p}_t^{c'} \boldsymbol{c}_t + \boldsymbol{p}_t^{n'} \boldsymbol{n}_t = m)$$
$$\boldsymbol{D}^n(\boldsymbol{p}, m) = \underset{all\ \boldsymbol{n}_t}{argmax}(\sum_{t=0}^{\infty}(\frac{1}{1+\rho})^t u(\boldsymbol{c}_t, \boldsymbol{n}_t) | \sum_{t=0}^{\infty} \boldsymbol{p}_t^{c'} \boldsymbol{c}_t + \boldsymbol{p}_t^{n'} \boldsymbol{n}_t = m)$$

where

$$\boldsymbol{D}^c(\boldsymbol{p}, m) = [\boldsymbol{d}_0^c(\boldsymbol{p}, m),\ \boldsymbol{d}_1^c(\boldsymbol{p}, m),\ ..,\ \boldsymbol{d}_t^c(\boldsymbol{p}, m),\ ...]$$
$$\boldsymbol{D}^n(\boldsymbol{p}, m) = [\boldsymbol{d}_0^n(\boldsymbol{p}, m),\ \boldsymbol{d}_1^n(\boldsymbol{p}, m),\ ..,\ \boldsymbol{d}_t^n(\boldsymbol{p}, m),\ ...]$$

Having defined uncompensated demand functions, we can characterize the equilibrium KKT conditions in terms of the above three classes, (i)-(iii), of equations.
The zero profit conditions with associated variables are:

$$\boldsymbol{p}_t^s \geq \boldsymbol{p}_{t+1}^{s\prime} Q + \nabla'_{\boldsymbol{s}_t} \boldsymbol{f}(\boldsymbol{s}_t) \boldsymbol{p}_t^n \ \perp\ \boldsymbol{s}_t \geq \boldsymbol{0}$$
$$\boldsymbol{p}_{t+1}^{s\prime}(I - B) \geq \boldsymbol{p}_t^c \ \perp\ \boldsymbol{h}_t \geq \boldsymbol{0}$$

The market clearance conditions in each period are:

$$\boldsymbol{f}(\boldsymbol{s}_t) \geq \boldsymbol{d}_t^n(\boldsymbol{p}, m) \ \perp\ \boldsymbol{p}_t^n \geq \boldsymbol{0}$$
$$\boldsymbol{h}_t \geq \boldsymbol{d}_t^c(\boldsymbol{p}, m) \ \perp\ \boldsymbol{p}_t^c \geq \boldsymbol{0}$$
$$Q\boldsymbol{s}_t - (I - B)\boldsymbol{h}_t \geq \boldsymbol{s}_{t+1} \ \perp\ \boldsymbol{p}_{t+1}^s \geq \boldsymbol{0}$$
$$\bar{\boldsymbol{s}}_0 \geq \boldsymbol{s}_0 \ \perp\ \boldsymbol{p}_0^s \geq \boldsymbol{0}$$

where m is an augmented version of income in which non-market valuation of factors earning income are implicitly incorporated into the price of those factors. The income earning factor in the economy is the stock of forest, the price of which contains not only the market timber price, but also the non-market valuation of the forest stock.

An income balance constraint relates the value of expenditure to factor earnings:

$$m = \boldsymbol{p}_0^{s'}\bar{\boldsymbol{s}}_0 \;\perp\; m \geq 0$$

Note that, by assuming non-satiation, we also get[2].

$$\boldsymbol{p}_0^{s'}\bar{\boldsymbol{s}}_0 = \sum_{t=0}^{\infty} \boldsymbol{p}_t^{n'}\boldsymbol{n}_t + \boldsymbol{p}_t^{c'}\boldsymbol{c}_t$$

3.3 Terminal conditions

In the equilibrium of the classical forest rotation model in Faustmann (1849) forest growth, timber volume and annual harvesting are constant over time. This outcome is usually referred to as the *normal forest* and is a commonly used assumption in forest management. However, present economic research indicates that under positive discounting, optimal forest vintage structure may evolve into stationary cycles without convergence towards the normal forest (see, for example, Mitra and Wan Jr (1985) and Wan Jr (1994)). Nevertheless, in an extension, Salo and Tahvonen (2002) shows that, with alternative land use, the stationary cycles are replaced by a saddle point path with damped oscillations and convergence towards the normal forest. The reason for this is *"[c]yclical timber harvesting would imply that the value of the bare forest land would either exceed or be below the marginal land value in the alternative use. Such a situation cannot be optimal, implying that in equilibrium the cycles vanish."* (Salo and Tahvonen 2002, p. 19). There does not seem to be any theoretical consensus in the literature as to whether or not the forest will reach a stationary point (normal forest) or a stationary cyclic rotation. Since this model is meant to be used in empirical studies where alternative land use would probably prevail in the long run, it is not unreasonable to assume that at some future time, T, the normal forest will be reached. Stationary rotation, or a steady state, in this model of forest growth, means that the intensity of harvest is at a constant level that keeps the stock (state) of forest constant in each period; harvest equals the growth of the forest. The state and harvest of the forest stock at period $T+1$ are

[2] Use of the present value of consumption along an optimal path as a measure of 'social income' has its proponents in the literature, e.g., Heal and Kriström (2008).

assumed to be stationary and this is stated as:

$$\boldsymbol{s}_{T+1} = \boldsymbol{s}_T = Q\boldsymbol{s}_T - (I - B)\boldsymbol{h}_T$$

Following Lau et al. (2002), the infinite horizon planning problem is decomposed into two distinct problems: one defined over the finite interval $[0, T]$, and the second defined over the infinite interval $[T+1, \infty]$. The two subproblems are linked through the stock of forest in period T+1, which depends on the stock and harvest in period T. This decomposition is possible due to the time-separability of the utility function. The finite horizon problem for the representative household is:

$$max \sum_{t=0}^{T} (\frac{1}{1+\rho})^t u(\boldsymbol{c}_t, \boldsymbol{n}_t)$$

subject to the inter-temporal budget constraint:

$$\sum_{t=0}^{T} \boldsymbol{p}_t^{c'} \boldsymbol{c}_t + \boldsymbol{p}_t^{n'} \boldsymbol{n}_t = \boldsymbol{p}_0^{s'} \overline{\boldsymbol{s}}_0 - \boldsymbol{p}_{T+1}^{s'} \boldsymbol{s}_{T+1}$$

The infinite horizon problem is then:

$$max \sum_{t=T+1}^{\infty} (\frac{1}{1+\rho})^t u(\boldsymbol{c}_t, \boldsymbol{n}_t)$$

subject to the inter-temporal budget constraint:

$$\sum_{t=T+1}^{\infty} \boldsymbol{p}_t^{c'} \boldsymbol{c}_t + \boldsymbol{p}_t^{n'} \boldsymbol{n}_t = \boldsymbol{p}_{T+1}^{s'} \boldsymbol{s}_{T+1}$$

With the model decomposed and the assumption of normal forest from (at least) period T as a terminal approximation, the focus shifts to specifying the finite horizon problem. In order to achieve this end, variables for the prices of post-terminal stock are introduced to the MCP equilibrium conditions, and an extra set of equations are necessary to control the levels of these variables. Let T indicate the last period of the finite horizon, then the extra market clearance condition will be[3]:

$$Q\boldsymbol{s}_T - (I - B)\boldsymbol{h}_T \geq \boldsymbol{s}_T \;\perp\; \boldsymbol{p}^s_{T+1} \geq \mathbf{0}$$

and the correction of the income balance constraint becomes:

$$m = \boldsymbol{p}^{s'}_0 \overline{\boldsymbol{s}}_0 - \boldsymbol{p}^{s'}_{T+1}\boldsymbol{s}_{T+1} \;\perp\; m \geq 0$$

where by non-satiation we have:

$$\boldsymbol{p}^{s'}_0 \overline{\boldsymbol{s}}_0 - \boldsymbol{p}^{s'}_{T+1}\boldsymbol{s}_{T+1} = \sum_{t=0}^{T} \boldsymbol{p}^{c'}_t \boldsymbol{c}_t + \boldsymbol{p}^{n'}_t \boldsymbol{n}_t$$

Note that with this assumption on the long run steady-state value of the forest stock, the model horizon should be sufficiently long to converge to the steady state after a policy shock.

3.4 Scenarios

In demonstrating the usefulness of this model two scenarios were considered in simulations. In the first scenario, the representative agent obtains an increased sense of wellbeing from recreational values of the forest. In the second, the wellbeing is increased by increased carbon sequestration in the forest. It is assumed that the recreational or biodiversity services are provided by the oldest and most voluminous parts of the forest, i.e., old-growth forest, see, for example, Haqen et al. (1992) in support of this assumption. The carbon sequestration takes place in all compartments of the forest, but at different rates (explained below).

As before, the "non-market quantities" are represented by the function $\boldsymbol{f}(\boldsymbol{s}_t)$. We can now specify it further by separating it into parts:

$$\boldsymbol{f}(\boldsymbol{s}_t) = [k(\boldsymbol{s}_t)\; l(\boldsymbol{s}_t)]'$$

where $k(\boldsymbol{s}_t)$ represents the quantity of recreation and $l(\boldsymbol{s}_t)$ represents the quantity of carbon sequestrated in each period. As a measure of the quantity

[3] Lau et al. (2002) includes the post-terminal capital stock as an endogenous variable and controls that variable with an equation relating the growth rate of investment in the terminal period to the growth rate of output. Here the post-terminal forest stock is determined by the harvest and the forest stock at the terminal period owing to the normal forest assumption.

of recreation, the size of the area in the highest age and volume class is used. The carbon sequestrated is computed by taking the difference in carbon content per hectare between periods and multiplying by the area distribution vector.

$$k(\boldsymbol{s}_t) = \boldsymbol{e}'\boldsymbol{s}_t$$
$$l(\boldsymbol{s}_t) = \Delta\boldsymbol{c}\boldsymbol{s}_t$$
$$\Delta\boldsymbol{c} = \boldsymbol{c}'(Q' - I)$$

where $\boldsymbol{e}$ is a unit vector $[0\ 0\ ...\ 0\ 1]'$ with 1 in the position of the highest age and volume class, $\boldsymbol{c}$ is the vector of carbon content per hectare of forest in the corresponding age and volume class, and $\Delta\boldsymbol{c}$ is a measure of carbon sequestration per hectare and period in the corresponding age and volume class.

From the specification of the function $\boldsymbol{f}(\boldsymbol{s}_t)$ above it becomes clear that the "non-market quantities" $\boldsymbol{n}_t$, and the prices thereof, $\boldsymbol{p}_t^n$, will reduce to vectors with two elements representing recreational amenity and carbon sequestration.

4 Results

Artificial data were used in the simulation, but the forest growth characteristics were based on a reduced form of data supplied by the EFISCEN software. The state of the forest was divided into four age classes and four volume classes, with bare land being one compartment, resulting in seven different compartments. The harvest was restricted to the three compartments residing in the highest age class.

Numerically, the model was implemented in MPSGE (Rutherford 1999) as a subsystem of GAMS (Brooke et al. 1996) using PATH (Dirkse and Ferris 1995) for solving the MCP problem[4].

The simplest assumption for replicating a Şbusiness as usualŤ benchmark is to assume stationary rotation of the forest stock as a starting point for analysis. Stationary rotation, or a steady state, in this model of forest growth, means that the intensity of harvesting is at a constant level that keeps the stock (state) of forest constant in each period. The two scenarios were implemented by increasing the weights of the utility function of the recreational

[4] The code is available from the author upon request.

value and sequestration value, respectively, i.e. by changing the shape of the instant utility function. The results presented for the benchmark and the two scenarios are aggregated harvest, aggregated stock, average age and carbon sequestrated over the horizon of interest. The focus is on the development of the forest. Aggregated variables were chosen in order to avoid being overwhelmed by details, but it should be borne in mind that the changes are different in different compartments of the forest.

In figure 2, we see that the harvest decreases, at a declining rate, when the value of recreation is increased. The declining rate is due to the fact that recreational value is defined for only one, the oldest and most voluminous, forest compartment and it takes time for the system to accommodate the shock. In short, it takes time for the forest to grow old and produce recreational value.

The effect on harvest due to an increased value of carbon sequestration is more noticeable. The harvest shifts up (and rapidly finds a constant value) because, in contrast to recreational value, the carbon sequestrating ability of the forest lies in the younger parts of the forest. No waiting for cutting down old forest is needed to obtain a higher rate of carbon sequestration. The results displayed in figure 2 (and figures 3, 4, and 5) clearly show that there is a conflict of interest between recreational values and carbon sequestration. The two different scenarios display opposite effects on harvest behavior.

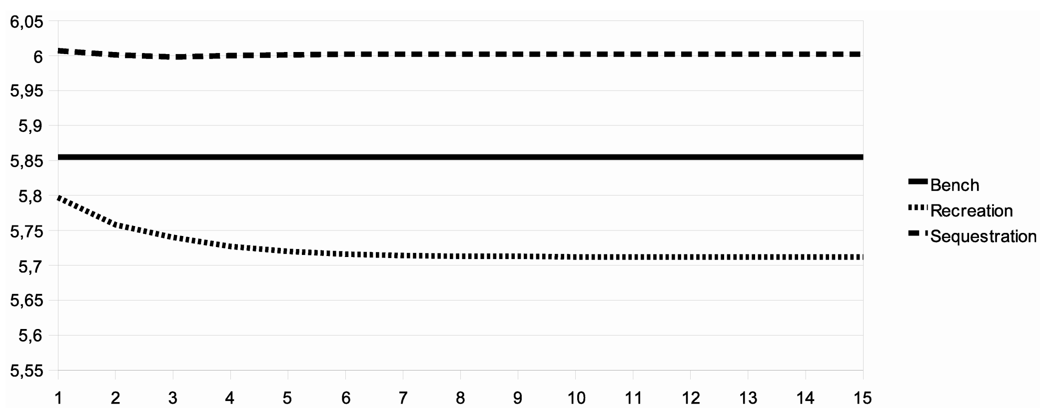

Figure 2: Changes in aggregate harvest with time, under benchmark conditions and scenarios in which recreational values and carbon sequestration have increased importance.

Figure 3 displays changes in the total volume of biomass that occur with the scenario shifts. The stock of biomass is of course a function of harvest, and when harvest decreases in response to the higher value of recreation, the stock gradually increases until it reaches a steady state. The reverse happens when harvest increases as a result of the value of carbon sequestration increasing; there is a progressive increase in aggregate stock volume. Note that aggregate stock reaches a steady state earlier in the increased valuation of carbon sequestration scenario, in accordance with the harvest behavior findings presented in figure 2.

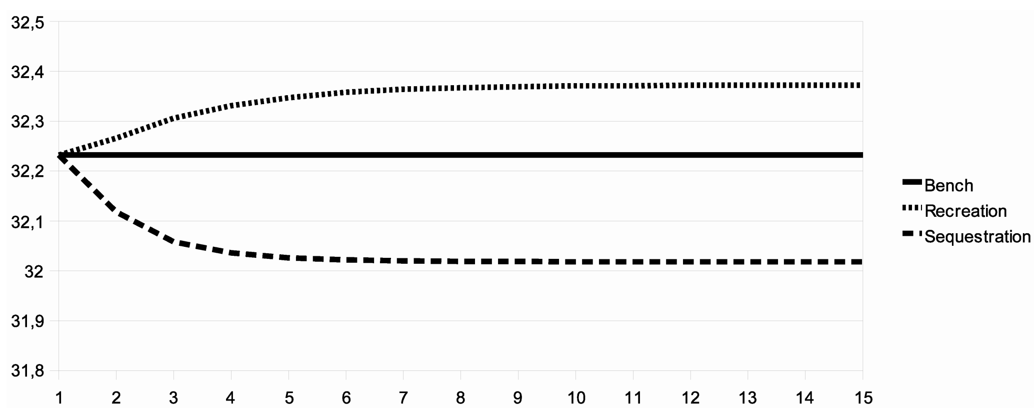

Figure 3: Changes in aggregate stock with time, under benchmark conditions and scenarios in which recreational values and carbon sequestration have increased importance.

The changes in the average age of the forest are illustrated in figure 4. The average age is computed as a weighted average of the mean age times the biomass volume of the different compartments. It can be seen that the average age goes up when recreation has a higher value, and down when carbon sequestration is of greater concern. This figure merely reflects patterns that can be seen in figure 3, but it shows the differences in age in the two scenarios. Older forest is associated with higher recreation values, while the carbon sequestration capacity is greater in younger forest.

Figure 5 shows carbon sequestration adoption in response to the scenario shifts. Carbon sequestration is reduced when the age of the forest increases as a consequence of the higher value of recreation and, obviously, carbon sequestration is increased when its value is increased.

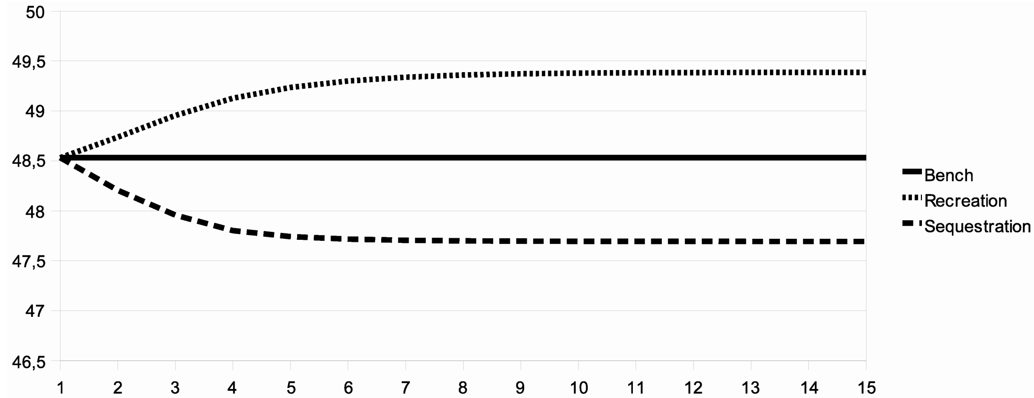

Figure 4: Changes in average age with time, under benchmark conditions and scenarios in which recreational values and carbon sequestration have increased importance.

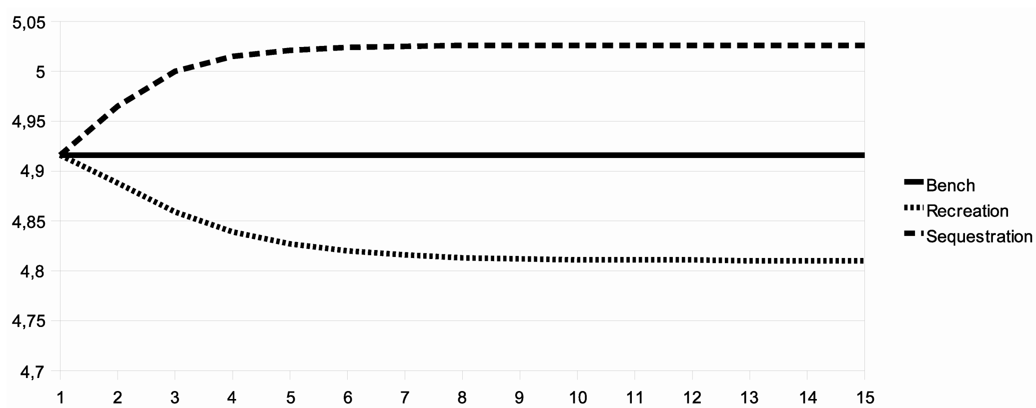

Figure 5: Changes in carbon sequestration with time, under benchmark conditions and scenarios in which recreational values and carbon sequestration have increased importance.

To summarize, changes in the valuation of non-marketed amenities provided by the forest biomass stock alter the harvest behavior of the representative agent. When recreational values are held in higher regard the area harvested declines. When, on the other hand, carbon sequestration efficiency is held in greater esteem, the area harvested increases. These opposing responses reflect the age-specificity of the different amenities.

5 Conclusion

This study propose an inter-temporally consistent model for CGE modeling of renewable biomass stocks in forests, in which the growth and the harvest have implications for economic activities. The model pays special attention to age-specific properties of the biomass stock studied. Harvests of, and demand for, the renewable biomass stocks are determined endogenously in an inter-temporally consistent way. The growth process of the stock is governed by a transition probability matrix, commonly known as a Markov matrix.

It has been explained how changes in the valuation of non-marketed amenities provided by the forest biomass stock alter the harvest behavior of the owner of the stock. When recreational values are held in higher regard the area harvested declines. When, on the other hand, carbon sequestration efficiency is held in greater esteem, the area harvested increases. These outcomes are reflections of the age-specificity of the different amenities. The results of the study also reveal the conflict of interest between recreational values and carbon sequestration.

The framework can be extended to include additional economic sectors and fed with available data from national accounting and national forest inventories to provide for scenario analysis, either as a CGE model or a PE model focusing on the forest dependent sectors. For scenario analysis, the assumption that the forest is in a steady state at the start of the time horizon might not be a feasible construct. Data for a base period may be inconsistent with a steady-state growth path. Data supplied from the Swedish forest inventory, for example, show that forest growth exceeds the harvest. Therefore, some assumption has to be made regarding how the forest and harvest will evolve. One possible solution for model calibration in cases of non-steady-state data is to assume that growth initially exceeds the harvest, but converges to a steady-state growth and harvest conditions over time. Calibrating dynamic models to benchmark data which are not steady-state means finding a path along which prices, demand and production coincide and end up in a steady state.

The MCP format provides for discriminating between different groups of preference systems. This seems to be an interesting aspect of this forest model for future investigation, since a number of econometric studies have revealed that harvesting decisions depend on owner-specific characteristics such as non-forest income, wealth and owner's age (e.g., Binkley (1981), Romm et al. (1987), Dennis (1988), Dennis (1990), Jamnick and Beckett (1988) and Kuuluvainen and Salo (1991)).

While this paper focuses on the forest as a renewable biomass stock, the model presented could be translated to other biomass stocks with similar age-structured properties that require economic examination. The growth and harvest of fish, for example, have been modeled by transition probability matrices in several studies, see Getz and Swartzman (1981), Rothschild and Mullen (1985), and Evans and Rice (1988).

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