Three Essays on Swedish Energy and Climate Policy Options -

Dynamic CGE-models with Heterogeneous Forests and an Econometric Model of Fuel Substitution in District Heating Plants

Örjan Furtenback

Faculty of Forest Sciences,
Department of Forest Economics,
Umeå

Doctoral Thesis
Swedish University of Agricultural Sciences
Umeå 2011

Acta Universitatis agriculturae Sueciae
2011:81

ISSN, 1652-6880
ISRN, 978-91-576-7625-2

Print: Arkitektkopia, Umeå 2011

Three Essays on Swedish Energy and Climate Policy Options -
Dynamic CGE-models with Heterogeneous Forests and an Econometric Model of Fuel Substitution in District Heating Plants

Abstract
This thesis contains three papers.

Paper I: *Demand for waste as fuel in the Swedish district heating sector: a production function approach*
This paper evaluates inter-fuel substitution in the Swedish district heating industry by analyzing the district heating plants in Sweden in the period 1989 to 2003, specifically those plants incinerating waste. A multi-output plant-specific production function is estimated using panel data methods. A procedure for weighting the elasticities of factor demand to produce a single matrix for the whole industry is introduced. The price of waste is assumed to increase in response to the energy and CO_2 tax on waste-to-energy incineration that was introduced in Sweden on 1 July 2006. Analysis of the plants involved in waste incineration indicates that an increase in the net price of waste by 10% is likely to reduce the demand for waste by 4.2%, and increase the demand for bio-fuels, fossil fuels, other fuels and electricity by 5.5%, 6.0%, 6.0% and 6.0%, respectively.

Paper II: *Towards a dynamic Ecol-Econ CGE model with forest as biomass capital*
This study presents a dynamic Computable General Equilibrium (CGE) 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 simple simulation illustrates harvest behavior when the economy is subjected to shocks.

Paper III: *A dynamic CGE-model with heterogeneous forest biomass: Applications to climate policy.*
This study introduces a framework for modeling a renewable forest biomass stock interacting with economic sectors in a competitive economy. The equilibrium is formulated as a mixed complementary problem (which explicitly represents weak inequalities and complementarity among decision variables and equilibrium conditions). The complementarity format permits detailed modeling of the growth and harvest of a biomass stock together with a second-best characterization of the overall economy. First the complementarity features of economic equilibrium and its integration with an ecological representation of the biomass stock are provided. Then a stylized numerical example of a dynamic computable general equilibrium model is presented. Finally, illustrative applications of the model for gauging the likely effects of environmental subsidies and taxes intended to promote increases CO_2 storage in forest biomass are given, the results are discussed.

Keywords: Cobb-Douglas production function, factor demand, inter-fuel substitution, waste management, Dynamic CGE, Markovian growth, Inter-temporal optimization, Infinite-

horizon equilibria

Author's address: Örjan Furtenback, SLU, Department of Forest Economics, SLU, 901 83 Umeå, Sweden.
E-mail: orjan.furtenback@slu.se

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text: (Article I reproduced under permission by *Journal of Waste Management*):

I Demand for waste as fuel in the Swedish district heating sector: a production function approach.

II Towards a dynamic Ecol-Econ CGE model with forest as biomass capital.

III Dynamic CGE-model with heterogeneous forest biomass: Applications to climate policy. Under review in Natural Resource Modeling

Contents

1 Introduction

The forest resource in Sweden has traditionally been used in saw mills, board industry, and paper and pulp industries. Since the 1980s, District heating, using forest bio-mass residues as input in the production of heat, increased significantly. Also, amenity values, such as recreation and carbon sink services have become increasingly important.

The use of the forest resource has changed over time, from being primarily an input to saw mills and pulp and paper production, to also include provision of a wide array of amenities, and as a source of bio-energy.

Figure 1 shows how forest bio-mass resources flow from the forest owner into the forest industry (saw mills, board industry, and pulp industry), between agents within the forest industry, and into the final products industry in 2004. Forest industry agents are represented by rectangular boxes, boxes with rounded bottoms represents storage of specific bio-mass, input from forest owners enter from the left, and output to the final products industry resides on the right hand side. Shaded areas indicate quantities used for energy purposes. Note that values indicated at arcs are in Mt dry bio-mass matter. The data is based on Nilsson (2006).

As can be deduced from figure 1, the 32,650 Mt of dry matter is broadly used as follows: one quarter attributed to sawn goods, one third to pulp, one-hundredth to boards and one tenth to district heating and briquettes or pellets. Approximately one third is used in the forest industry, mainly to heat for drying and to some extent to produce electricity.

The value of forest raw material as a source of energy has increased considerably since the oil crises of the 1970s and continues to increase with increasing prices of fossil fuels. The expansion of bio-fuels has been extensive in recent years and will most likely continue.

The European Union has intensified its energy and climate change ambitions and, as a Member State, Sweden is expected to make an effort to meet these ambitions. The Commission of the European Communities, SEC (2008) 85/3, Impact Assessment, originates from an agreement between the EU Member States and contains proposals for how the burden of reaching energy and climate targets could be shared amongst nations. Taken together the Member States have agreed to reduce greenhouse gases by at least 20 percent by 2020 compared to 1990, and provided that a comprehensive international agreement on reductions comes about, the target is set to a 30 percent reduction. In addition, the Member States decided that renewable energy should constitute 20 percent of total energy consumption within the EU, including a 10 percent bio-fuels target for transports. The legally-binding targets amongst EU's Member States vary and the targets assigned for Sweden is a 17 percent reduction of greenhouse gases emissions compared to 2005 and a share of renewable energy amounting to 49 percent by 2020, up from 43.9 percent in 2007 (Swedish energy Agency, 2009).

The arguments used by countries for justifying this development are mainly connected to positive environmental and economic effects, that could be summarized as in Lundgren et al. (2008):

- Climate effects

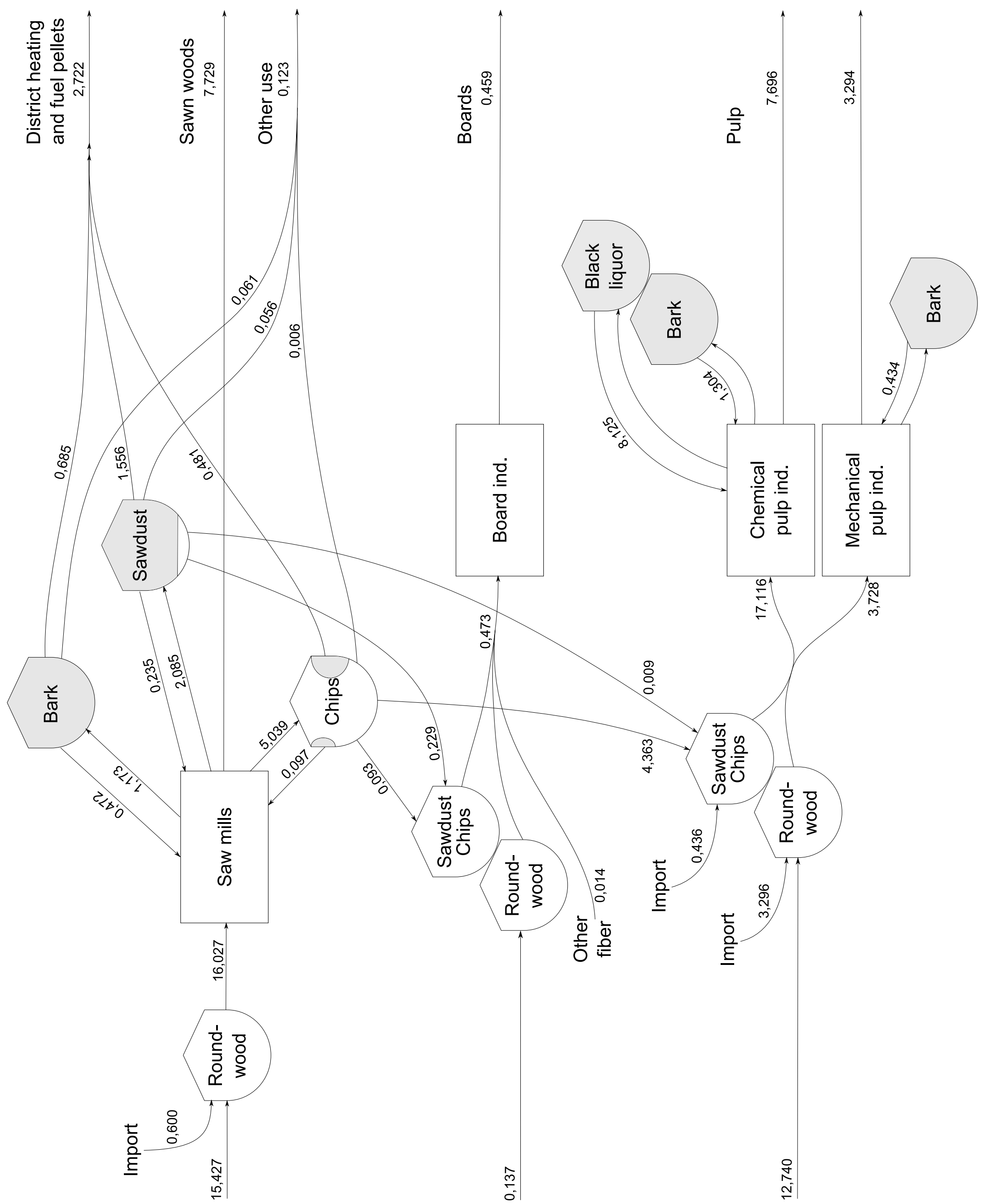

Figure 1: Commodity inputs to the forest industry and the flow through process to final products in 2004. Modified from Nilsson (2006). Numbers referes to Mt dry bio-mass matter.

- Environmental effects (other than climate effects)
- Energy security effects
- Net economic effects (e.g., on employment and income)

If the combined impact of these effects has a nonnegative net effect on welfare, the conversion from fossil energy sources to bio-energy sources is justifiable from a societal point of view.

Forest raw material is expected to be sufficient to cater for the demand of traditional products such as sawn goods, paper and packaging, district heating, and for new purposes such as electricity generation and fuels in the transport sector. Furthermore, the Swedish government (the department of agriculture) recently announced a proposition to increase the role of the forests as a carbon sink as well as an increase in the use of forest biomass for energy Government Bill 2007/08:108, (2008).

In short, the claim on forests and forest resources has increased significantly both from the traditional forest sector and from entirely new groups.

The general aim is to analyze welfare effects in Sweden of energy and climate policy. Most current research within this field considers a part of the economy, and ecological constraints are not described in much detail.

The general purpose of the thesis is therefore to contribute to the development of tools that could be used to shed light on energy and climate policies with focus on the forest resource.

2 Assessing the effects of environmental policy - Partial and General Equilibrium

This thesis contains three papers. The first paper is different from the other two, but share some common features with those, i.e. the focus on:

- The utilization of forest and other non-fossil recourses
- Environmental policies and their implications

The first paper of this thesis uses partial equilibrium analysis of policy decisions that affects the environment. Partial equilibrium models assume that the impact on other markets is negligible thus allowing a more detailed analysis of the effect a specific policy might have on commodity markets (Lundmark and Mansikkasalo, 2009). The modeling framework has its foundations in applied production economics (see e.g. Chambers (1988)). Partial equilibrium analysis *of one market* is based on the assumption that all relevant variables except the price in question are constant. The focus is on the impact of a policy in one market, without worrying about second round effects from other markets. In many cases partial equilibrium analysis is debatable, but in others it is a very useful tool. Generally, the more narrowly the market is defined, the more appropriate PE analysis is. The analysis in the first paper considers the substitution effects of inputs used in the district heating industry resulting from the introduction of a tax on incineration of waste, (SFS 2006:592, 2006), to curb CO_2 emissions. It is assumed that the net price of waste for the waste incineration industry changes in response to the introduction of a tax on the incineration of waste, and that the tax will not cause significant changes in the price of input substitutes (fossil fuel, bio-fuel, electricity) or output substitutes. The study is an econometric examination of the district heating sector where bio-mass enters as an input fuel and is similar to Brännlund and Kriström (2001), where the impact of energy taxation on the Swedish district heating industry was examined, but without specifically considering waste as an input.

Figure 1 shows that the forest industry and final product industry are highly interconnected. General equilibrium effects might be present in such a case. Paper two and three of the thesis takes this into account and attempts to introduce a more holistic approach to the economic analysis of the use of forest products. Two different frameworks for evaluation of ecological aspects of the forest in combination with the economy in a general equillilbrium setting are introduced.

Many CGE models are static: they model the reactions of the economy at only one point in time. For policy analysis, results from such a model are often interpreted as showing the reaction of the economy in some future period to one or a few external shocks or policy changes. That is, the results show the difference (usually reported in percent change form) between two alternative future states (with and without the policy shock). The process of adjustment to the new equilibrium is not explicitly represented in such a model, although details of the closure (for example, whether capital stocks are allowed to adjust) lead modelers to distinguish between short-run and long-run equilibrium. Seminal work in this area include Johansen (1960) who formulated the first empirically based, multi-sector, price-endogenous model analyzing resource allocation issues, and Harberger (1962), which was the first to investigate tax policy questions numerically in a two sector general equilibrium framework. Mathiesen (1985b) formulated the problem of solving a CGE by stating the CGE as a system of weak inequalities with corresponding variables featuring complementary slackness with the inequalities. This is commonly referred to as a "Mixed Complementary Problem" (MCP) in mathematics.

Dynamic CGE models explicitly trace each variable through time, often at annual intervals. These models are more realistic, but more challenging to construct and solve, they require for instance that future changes are predicted for all exogenous variables, not just those affected by a possible policy change. The dynamic elements may arise from partial adjustment processes or from stock/flow accumulation relations, for example between capital stocks and investment. An pedagogical example on how to construct a dynamic CGE model is Lau et al. (2002), which uses the well known Ramsey model, Ramsey (1928), in the MCP setting.

The second part of the thesis presents two papers based on dynamic CGE analysis and treats forest as a biomass capital stock which is related to the flow variables harvest and growth. Harvest of the forest, and amenities provided by the standing stock of forest, enters into the economy specified by the preference system's demand functions. The dynamics of the models are governed by different growth processes of the forest, and harvest is determined endogenously. In both papers the models are based on the mixed complementarity format which permits detailed modeling of the growth and harvest of a biomass stock.

Beyond the direct integration of ecology and the economy, the complementarity representation readily accommodates income effects and important second-best characteristics such as tax distortions or market failures (externalities). The utilization of weak inequalities allows modeling of problems where, for at least some of these inequalities, we do not know a priori which will hold as strict inequalities and which will hold with equality at an equilibrium. For example, inequalities may appear if production of a commodity is specified by alternative technical processes, or the economic problem under consideration may involve various types of institutional constraints on prices or quantities. These features of the complementarity format makes it particularly valuable in policy analysis.

3 Complementarity in a competitive market equilibrium

This section provides an introduction to the mixed complementarity problem (MCP), and relates the MCP format to a competitive economic equilibrium. The purpose is primarily pedagogic, but the difference between this section's static equilibrium and the inherently dynamic equilibrium (due to the nature of biomass growth) presented later in paper 2 and 3, is not overwhelming.

Mathematically, the MCP is a square system of functional relations, $\mathbf{f}(\mathbf{z})$, and variables, $\mathbf{z}$, which can be stated as:

Find $\mathbf{z}$ such that:

$$f_i(\mathbf{z}) = 0 \text{ and } lo_i \leq z_i \leq up_i, \quad i = 1, \ldots, n$$

or

$$f_i(\mathbf{z}) \geq 0 \text{ and } z_i = lo_i$$

or

$$f_i(\mathbf{z}) \leq 0 \text{ and } z_i = up_i$$

where:

$\mathbf{z}$	is a vector of variables to be found
$\mathbf{f}(\mathbf{z})$	is a (possibly nonlinear) vector-valued function
up and **lo**	are vectors of upper and lower bounds on the variables, where elements in **lo** may be $-\infty$ and elements in **up** may be $+\infty$.

When modeling an economic equilibrium the variables typically describe activity levels and non-negative prices, see Mathiesen (1985a), hence lower bounds are at zero ($\mathbf{lo} = 0$), upper bounds at infinity ($\mathbf{up} = \infty$), and the system of relations reduces to:

Find $\mathbf{z}$ such that:

$f_i(\mathbf{z}) = 0$ and $z_i \geq 0$

or

$f_i(\mathbf{z}) \geq 0$ and $z_i = 0$

The dimensions of $\mathbf{z}$ and $\mathbf{f}(\mathbf{z})$ are equal, producing a square system.

The problem can be written compactly as:

$$\mathbf{f}(\mathbf{z}) \geq 0 \perp \mathbf{z} \geq 0 \tag{1}$$

where the $\perp$ ("perpendicular to") symbol indicates pair-wise complementarity between the vector-valued elements of function $\mathbf{f}(\mathbf{z})$ and the variables $\mathbf{z}$. Note that the MCP does not have an objective function as in an optimization problem.

Consider a closed competitive market economy, Arrow and Debreu (1954), were individuals are price takers and engage in cost-minimization behavior. There are n tradable commodities (goods and factors) in the economy, some of which at least are produced in m (positive homogeneous) non-increasing return to scale (NIRS) production activities. There are h households or consumption units, each with an initial endowment, w, of commodities. The decision variables of the economy can be classified into four categories:

- $\mathbf{p}$ is a vector ((n x 1) with index i) in prices for all goods and factors,
- $\mathbf{y}$ denotes a vector ((m x 1) with index j) of activity levels of NIRS production activities,
- $\mathbf{m}$ signifies a vector ((h x 1) with index k) of income levels for households,
- $\mathbf{u}$ represents a vector ((h x 1) with index k) of utility index for households, and
- $\mathbf{p}^u$ indicates a vector ((h x 1) with index k) of prices of the utility indexes.

The original formulation by Mathiesen (1985a) contained only prices of goods and factors, $\mathbf{p}$, and activity levels, $\mathbf{y}$. The variables $\mathbf{m}$, $\mathbf{u}$, and $\mathbf{p}^u$ are introduced for convenience, but could be taken away.

The competitive market equilibrium is characterized by the following five conditions:

- Zero profit: implies that no economic activity earns positive economic profit:

$$-\pi_j(\mathbf{p}) = c_j(\mathbf{p}) - r_j(\mathbf{p}) \geq 0, \ \forall j \tag{2}$$

where:

$$c_j(\mathbf{p}) \equiv \min_{\mathbf{a}_j} \left\{ \sum_i p_i a_{i,j} \middle| f_j(\cdot) = 1 \right\} \quad \text{and}$$
$$r_j(\mathbf{p}) \equiv \max_{\mathbf{b}_j} \left\{ \sum_i p_i b_{i,j} \middle| g_j(\cdot) = 1 \right\}$$

defines the cost and revenue functions per unit activity level of activity j, resulting from cost-minimization and revenue-maximization behavior,

$\mathbf{a}_j$	denotes the feasible commodity input bundle per unit activity level of activity j,
$\mathbf{b}_j$	denotes the feasible commodity output bundle per unit activity level of activity j,
f_j, g_j	describes the feasible input- and output-combinations of production in activity j,
$\pi_i(\mathbf{p})$	denotes the unit-profit function for NIRS production activities,

- Market clearance: requires that no commodity is in excess demand, or equivalently, excess supply is non-negative[1]:

$$\xi_i(\mathbf{p},\mathbf{y}) = \sum_j y_j \frac{\partial \pi_j(\mathbf{p})}{\partial p_i} + \sum_k \left[w_{i,k} - \frac{\partial e_k(\mathbf{p})}{\partial p_i} m_k \right] \geq 0,\ \forall i \qquad (3)$$

where:

$$e_k(\mathbf{p}) \equiv \min_{\mathbf{x}_k} \left\{ \sum_i p_i x_{i,k} \,|\, u_k(\mathbf{x}_k) = 1 \right\}$$

	defines the compensated expenditure per unit utility for good i by household k resulting from expenditure-minimization behavior,
$\mathbf{x}_k$	denotes the consumption commodity bundle per unit utility for household k,
$u_k(\cdot)$	is a linear homogeneous utility function resulting from any homothetic preference ordering system,
m_k	indicates the income level of household k,
$w_{i,k}$	indicates the initial non-negative endowment of commodity i by household k,
$\frac{\partial e_k(\mathbf{p})}{\partial p_i}$	indicates the compensated demand for good i per unit utility of household k,
$\frac{\partial \pi_j(\mathbf{p})}{\partial p_i}$	is the supply of good i per unit operation of activity j,
$\xi_i(\mathbf{p},\mathbf{y})$	represents the excess supply function for commodity i.

- Income balance: This is not a condition for equilibrium but rather a definition, introduced for convenience, of the income, m_k, for each household as the sum of the value of initial endowments:

$$m_k \equiv \sum_i p_i w_{i,k},\ \forall k \qquad (4)$$

- Zero profit (utility): This constraint, together with constraint (6), is introduced to control the levels of the variables $\mathbf{u}$ and $\mathbf{p}^u$. The constraint is not necessary for the equilibrium but introduced for convenience and states that unit expenditure equals the marginal price of utility:

$$e_k(\mathbf{p}) = p_k^u,\ \forall k \qquad (5)$$

[1]Note that from the assumption of linear homogeneity of utility we have $e_k(\mathbf{p}, m_k) = e_k(\mathbf{p}) m_k$.

- Market clearance (utility): This constraint, together with constraint (5), is introduced to control the levels of the variables $\mathbf{u}$ and $\mathbf{p}^u$. The constraint is not necessary for the equilibrium but introduced for convenience[2]:

$$u_k = \frac{m_k}{p_k^u},\ \forall k \tag{6}$$

- Irreversibility: All activities are operated at non-negative levels:

$$\begin{array}{lcl} \mathbf{y} & \geq & 0 \\ \mathbf{u} & \geq & 0 \end{array} \tag{7}$$

- Free disposal: Prices remain non-negative:

$$\begin{array}{c} \mathbf{p} \geq 0 \\ \mathbf{p}^u \geq 0 \end{array} \tag{8}$$

- Non-satiation: Assuming that underlying utility functions exhibit non-satiation, household expenditure will exhaust income, hence:

$$\sum_i p_i \left(w_{i,k} - \frac{\partial e_k(\mathbf{p})}{\partial p_i} m_k \right) = 0,\ \forall k \tag{9}$$

Walras' law together with conditions (3) and (8) imply:

$$p_i \xi_i(\mathbf{p}, \mathbf{y}) = 0,\ \forall i \tag{10}$$

This means that, in equilibrium, a commodity in excess supply must have zero price, and for a commodity with positive price the market must clear.

From conditions (3) and (9) and equation (10) we obtain[3]:

$$\sum_i p_i \xi_i(\mathbf{p}, \mathbf{y}) = 0 \tag{11a}$$

$$\sum_i p_i \left[\sum_j y_j \frac{\partial \pi_j(\mathbf{p})}{\partial p_i} + \sum_k \left[w_{i,k} - \frac{\partial e_k(\mathbf{p})}{\partial p_i} m_k \right] \right] = 0 \tag{11b}$$

$$\sum_j y_j \sum_i p_i \frac{\partial \pi_j(\mathbf{p})}{\partial p_i} + \sum_k \left[\sum_i p_i \left[w_{i,k} - \frac{\partial e_k(\mathbf{p})}{\partial p_i} m_k \right] \right] = 0 \tag{11c}$$

$$\sum_j \lambda_j y_j \pi_j(\mathbf{p}) = 0 \tag{11d}$$

$$\sum_j y_j \pi_j(\mathbf{p}) = 0 \tag{11e}$$

[2]Note that with linear homogeneous utility, the indirect utility function can be written $V(\mathbf{p}, m) = \frac{m}{e(\mathbf{p})}$.

[3]With the assumption of NIRS, unit profit functions are positive homogeneous in prices and by Euler's homogeneous function theorem $\lambda_j \pi_j(p) = \sum_i p_i \frac{\partial \pi_j(\mathbf{p})}{\partial p_i}$, where $0 < \lambda_j \leq 1$ is the degree of homogeneity

where $0 < \lambda_j \leq 1$ is the degree of homogeneity for production activity j.

Conditions (2) and (9) together with equation (11e) imply:

$$-y_j \pi_j(\mathbf{p}) = 0, \quad \forall j \tag{12}$$

This means that, in equilibrium, an activity that earns negative profit is non-active, enabling the modeling of non-profitable benchmark activities that may become active when a policy instrument is applied, e.g. the stimulation of an ineffective sector when the taxable sector is taxed. The reverse can also be modeled, of course, i.e. the decline of a previously profitable activity when a policy that disfavors it is introduced, as will be shown in one scenario addressed in this paper.

To summarize:
Conditions (2) and (7), and equation (12) reveal the complementarity relation between the profit function, $\pi(\mathbf{p})$, and the activity levels, $\mathbf{y}$:

$$-\pi_j(\mathbf{p}) \geq 0, \quad y_j \geq 0, \quad -y_j \pi_j(\mathbf{p}) = 0, \quad \forall j \tag{13}$$

From (3), (8), and (10), we see the complementarity relation between the excess supply function, $\xi(\mathbf{p}, \mathbf{y})$, and prices, $\mathbf{p}$:

$$\xi_i(\mathbf{p}, \mathbf{y}) \geq 0, \quad p_i \geq 0, \quad p_i \xi_i(\mathbf{p}, \mathbf{y}) = 0, \quad \forall i \tag{14}$$

Finally, identity (4) for income can be written in terms of complementarity to itself,

$$m_k - \sum_i p_i w_{i,k} = 0, \quad m_k \geq 0, \quad m_k(m_k - \sum_i p_i w_{i,k}) = 0, \quad \forall k \tag{15}$$

and constraints (5) and (6) can be stated in terms of complementarity to variables $\mathbf{u}$ and $\mathbf{p}^u$ according to:

$$e_k(\mathbf{p}) - p_k^u = 0, \quad u_k \geq 0, \quad u_k(e_k(\mathbf{p}) - p_k^u) = 0, \quad \forall k \tag{16}$$

$$u_k - \frac{m_k}{p_k^u} = 0, \quad p_k^u \geq 0, \quad p_k^u(u_k - \frac{m_k}{p_k^u}) = 0, \quad \forall k \tag{17}$$

Relations (13), (14), (15), (16), and (17) can be written more compactly as:

$$\begin{aligned} -\pi(\mathbf{p}) \geq 0 &\perp \mathbf{y} \geq 0 \\ \mathbf{e}(\mathbf{p}) - \mathbf{p}^{\mathbf{u}} = 0 &\perp \mathbf{u} \geq 0 \\ \xi(\mathbf{p}, \mathbf{y}) \geq 0 &\perp \mathbf{p} \geq 0 \\ \mathbf{u} - \frac{\mathbf{m}}{\mathbf{p}^u} = 0 &\perp \mathbf{p}^u \geq 0 \\ \mathbf{m} - \mathbf{W}\mathbf{p} = 0 &\perp \mathbf{m} \geq 0 \end{aligned}$$

Which is equivalent to:

$$\begin{aligned}
\mathbf{c}(\mathbf{p}) &\geq \mathbf{r}(\mathbf{p}) && \perp\ \mathbf{y} \geq 0 && \text{(18a)}\\
\mathbf{e}(\mathbf{p}) &= \mathbf{p}^{u} && \perp\ \mathbf{u} \geq 0 && \text{(18b)}\\
\mathbf{y}^T \nabla_p \mathbf{r}(\mathbf{p}) + \mathbf{1}^T \mathbf{W} &\geq \mathbf{y}^T \nabla_p \mathbf{c}(\mathbf{p}) + \mathbf{m}^T \nabla_p \mathbf{e}(\mathbf{p}) && \perp\ \mathbf{p} \geq 0 && \text{(18c)}\\
\mathbf{u} &= \frac{\mathbf{m}}{\mathbf{p}^{u}} && \perp\ \mathbf{p}^{u} \geq 0 && \text{(18d)}\\
\mathbf{m} - \mathbf{W}\mathbf{p} &= 0 && \perp\ \mathbf{m} \geq 0 && \text{(18e)}
\end{aligned}$$

where:

$\pi(\mathbf{p})$	is the vector-valued (m x 1) unit profit function,
$\xi(\mathbf{p},\mathbf{y})$	denotes the vector-valued (n x 1) excess supply function,
$c(\mathbf{p})$	indicates the vector-valued (m x 1) unit cost function,
$r(\mathbf{p})$	signifies the vector-valued (m x 1) unit revenue function,
$e(\mathbf{p})$	represents the vector-valued (h x 1) expenditure function, and
$\frac{m}{\mathbf{p}^{u}}$	is defined as the per element division.

In equilibrium, commodities in excess supply must have zero prices, and where commodities have positive prices, markets must clear. An activity that earns negative economic profit is idle, and an activity with a positive activity level must earn zero economic profit. Further, negative prices, negative activity levels, negative excess supply, or positive economic profit cannot exist in equilibrium due to the restrictions $0 \leq \mathbf{p} < \infty$, on prices, and $0 \leq \mathbf{y} < \infty$ on activity levels.

4 Summary of articles

4.1 Demand for waste as fuel in the Swedish district heating sector: a production function approach

This study investigates fuel substitutions in Swedish district heating plants due to changes in the price of waste. It assesses the extent to which the Swedish district heating industry is likely to change its choice of fuel if the price of waste changes. While the operators of waste incinerators charge fees for handling and disposing of waste, it also provides fuel. This industrial enterprise is modeled as a multi-output production system, in which the plants both generate energy (for district heating) and provide a waste disposal service. The waste incinerator plants are therefore considered as bearing extra costs for the handling and disposal of the waste they receive as a fuel input. This implies that the waste incineration industry incurs a net cost for the waste it utilizes. The net price of waste for the waste incineration industry is assumed to change in response to new taxes on waste incineration SFS 2006:592 (2006).

A multi-output plant-specific production function is estimated using panel data methods. A procedure for weighting the elasticities of factor demand to produce a single matrix for the whole industry is introduced. The price of waste is assumed to increase in response to the energy and CO_2 tax on waste-to-energy incineration that was introduced in Sweden on July 1, 2006. The study reveals that price changes for waste fuel have the expected result, i.e. negative own-price and positive cross-price elasticities. Analysis of the plants involved in waste incineration indicates that an increase in the net price of waste by 10% is likely to reduce the demand for waste by 4.2%, and increase the demand for bio-fuels, fossil fuels, other fuels and electricity by 5.5%, 6.0%, 6.0% and 6.0%, respectively.

4.2 Towards a dynamic Ecol-Econ CGE model with forest as biomass capital

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).

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[4]. 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 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

[4]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.

initial Area Distribution Vector, describing the state of the forest, and a Transition Probability Matrix, which describes the growth process 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.

4.3 Dynamic CGE-model with heterogeneous forest biomass: Applications to climate policy.

This study presents a dynamic computable general equilibrium (CGE) model that combines (in richer detail than similar, previous models) a general equilibrium description of an economy and an ecological model describing changes in forest biomass. The ecological model is a straightforward forest growth model describing the population dynamics of forests in which a clear-cut harvesting regime is applied. The model's main intended uses include modeling the likely effects of economic policy measures that could be introduced to foster carbon sequestration. For such purposes, a key parameter is the total biomass present in forest stocks, which can be fairly easily estimated. However, in order to model changes in total biomass, knowledge of other ecological aspects (notably the age-class distribution of the trees and rotation lengths) must be known (Getz and Haight, 1989). Therefore, the ecological model of the forest biomass stock presented here has a detailed age-structured representation of growth and harvests, interlinked with the economy. Harvests and demand for forest products are determined endogenously in an inter-temporally consistent way. The CGE is formulated as a mixed complementarity problem (Mathiesen, 1985a).

The role of forestry in climate policy has been extensively studied from an economic perspective (see Sedjo et al. (1995) or Parks et al. (1997) for summaries of the economic aspects, and Sedjo et al. (1997) for summaries of the relevant literature from a broader perspective). Forest ecosystems constitute large carbon pools and could have significant impacts on changes in the carbon dioxide (CO_2) concentration in the atmosphere (Birdsey (1992), Dixon et al. (1994),Houghton (1991), Winjum et al. (1992)). Thus, adding forest sequestration as an option to a country's climate policy can offer significant net benefits, although these benefits are likely to vary considerably across countries.

Sequestration of CO_2, has attracted growing interest among government policy makers recently. For example, the Swedish government bill Government Bill 2007/08:108, (2008), states that it is *important to analyze the conditions for the instruments and controls eligible for the forestry sector to contribute further to a cost-effective achievement of Swedish climate policy*.

Technically, there are several ways to increase the CO_2 sequestration of forests, such as increasing the forest area, changing management regimes for existing forests, prolonging the lifetime of timber products and increasing the utilization of bioenergy. Of course, forests sequestrate CO_2 even if they are not managed for this purpose. However, CO_2 sequestration is not completely compatible with all the other objectives of forest management. Thus, optimizing the utilization of forest resources to increase CO_2 sequestration may require adjustment of forestry practices. This paper focuses on the management of existing forests, particularly on the incentive schemes that could be applied to increase CO_2 sequestration by forest owners. Effects of policies on other sectors that are heavily dependent on forest biomass, such as the pulp, wood, and (at least in Sweden) biomass incineration for energy production sectors, are also specifically considered. The policy instruments considered can be described as follows.

Scenario 1 Awards of payments to forest owners for CO_2 sequestrated due to forest growth in each time period, and deductions of tax for the CO_2 content of each harvest.

Scenario 2 In addition to the measures applied in Scenario 1, the provision of rebates for forest owners on CO_2 payments related to harvest, depending on the final products the harvested roundwood biomass is used to make, and how long these products prevent the sequestrated CO_2 from entering the atmosphere.

Scenario 3 In addition to the measures applied in Scenarios 1 and 2, provision of rebates for forest owners on CO_2 payments related to harvest, depending on stumpage left in the forest and how long the stumpage prevents the sequestrated CO_2 from entering the atmosphere.

Effects of similar types of policy instrument have been investigated in other studies, see for example Van Kooten et al. (1995) and Gong and Kriström (1999). The main difference here is in the heterogenity of the biomass.

The results suggest that the cost to society of the investigated policy scenarios, would be larger in the beginning of the planning horizon, but there might be a considerable delay before carbon storage in the forest increased significantly. The analysis of the examined policy scenarios also indicates that large money transfers among the forest owners are likely to occur as the values of the harvest tax and growth subsidies relative to total income tend to be considerable.

The analysis indicates that biomass use is likely to shift from the pulp industry towards the wood industry, due to differences in the age-specific types of biomass used by the industries. This is intuitively plausible, since the sequestration policy makes the forest older.

The results also suggest that introduced policies would induce wealth transfer to forest owners from other economic agents. These transfers are likely to be further enhanced if tax rebates are established. Tax rebates targeting CO_2 storage in products (Scenario 2), tend to increase total CO_2 storage, while a tax rebate directed at CO_2 storage in stumpage left in the forest (Scenario 3) might decrease total CO_2 storage. The introduction of tax rebates increases social costs of these CO_2 storage-increasing policies, and the most expensive, Scenario 3, might also result in lower CO_2 storage compared with the other scenarios.

References

Arrow, K. and G. Debreu (1954). Existence of an Equilibrium for a Competitive Economy. *Econometrica 22*(3), 265–290.

Binkley, C., M. Percy, W. Thompson, and I. Vertinsky (1994). A general equilibrium analysis of the economic impact of a reduction in harvest levels in British Columbia. *Forestry Chronicle 70*(4), 449–454.

Birdsey, R. (1992). Carbon storage and accumulation in United States forest ecosystems. *Notes*.

Brännlund, R. and B. Kriström (2001, october). Too hot to handle? - benefits and costs of stimulating the use of biofuels in the swedish heating sector. *Resource and Energy Economics 23*(4), 343–358.

Chambers, R. (1988). *Applied production analysis: a dual approach*. Cambridge Univ Pr.

Dixon, R., S. Brown, R. Houghton, A. Solomon, M. Trexler, and J. Wisniewski (1994). Carbon pools and flux of global forest ecosystems. *Science(Washington) 263*(5144), 185–189.

Getz, W. and R. Haight (1989). *Population harvesting: demographic models of fish, forest, and animal resources*. Princeton University Press.

Gong, P. and B. Kriström (1999). Regulating Forest Rotation to Increase CO_2 Sequestration. *Working paper 272, Department of forest economics, Swedish University of Agricultural Sciences, S-901 83 Umeå, Sweden* (272).

Government Bill 2007/08:108, (2008). A forest policy in line with the times, Swe: En skogspolitik i takt med tiden.

Harberger, A. (1962). The incidence of the corporation income tax. *The Journal of Political Economy*, 215–240.

Haynes, R., D. Adams, and J. Mills (1995). The 1993 RPA timber assessment update. USDA For. Serv. *General Technical Report RM-259. USDA Forest Service. Ft Collins, CO 66*.

Houghton, R. (1991). Tropical deforestation and atmospheric carbon dioxide. *Climatic change 19*(1), 99–118.

Johansen, L. (1960). *A multi-sectoral study of economic growth*. North-Holland Amsterdam.

Lau, M. I., A. Pahlke, and T. F. Rutherford (2002). Approximating infinite-horizon models in a complementarity format: A primer in dynamic general equilibrium analysis. *Journal of Economic Dynamics and Control 26*(4), 577 – 609.

Lundgren, T., P. Marklund, R. Brännlund, and B. Kriström (2008). The Economics of Biofuels. *International Review of Environmental and Resource Economics 2*(3), 237–280.

Lundmark, R. and A. Mansikkasalo (2009). European trade of forest products in the presence of EU policy. *Journal of Cleaner Production (forthcoming, available online).*

Mathiesen, L. (1985a). Computation of economic equilibria by a sequence of linear complementarity problems. *Mathematical Programming Study 23*, 144–162.

Mathiesen, L. (1985b). Computational experience in solving equilibrium models by a sequence of linear complementarity problems. *Operations Research 33*(6), 1225–1250.

New Zealand Forest Research Institute (1999). Study of Non-Tariff Measures in the Forest Products Sector.

Nilsson, P. (2006). Biomassaflöden i svensk skogsnäring 2004. *Skogsstyrelsens Rapporter* (23).

Parks, P., D. Hall, B. Kriström, O. Masera, R. Moulton, A. Plantinga, J. Swisher, and J. Winjum (1997). An economic approach to planting trees for carbon storage. *Critical Reviews in Environmental Science and Technology 27*, 9–21.

Ramsey, F. (1928). A mathematical theory of saving. *The Economic Journal*, 543–559.

Sallnäs, O. (1990). A matrix growth model of the Swedish forest. *Studia Forestalia Suecica 183*, 23.

Schelhaas, M., J. Eggers, M. Lindner, G. Nabuurs, A. Pussinen, R. Päivinen, A. Schuck, P. Verkerk, D. Van der Werf, and S. Zudin (2007). *Model documentation for the European Forest Information Scenario model (EFISCEN 3.1. 3).* Alterra.

Sedjo, R., R. Sampson, and J. Wisniewski (1997). *Economics of carbon sequestration in forestry*. CRC Press.

Sedjo, R., J. Wisniewski, A. Sample, and J. Kinsman (1995). The economics of managing carbon via forestry: assessment of existing studies. *Environmental and Resource Economics 6*(2), 139–165.

SFS 2006:592 (2006). *Lag om ändring i lagen (1994:1776) om skatt på energi*. Svensk författningssamling.

Swedish energy Agency (2009). Energy in Sweden 2008. (2058).

Van Kooten, G., C. Binkley, and G. Delcourt (1995). Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. *American Journal of Agricultural Economics 77*(2), 365–374.

Winjum, J., R. Dixon, and P. Schroeder (1992). Estimating the global potential of forest and agroforest management practices to sequester carbon. *Water, Air, & Soil Pollution 64*(1), 213–227.

Acknowledgements

I would like to thank my supervisor Tommy Lundgren for his involvement and excellent supervising, my deputy supervisor Bengt Kriström for his laid back approach to research and his generosity in sharing of his great knowledge in the field of economics. I would also like to thank friends and colleagues at the Department of Forest Economics to which I owe a lot. Furthermore I would like to gratefully acknowledge the generous financial support from The Swedish Research Council Formas. Last but not least I would like to thank friends and family for their invaluable support.