Economics of Timber Production and Climate Change Mitigation

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Abstract

Timber and bioenergy production and forest carbon sequestration are intrinsically interrelated with one another. Consisting of four papers, this thesis addresses their interactions from different perspectives in Sweden. The motivation for the thesis is triggered by two of the national environmental quality objectives, Reduced Climate Impact and Sustainable Forests. The overall goal of the thesis is to increase understanding of the potential trade-offs and synergies between timber production, bioenergy, and forest carbon sequestration.

To achieve the goal of the study, a partial equilibrium (PE) model of Swedish timber market is calibrated in paper I and developed in paper II to paper IV. Respectively, in paper I the model is extended to include non-timber benefits and then the model is calibrated by finding a proper level of the non-timber benefits. By examining the interaction between timber production and forest sequestration under alternative hypothetical carbon prices, paper II estimates the cost of enhancing forest carbon sequestration. Paper III focuses on the impacts of increasing fuelwood demand on the Swedish forest sector. The interactions between three major timber products and forest resources are examined. Besides fuelwood, paper IV encompasses a wider range of biomass feedstock for bioenergy. The complex interdependence between bioenergy, timber production, and forest carbon are addressed explicitly. In addition, carbon balance associated with bioenergy expansion is projected over time to reveal the complex dynamics involved in forest-based carbon mitigation.

The results of these papers show that the inclusion of non-timber benefits in the forest sector modeling framework can more accurately reflect the objectives of forest owners. Promoting forest carbon sequestration in Sweden to mitigate climate change can be a relatively low-cost option, and it is more effective in the short term. The potential expansion of bioenergy will change the optimal mix of timber and non-timber products and services, causing competition between timber markets and affecting forest carbon. It is worth noting that the climate benefits of using bioenergy compared to fossil fuels are time dependent. The findings of this thesis will contribute to informing policymakers of the potential impacts of the different policy instruments, assisting them in handling trade-offs between sometimes conflicting policy goals.

Keywords: forest sector modeling, carbon sequestration, partial equilibrium model, bioenergy, climate change

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Dedication

To my loving family

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Gong, P., Guo, J. (2017). Estimating landowners' valuation of non-timber benefits based on the optimal timber supply. (manuscript).

II Guo, J., Gong, P. (2017). The potential and cost of increasing forest carbon sequestration in Sweden. *Journal of Forest Economics, 29,* 78–86.

III Guo, J., Gong, P. (2018). Assessing the impacts of rising fuelwood demand on Swedish forest sector: An intertemporal optimization approach. (manuscript).

IV Guo, J., Gong, P., Brännlund R. (2018). Impacts of increasing bioenergy production on timber harvest and carbon emissions. (manuscript).

Papers II is reproduced with the permission of the publisher.

The contribution of authors to the papers included in this thesis was as follows:

I Peichen Gong developed the idea and wrote the manuscript. Jinggang Guo performed the analysis and helped in the interpretation of results.

II The authors jointly developed the idea. Jinggang Guo developed the model, performed the analysis, and wrote the manuscript. Peichen Gong helped in interpretation of the results and substantially revised the manuscript.

III The authors jointly developed the idea. Jinggang Guo developed the model, performed the analysis, and wrote the manuscript. Peichen Gong contributed with recommendation and corrections to the manuscript.

IV The authors jointly developed the idea, discussed the results, and commented on the manuscript. Jinggang Guo developed the model, performed the analysis, and wrote the manuscript.

1 Introduction

1.1 Background and objective

Climate change is one of the major challenges of our generation. The Paris Agreement, which came into force on November 4, 2016, aims to keep the worldwide temperature increase below 2 °C to reduce the impacts and risks of climate change (United Nations Framework Convention on Climate Change [UNFCCC], 2016). Using forests to mitigate carbon emissions has been gaining considerable interest in the policy discussions and are considered a critical factor in achieving Paris Agreement goals (UNFCCC, COP22). One way of reducing atmospheric CO_2 is to increase the carbon sink in forests. The world's forests store an estimated 296 gigatons (Gt) of carbon in the form of biomass (Forest Resources Assessment [FAO], 2015) and have a substantial impact on the global carbon cycle (Intergovernmental Panel on Climate Change [IPCC], 2007), thereby affecting the climate. Numerous studies have recognized forests as an effective tool for mitigate carbon emissions (e.g., Barker et al., 2007; Bosetti et al., 2009; Murray et al., 2009; Smith et al., 2014; Sohngen and Mendelsohn, 2003). However, the inclusion of forest sequestration in the climate policy framework is still hotly debated. The cost of using this option is an important factor that policymakers take into account when exploring the potential for the use of forest carbon sinks as a mitigation policy option. A comprehensive estimate of the cost of forest sequestration will help understand the potential and economics of this option, and offer a benchmark for comparing alternative mitigation policies, especially in the context of a bio-economy that encourages the use of biomass for bioenergy.

Using forest-based biomass to substitute fossil fuels is another way of reducing carbon emissions. Forest bioenergy is considered carbon-neutral in the current European energy policy framework (European Directives 2009/28/EC and 2009/29/EC), which means the use of bioenergy will not add extra carbon to the atmosphere. The use of bioenergy also helps reduce dependence on fossil fuels and improve the country's energy security. In the past few years, many countries have introduced policies designed to support bioenergy, such as feed-in tariffs, feed-in premiums, biofuel mandates, and green certificates. The forest sector as a whole is the largest supplier for bioenergy and wood biomass accounts for 87% of the supply of bioenergy globally (World Bioenergy Association [WBA], 2017). As bioenergy use expands, multiple concerns have been raised about the interactions and provision of timber products, and other ecosystem services, e.g., recreation, biodiversity, and forest sequestration. A clear idea of the possible interactions in the use of forest resources will help policymakers determine the optimal mix of timber and non-timber products, and reduce the adverse impacts of bioenergy expansion.

The overall goal of the thesis is to enhance understanding of two research questions: (1) What are the costs and impacts of increasing forest sequestration? (2) How will rising bioenergy demand impact the interdependence between timber markets and the dynamics of forest resources in Sweden? The thesis is based on a partial equilibrium (PE) model of the Swedish timber market (STIMM) built by Gong and Löfgren (2003). To accommodate the overall goal, calibration and further extensions have been made to the prototype STIMM model. Specifically, the objective of each paper is as follows:

- Paper I aims to develop the STIMM model to make it suitable for quantitative analysis of forest policy or market structure changes.
- Paper II aims to assess the impacts of a carbon tax/subsidy scheme on timber production, forest sequestration, and other non-timber benefits, and to estimate the cost of such an incentive scheme in enhancing forest carbon sequestration.
- Paper III aims to examine the impacts of growing fuelwood demand on the timber markets, and to evaluate the interdependence between different timber products and forest carbon stocks.
- Paper IV aims to investigate the interaction between timber, bioenergy products, and forest carbon sequestration, to project the carbon flow path given different bioenergy targets, and to explore the contribution of forest residues in the future bioenergy supply.

The thesis consists of this summary and four papers. The summary is structured as follows. A brief overview of related studies is presented in the rest of Chapter 1. Chapter 2 gives an overview of the method used in the thesis. Chapter 3 summarizes the main results of each of the four papers. Chapter 4 contains conclusions and discussion of future work.

1.2 Forest sequestration

Sweden has rich forest resources: The annual growth of Swedish forests is 120 million m^3 and about 90 million m^3 of standing volume is harvested each year (Swedish Forest Agency, 2015). The discrepancy between the growth and harvest indicates great potential for an increase in the carbon stored in Swedish forests. Due to the lack of incentive programs, however, this mitigation option has not received adequate attention. A proper estimate of forest sequestration costs will provide a benchmark for comparison with other abatement options and help policymakers consider the potential role of forest sequestration programs in a climate mitigation strategy.

The cost of carbon sequestration in mitigating CO_2 has been the subject of extensive studies. The methods, geographic scope, and assumptions differ greatly across studies (Dempsey et al., 2009). Richards and Stokes (2004) estimated the costs of forest sequestration to be between about USD 10 and USD 150 per ton of carbon after reviewing 22 studies on carbon sequestration in forests. Substantial variations in the costs of forest sequestration can also be found in van Kooten et al. (2004), Stavins and Richards (2005), and van Kooten and Sohngen (2007). Many studies estimate the cost of forest sequestration through using hypothetical payment programs to create incentives for forest owners. Afforestation, reforestation, and avoided deforestation are the most widely examined options (Bosetti et al., 2011; Gren et al., 2012; Kindermann et al., 2008; Lubowski et al., 2006; Sohngen and Sedjo, 2006). Phan et al. (2014) synthesized 32 studies of costs of avoided deforestation in developing countries and found that the costs ranged vastly between USD 0.11 and USD 246 per ton of carbon.

Less attention has been paid to assessing how different forest management strategies can contribute to carbon sequestration and the associated costs. One example is Im et al. (2007) for the case of western Oregon. The authors developed a dynamic model to examine forest owners' response to carbon tax and demonstrated how forest owners would adjust harvest under a range of fixed levels of carbon tax. Their results showed that the introduction of carbon tax led to reduced harvest and enhanced carbon stocks in the forest. The average social cost of sequestration would rise to USD 185.3 per ton of carbon to achieve an additional 4.7 Mt of CO_2 to be sequestered. Backeus et al. (2005) conducted a case study of a 3.2 million ha boreal forest in northern Sweden. The authors developed the optimization model of Hoen and Solberg (1994) by assigning carbon storage a monetary value, and examined the trade-offs between carbon sequestration and timber production. The results showed that net forest carbon sequestration increased monotonically from 1.48 to 2.05 million tons of carbon per year given carbon prices from zero to SEK 2,308 per ton of carbon. Vass and

Elofsson (2016) focused on the cost-effectiveness of carbon sequestration through forest management for carbon mitigation at the European level. The authors concluded that the mitigation cost would be reduced by 23% through forest carbon sequestration compared with the decreased use of fossil fuels to meet the European Union (EU) 2050 mitigation target. However, the sequestration cost at the country level is not addressed in their paper. In general, the focus of previous studies examining the costs of carbon sequestration through forest management has been more on the regional level rather than the national level. In addition, how timber and other forest benefits react to the use of incentives for forest sequestration has not been fully addressed in previous studies. One exception is Sjølie et al. (2013) for the Norwegian forest sector. To our knowledge, there is still a lack of analysis of the potential and cost of using incentives to increase forest sequestration on a national scale in Sweden.

1.3 Forest bioenergy

Support for the use of bioenergy has a long history in the EU (Thornley and Cooper, 2008). By 2020, bioenergy is expected to contribute to more than half of the EU's 20% renewable energy target (European Environment Agency [EEA], 2013). Benefiting from political support and the integration of bioenergy production with the forest industry and district heating systems, Sweden is a frontrunner in promoting bioenergy in Europe. Bioenergy use amounted to 134 TWh in 2015, making it the leading energy source. Bioenergy supply accounts for 25% of the Swedish energy demand, more than 85% of which originates from the domestic forest sector (Svebio, 2015). Increased use of biomass feedstock for bioenergy production is likely to affect the interactions between timber product markets, bioenergy production, and biomass feedstock. The future development of bioenergy is of high interest for forest owners and forest industries due to its potential impacts on timber prices, the competitiveness of forest industries, forest carbon stocks, and other non-timber benefits. Understanding the impacts will also help policymakers to identify the winners and losers from future bioenergy policies, and minimize the distortions in timber markets.

A number of studies have examined the interaction between the prices and quantities of timber products and bioenergy in the face of rising bioenergy demand using econometric models (e.g., Du and Runge, 2014; Geijer et al., 2011; Kristöfel et al., 2016; Lundmark and Olsson, 2015; Susaeta et al., 2013). Some studies have applied computable general equilibrium (CGE) models to capture the interactions between the forest sector and the rest of the economy resulting from the increased demand for bioenergy (e.g., Kretschmer and

Peterson, 2010; Suttles et al., 2014). Since each sector is represented at a highly aggregate level in the CGE model, this type of model is less suitable for disaggregated analysis of a specific sector.

Partial equilibrium (PE) models have dominated the analysis of impacts of increased bioenergy demand, allowing the evaluation of forest sector responses to bioenergy demand with varying levels of detail. Among those with global coverage are the Global Forest Products Model ([GFPM], Buongiorno et al., 2003), the Global Biosphere Management Model ([GLOBIOM], Lauri et al., 2014), and the European Forest Institute Global Trade Model ([EFI-GTM], Kallio et al., 2004). Among those focusing on impacts at the country level are the French Forest Sector Model ([FFSM], Caurla et al., 2010), the SF-GTM for the Finnish forest sector (Ronnila, 1995), and the Norwegian Trade Model ([NTM], Trømborg and Solberg, 1995). Recent applications of these PE models can be found in Table 1. One strength of such PE models is that they include several major groups of primary, intermediate, and final forest products. For example, the newly updated EFI-GTM (Kallio et al., 2018) covers 5 round wood assortments, 30 forest industries and energy sector products, 3 forest chip categories, and 4 recycled paper grades, making it suitable for examining the economic implications of bioenergy expansion for forest industries in greater detail. Besides the economic implications, the environmental implications of bioenergy use are also of great importance. However, due to the simplified forest resource representation in the modeling structure, PE models are less capable of examining the impacts on the dynamics of forest resources and climate-related costs and benefits. Based on the work of Lestander (2011), Carlsson (2012) developed an EFI-GTM family model of the Swedish forest sector with a focus on the Swedish forest product markets. However, this model is a static one-period model with no incorporation of forest resource dynamics.

Table 1. *Overview of recent applications of PE models of the forest sector*

Study	Model	Region	Application
Kallio and Solberg (2018)	EFI-GTM	Norway	Estimate the magnitude of carbon leakage of forest harvest changes to other countries
Johnston and van Kooten (2016)	RPFTM	Global	Investigate the impacts of the expansion of wood pellets in the EU on global trade
Kallio et al. (2016)	SF-GTM	Finland	Look into carbon balance in the case of increasing use of wood for bioenergy
Moiseyev et al. (2014)	EFI-GTM	Global	Analyze the impact of various subsidies on the use and price of wood biomass for bioenergy
Mustapha et al. (2017)	NFSM	Nordic	Quantify the biofuel production allocation in the presence of techno-economic parameter change
Lauri et al. (2017)	GLOBIOM	Global	Estimate the impacts of reaching a 2 °C target on global woody biomass use
Pohjola et al. (2018)	FinFEP	Finland	Investigate carbon leakage issue associated with a specific government-imposed forest land conservation program
Lauri et al. (2012)	EUFASOM	EU	Analyze the impacts of the carbon emission tax on the use of wood in Europe
Lobianco et al. (2016)	FFSM	France	Project forest carbon sequestration and substitution in French forests
Steinbuks and Hertel (2016)	FABLE	Global	Determine the optimal profile for global land use to meet the growing demand for forest products
Tian et al. (2016)	GTM	Global	Illustrate how potential climate change will impact the global forest sector
Beach et al. (2015)	FASOM	US	Quantify the potential impacts of climate change on US agriculture and forestry

1.4 Contribution

Each paper of the thesis contributes to the existing literature on the multiple roles of forests in climate change from different angles. Paper I contributes to the development and calibration of the STIMM model by integrating non-timber benefits in the framework. After calibration, the model is suitable for quantitative assessment of the impacts of forest policy changes on the provision of different timber products and non-timber services at the country level. Paper II offers some insight into how the use of market-based incentives will impact the potential of forest sequestration and timber products. The cost of forest sequestration estimated in this paper provides a basis for comparison with other mitigation options. Paper III provides a numerical optimization method to estimate the elasticities for different timber products, and assess the dynamic relationship between major timber markets under different growth rates in demand for fuelwood over both the short and long term. The surplus analysis helps identify the winner or loser in the forest sector for future fuelwood development. Paper 4 assists in understanding the complex forest biomass feedstock for traditional forest products, for bioenergy production, and for forest carbon stocks. This paper also decomposes the contributions of forest sequestration and forest bioenergy to the carbon balance, which sheds some light on the complex issue of how to balance bioenergy and sequestration.

2 Overview of the model

The thesis is a collection of four papers. Although each paper focuses on different aspects of the forest sector, they are all based on the same dynamic PE model constructed by Gong and Löfgren (2003). In what follows, I elaborate on the reasons for choosing this model, with a brief discussion of some of the limitations associated with the model application.

Economic and policy analysis over the long term is necessary for the forest sector given the substantial delays between the time when changes in external factors happen and the time when the full impacts are realized. Optimization models with perfect foresight, which allow for intertemporal decision-making, seem more suitable for conducting such long-term analysis. However, the computational limitations severely restrict their application. Conversely, recursive dynamic (RD) forest sector models have been widely used in forest sector simulation. Due to the myopic foresight assumption, together the deterministic demand and supply functions applied, RD models are better suited to performing short-term projections. The STIMM model used in the thesis is an intermediate alternative to these two types. Like these models, the STIMM model includes timber supply, demand, and forest resources at a national level. It provides integrated analysis of how and to what extent the timber price, harvest level, forest standing volume, and consumers' and producers' surplus may change in response to policy and market changes. What makes this model different from other models is that it endogenizes the coefficients of supply function(s) instead of these being exogenously assigned. The STIMM model optimizes the coefficients of the supply function within a given policy context, which are characterized by maximization of the present value of the total surplus (see, e.g., Lyon and Sedjo, 1983), and then simulates the market equilibrium prices and quantities using the optimized supply function.

The impact of policy change on (the location and elasticity of) the supply function is captured by optimizing the supply function with and without taking into account the policy change, respectively. At the same time, using the supply function to determine the market equilibrium prices and quantities, instead of determining the optimal quantities directly, can greatly reduce the number of decision variables. This simplification makes it possible to handle stochastic variations in future demand. Moreover, the model can also keep track of the structure and dynamics of Swedish forests, allowing the examination of timber products and other non-timber services with regard to the state of the forests.

The approach has been applied to assess the effects of hypothetical changes in timber market regimes (Gong and Löfgren, 2003) and the productivity of forest land (Gong et. al., 2013). These two studies used a prototype timber market model, which recognizes only one timber assortment and ignores the non-wood benefits, assuming that forest owners maximize the net present value of timber profits. This prototype model is not suitable for real-world analysis of forest-related policy. Among other things, the exclusion of non-wood benefits leads to an overly high level of timber harvest. To overcome these two limitations, extensive amendments have been made to the model, which can be found in Papers I–IV. Some perspectives for future extension of the model are addressed in Chapter 4.

3 Summary of the papers

This section provides a concise summary of each appended paper, regarding the background, objectives, methods, and results.

3.1 Estimating landowners' valuation of non-timber benefits based on the optimal timber supply

Over the past years, the Swedish forest sector has been undergoing continuous changes, switching focus from traditional timber production to production of non-timber goods and services, such as recreation, biodiversity, and forest sequestration. The question of how the forest sector and forest resources will respond to potential economic and policy changes has gained considerable attention. PE models that integrate forest resources and forest markets have a long history of effective use for assessing such questions and projecting future market trends within the forest sector. The main objective of this paper is to develop a tool suitable for the quantitative evaluation of the impacts of possible policies or market development on the provision of various forest products and services at the country level.

We choose the PE model first constructed by Gong et al. (2013) as our starting point. The reason for using this model is that it is a dynamic model at the country scale with perfect foresight on the part of forest owners. Both the timber market and growing forest resources are explicitly included in the model. The reason for developing this model is that the model currently assumes that forest owners only maximize the net present value of timber profits. The exclusion of non-timber benefits leads to an overly high level of timber harvest, making it less suitable for forest-related policy analysis.

We choose a 3-parameter logistic function of the stand age to represent the monetary value of non-timber benefits of a hectare of forest stand. The total value of non-timber benefits is obtained by summing the non-timber value of the forest stand for each age class and then include this in the model. We exogenously assign a set of values to the parameters of the non-timber benefits function, and solve the market model to determine the optimal supply functions, and the market equilibrium price and quantity of timber product. We use the mean market supply and price of timber during 2010–2014 as the reference to calibrate the values of these parameters. The calibration process of non-timber benefits continues until proper values of these parameters are obtained, such that the model can generate realistic solutions in terms of the harvest level. The result shows that the non-timber value of the productive forests managed for timber production ranges from 6.41 and 7.37 billion SEK per year, which corresponds to 30–37 percent of the net revenue of timber production.

To date, only a handful of PE models have considered the value of non-timber benefits. After calibration, the STIMM model can serve as a useful tool for quantitatively evaluating an array of alternative futures and policy options with regard to their impacts on the market equilibrium prices, quantities of timber products, and market surplus, as well as the impacts on the dynamics of forest resources over time. This paper lays the basis for further development of the model.

3.2 The potential and cost of increasing forest carbon sequestration in Sweden

Concern over climate change has raised interest in the use of forests for mitigation. Although extensive analysis has shown that forests have great potential for carbon sequestration, and thereby mitigating carbon emissions, whether it is worthwhile keeping the forests growing to sequester carbon is still hotly debated today. The extent to which forest carbon sequestration should be increased depends greatly on the marginal cost of doing so. This paper aims to answer two questions: (1) What is the cost of forest-based carbon sequestration in Sweden? (2) How market-based incentives may affect timber production and forest sequestration?

We first introduce a tax/subsidy scheme in the STIMM model. Under such a scheme, forest owners are assumed to be paid when net forest sequestration takes place and taxed at the same rate for the net carbon loss from the forests. The total amount to be paid or taxed for forest sequestration is calculated by multiplying the net accumulated amounts of carbon stored in forests with different payment rates (carbon prices). In this way, the monetary value of forest sequestration is explicitly modeled. The sequestration cost in this paper is evaluated under six carbon price scenarios.

Our analysis covers about 20 million ha of managed forests in Sweden. The results show that increasing forest carbon sequestration is a relatively low-cost option for reducing net emissions of CO_2. With a subsidy/tax rate in the range of SEK 170–1428 per tonne of CO_2, carbon sequestration in the 20 million ha managed forests over the period 2015–2050 could be increased by 30.2 million tonnes to 218.3 million tonnes of CO_2. The associated cost, in terms of reduced total benefits of timber and other non-timber goods, excluding the subsidy payment, ranges from SEK 80 to SEK 105.8 per tonne of CO_2. The effect of the economic incentive for carbon sequestration declines with time. The change in carbon sequestration from the business-as-usual case beyond 2050 is small when the carbon subsidy/tax rate is SEK 680 per tonne or lower. A carbon subsidy/tax rate of SEK 1428 per tonne could increase carbon sequestration by 70 million tonnes over 2050–2070, and by 64 million tonnes over 2070–2170. A seemingly "surprising" result of the analysis is that the carbon subsidy/tax would result in a higher present value of the profits of timber production. In other words, forest owners in general will not incur any cost by reducing the timber harvest to promote carbon sequestration, as is commonly perceived. This result suggests that the increase in timber price (due to the decrease in supply) can more than compensate for the reduction in harvest. The cost of increasing forest carbon sequestration lies in the decrease in the profits of the forest industry.

The paper concludes that forest carbon sequestration is a relatively low-cost option, and is more effective than other methods for mitigating carbon in the short term. However, the potential increase in carbon sequestration is relatively small. Moreover, implementing such a policy would require transactions of large amounts of public funds to forest owners, which needs to be taken into account when deciding whether the sequestered carbon should be part of national portfolios of carbon offset credits.

3.3 Assessing the impacts of rising fuelwood demand on Swedish forest sector: An intertemporal optimization approach

One of the most obvious effects of the introduction of the carbon tax on oil and natural gas in 1991 has been a surge in bioenergy use in the Swedish district heating system. As an important source of feedstock for bioenergy production, demand for fuelwood is expected to increase, which poses a threat to sawlog and pulpwood production, since to some extent they can be used as a substitute for fuelwood. Concerns also arise about its potential impact on the total amount of harvests. The objective of this paper is to assess the impacts of increasing fuelwood demand on the interactions between different timber products and forest resources.

Econometric modeling is a widely used method for estimating the interactions between different economic markets. However, historical relationships may no longer hold in future periods. Instead, this paper uses a numerical optimization model, developed based on the previous work in Paper II, to assess the market relationship via estimating the supply functions. The forest sector model developed recognizes four types of market participants: the forest owners who supply sawlog, pulpwood, and fuelwood; the sawmill sector, which uses sawlog to produce lumber products; the pulp mill, which uses pulpwood to produce pulp and paper products; and the heating sector, which uses fuelwood to generate heat. The supply functions of these timber products are still treated as endogenous and determined by maximization of the present value of the total surplus. The novelty of this model lies in the fact that the cross-price elasticity of supply of different timber products can be evaluated, a useful indicator that reflects the relationship between the supply of different raw wood assortments. Fuelwood demand is assumed to stay constant throughout the simulation in the base scenario, while in the two alternative scenarios 1.5% and 3% annual growth rates in fuelwood demand are chosen. Differences between short-term and long-term impacts of increased fuelwood demand on traditional timber productions are also examined.

The results show that the sawlog supply function remains relatively constant across scenarios, implying that sawlog production is barely affected by the increased demand for fuelwood. The value of the cross-price elasticity of pulpwood supply with respect to the fuelwood price decreases in the two alternative scenarios compared with the base level, which indicates an increased degree of substitution between them. The change in the cross-price elasticity of fuelwood supply with respect to pulpwood price exhibits a high degree of consistency. Compared with a baseline scenario of no change in fuelwood demand trend, the results of the high fuelwood demand scenario suggest that the production of pulpwood will decrease by 1.2% and the total harvest will increase by 2.4% by 2030. The low growth rate of fuelwood demand has little impact on the total harvest level. The surplus analysis indicates that the pulp mills will suffer a loss of consumer surplus in the presence of increased fuelwood demand.

The ability to model the subdivided markets opens up the possibility of capturing the interactions among different wood raw materials. Given the small share of fuelwood in total wood raw material production, changes in fuelwood demand only have a limited impact on the provision of other timber products and on the quantity of timber harvested. Future research is needed to incorporate the wood by-products for use as bioenergy in the framework, which will help to provide a better evaluation of the interdependence between forest resources, the forest industry, and the energy sector in response to bioenergy support policies.

3.4 Impacts of increasing bioenergy production on timber harvest and carbon emissions

Sweden’s long-term energy policy goal has created increased demand for bioenergy. Besides the policymakers, the rising demand for bioenergy is also of great interest to forest owners and forest industries due to its potential impacts on the prices and quantities of timber products, forest carbon, and other non-timber goods and services. However, quantifying the impacts is a challenging task given the complex linkages between the forest sector and the energy sector, and few attempts to do have been made in Sweden so far. The objective of this paper is twofold: (i) to analyze the intricate interactions between timber and bioenergy production, and the state of forests, and (ii) to quantify the respective contribution of forest sequestration and bioenergy substitution to climate change mitigation over time.

To achieve these objectives, two major developments have been added to the STIMM. One is that logging residues, by-products from sawmill and pulp mills, apart from fuelwood, are included in the STIMM model as feedstocks for bioenergy production. Another is that the main carbon flow related to forest, timber products, and substitution carbon pools is accounted for in the model. We introduce two scenarios with additional bioenergy targets in the STIMM model that can be compared with a baseline in which the amount of bioenergy remains constant at the 2015 level. More specifically, we first calibrate the bioenergy level to 93 TWh. In the baseline scenario, we assume that bioenergy production stays at the same level of 93 TWh over the whole simulation period with a residue extraction rate of 40%. In the alternative bioenergy scenarios, all bioenergy production is projected to increase to 118 TWh by 2050, with different residue extraction rates of 40%, 60%, and 80% respectively. We run our simulation and let the model determine the optimal mix of biomass feedstock.

The results show that in the base scenario, the harvest level does not show much difference over the simulation, at around 74 million m^3. To realize the bioenergy targets in 2050, an additional 10-15 Mm^3 of timber is needed compared with the level in the base scenario. The share of pulpwood in the total harvests decreases, implying that part of pulpwood will be used as fuelwood, and the competition between them will intensify as the demand for bioenergy continues to grow. The substitution effect has a greater impact on the carbon balance in the short term than the sequestration and storage effect. Using forest residues for bioenergy can generate more climate benefits in terms of CO_2

avoided. This strategy postpones the harvesting of timber and allows more carbon to be sequestered in the forests. The results also show that the carbon balance is sensitive to the timing and quantity of harvesting, as well as the model assumptions.

To our knowledge, this paper is one of the few attempts collectively to assess timber production and forest carbon using a dynamic economic optimization model in Sweden. This paper offers insights into future developments, and interactions of timber markets and forest resources, and provides support for policymakers in making their decisions regarding forest sequestration and forest bioenergy. Swedish bioenergy already has a very large share in the energy mix. The competition for feedstock created by increased demand for bioenergy has negative impacts on the surplus of traditional timber markets. Currently, only a small share of the available forest residues is utilized. Enhancing the use of the forest residues will assist in the co-development of forest biomass for timber products and energy. However, the environmental risk related to the removal of forest residues for bioenergy still requires further assessment.

4 Concluding remarks and future work

4.1 Overall synthesis

The national environmental objectives of Sustainable Forests and Reduced Climate Impact require that Swedish forests should be managed to provide a balanced delivery of multiple products and services. The management and utilization of forests are affected not only by forest policy, but also by policies on, for example, energy, the climate, the environment, and so on. These policies may have different focuses, each of which is likely to affect the provision of different kinds of forest products and services. This thesis focuses on certain potential policy and market changes that may take place within the Swedish forest sector, and it contributes to the understanding of trade-offs and synergies between timber production, bioenergy production, and forest sequestration. This section will highlight some of the key implications of the thesis, with an emphasis on policy considerations.

First, when managing forests, forest owners do not just maximize net timber profits; they also consider the non-timber outputs from their forests. A modeling framework that gives little or no consideration to non-timber benefits may overestimate the actual timber harvest. Second, the costs of forest sequestration can serve as a useful indicator for evaluating whether forest sequestration should be included in the future mitigation portfolio. Although higher carbon prices lead to increased forest sequestration, there are some effective ranges of carbon prices to encourage additional forest carbon. Third, increased fuelwood demand can generate a slight shortage of raw material supply for pulpwood. Policies that seek to encourage demand for bioenergy should be accompanied by policies that ensure the long-term supply of paper and pulp products. A high growth rate of fuelwood demand will inevitably lead to a rise in fuelwood price, together with concerns about its effectiveness as a renewable source of energy in the heating sector. The government may also need to provide financial incentives for the use of fuelwood to make it price competitive against fossil fuels. Next, the decrease in the forest carbon may partly or fully offset the carbon savings from the increased use of bioenergy. The current climate policy framework does not fully account for forest carbon stock changes. This may overstate the CO_2 reduction benefits of bioenergy. Finally, the climate benefits of using forest bioenergy are heavily associated with the structure of forests, specific bioenergy targets, the bioenergy feedstock, and economic incentives. To utilize the climate benefits brought by bioenergy consumption effectively, policymakers should diversify the source of bioenergy feedstock. It will help relieve harvesting pressure on the standing forest and leave room for carbon accumulation in Swedish forests.

Although the results of this thesis are not entirely comparable to existing studies due to the different methods, assumptions, and geographic scope, some general conclusions drawn in the thesis still exhibit some consistency with those of previous studies. One is that forest sequestration could offer relatively low costs in reducing carbon emissions. Another is that the competition between bioenergy and pulpwood is more likely to happen, resulting in a modest increase in the pulpwood price. The thesis also agrees that the role of forest residue in meeting bioenergy targets and reducing the CO_2 should be strengthened. Swedish bioenergy is highly integrated with the forest product industry and already has a very large share in the energy mix. The competition for feedstock created by increased demand for bioenergy has negative impacts on the surplus of traditional timber markets. To alleviate the negative impacts and further increase the share of bioenergy, increasing the share of biofuels in the transport sector could be a good solution.

4.2 Future work

These results in the thesis should be interpreted with caution given the partial equilibrium (PE) analysis. Like other PE models, the STIMM model is unable to account for the economic feedback effects between the forest sector and the rest of the economy, which means that the estimated surplus loss caused by alternative policy options or market shifts is not on society as a whole. The conclusion drawn from the PE analysis may become shaky as the cross-sectional linkages of the forest sector with other sectors, such as the transportation, energy, and agricultural sectors progress. To capture the distribution impacts, combining a CGE model could be a solution. Some work has been done regarding the model combination. Golub et al. (2008) established a soft link between the GTAP model and the GTM (Sohngen et al., 1999, 2002) to provide a better explanation of the role of the forest sector in the whole economy. There is considerable room for advancing the links between CGE and PE models. Another potential direction for future model development is to establish a soft link between the STIMM model and other forest decision support systems, for example, the Heureka system. The timber harvest obtained from the STIMM can be explicitly treated as a constraint in the Heureka system, which will allow implementation of a larger number of management plans for forestry, and management of forests to meet the overall goals of society in an optimal manner. In addition, when projecting the long-term development of the forest sector, there is an array of sources of risks and uncertainties that can greatly impact forest management and timber markets. Currently, only timber demand uncertainty is considered in the analysis presented, and it is thus necessary to incorporate further different types of uncertainty, such as natural disturbances, in the framework.

As well as developing the model itself, the studies in the thesis could also be further extended in several ways. Specifically, in Paper I a logistic growth function is used to represent roughly the value of non-timber benefits. Other forms of the non-timber benefits function also need to be tested. In Paper II carbon prices are assumed to be constant over the entire period. Van’t Veld and Plantinga (2005) have argued that rising carbon prices will delay carbon sequestration projects and increase the costs of such projects. The impacts of rising carbon prices on sequestration rates and costs are worth further exploration. In Paper III the results are highly related to the absolute value of the price elasticity of demand for fuelwood since this directly affects the calculation of consumers’ surplus. Sensitivity analysis is necessary to test the robustness of results to varying fuelwood demand elasticities. For Paper IV, the linkages between the forest sector and energy sector should be emphasized in the future. The sawmill sector may benefit from the higher prices paid by the bioenergy sector for selling sawdust, bark, and chips. In addition, how increased forest productivity and bioenergy efficiency could relieve the pressure on timber removals may need to be addressed in future research.

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