Cost-Efficient Carbon Abatement Strategies in the EU with Specific Focus on Forest Carbon Sequestration

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Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2015

Acta Universitatis agriculturae Sueciae
2015:115

Cover: Forest on family property, Soltomta, Värmland
(photo: E. Akre)

ISSN 1652-6880
ISBN (print version) 978-91-576-8428-8
ISBN (electronic version) 978-91-576-8429-5

Print: SLU Service/Repro, Uppsala 2015

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Abstract

Forests can contribute to the reduction of carbon emissions by storing carbon in standing biomass or in products made of wood. Alternatively, harvested biomass can be used as bioenergy and replace fossil fuels. This thesis analyses the cost-efficiency of introducing forest carbon sequestration (FCS) into EU climate policy. Quantification of the potential and cost of FCS is important from a policy perspective, since this abatement method is being considered for inclusion in future EU climate policy.

The quantification in this thesis is based on a mathematical optimisation model that aims to find the least costly combination of abatement strategies to reach a specific carbon emission target. The model covers the EU-27 member states and can be applied in static and stochastic form (paper I) or dynamic form (paper II-IV). The main research questions investigated in the four separate studies are: i) The cost-efficiency and equity of including FCS in EU climate policy to 2020; ii) whether it is worth increasing FCS at the expense of bioenergy and forest products; iii) whether renewable energy forms (wind, hydro and photovoltaics) can compete with FCS as abatement methods; and iv) what the effects of climate change in terms of increased/reduced FCS will be during the current century and the accompanying implications on the cost of EU climate policy.

The results, which can be useful for policy making, demonstrate cost efficiency in using FCS as an abatement method. However, this may be at the expense of reduced equity among EU member states, since forests are distributed unequally throughout the EU. Furthermore, FCS seems to be a more cost-efficient option in terms of carbon abatement than bioenergy and, to some extent, forest products. This is also the case when comparing the cost-efficiency with that of renewables, even on modelling renewables with endogenous technological change in the form of learning-by-doing. The results provide indications of increasing FCS during the current century due to climate change, in particular in northern Europe, where warmer seasons and more precipitation are expected. This would have a positive effect on the cost of reaching the emissions target, meaning that the overall abatement cost would be reduced.

Keywords: forest carbon sequestration, renewable energy, climate change, cost efficiency, EU climate policy, abatement

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Dedication

To Andreas and our children Nils, Alice and Emilia, who were all born during my years as a PhD student.

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 Münnich Vass, M., Elofsson, K., Gren, I-M. (2013). An equity assessment of introducing uncertain forest carbon sequestration in EU climate policy. *Energy Policy* 61, 1432-1442. doi:10.1016/j.enpol.2013.07.010

II Münnich Vass, M., Elofsson, K. (2014). Is forest sequestration at the expense of bioenergy and forest products cost-efficient in EU climate policy to 2050? (Manuscript).

III Münnich Vass, M. (2014). Can renewable energies with learning-by-doing compete with forest carbon sequestration to cost-efficiently meet the EU carbon target for 2050? (Manuscript).

IV Münnich Vass, M. (2015). Consequences of climate change for European forests and associated implications for the cost of EU climate policy. (Manuscript).

Paper I is reproduced with the permission of Elsevier.

The contribution of Miriam Münnich Vass to the papers included in this thesis was as follows:

I Planned the methodology together with the co-authors. Performed the modelling work, calculations and analysis of the results together with the co-authors. Wrote the text with some input from the co-authors.

II Planned the modelling set-up together with the co-author. Performed the modelling work and all calculations. Analysed the results together with the co-author. Wrote the text with some input from the co-author.

III Sole author.

IV Sole author.

Abbreviations

BAU	Business as Usual
CO_2	Carbon dioxide
ETS	Emissions Trading System
EU	European Union
FCS	Forest Carbon Sequestration
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
UN	United Nations

1 Introduction

The recently published climate change assessment report of the Intergovernmental Panel on Climate Change (IPCC) states that the increasing level of anthropogenic greenhouse gas (GHG) emissions is extremely likely to have caused the observed global warming since the mid-20th century (IPCC, 2014). Higher concentrations of GHGs in the atmosphere lead to changes in temperature and precipitation, which may have far-reaching consequences for the environment and hence for human well-being. With continuing increases in GHGs, among which carbon dioxide (CO_2) is the largest contributor, the future of mankind is threatened.

Due to its global nature, climate change is inherently a complex environmental problem to tackle. Consequently, there is currently no international agreement after the Kyoto Protocol on GHG emissions reductions for the decades to come. However, there are hopes of an agreement during the upcoming United Nation meeting in Paris at the end of 2015. Meanwhile international discussions are ongoing to formulate an agreement to reduce emissions; the European Union (EU) has taken a leading position in the fight against climate change. For example, the EU has already agreed emissions reduction targets for 2020 and 2030 and a roadmap with ambitious goals for 2050. The targets for 2020 and 2030 are to reduce carbon emissions by at least 20% and 40%, respectively, compared with the 1990 level. The roadmap for 2050 aims to reduce carbon emissions by 80-95% compared with the base year 1990. The overall stated objectives are to reach the emissions reduction targets cost-efficiently and to distribute the cost burden in a fair manner across EU countries. The focus on equity is due in particular to the large differences in economic wellbeing, measured as gross domestic product (GDP) per capita, between EU countries. The objective of reaching the emissions reduction targets cost-efficiently can potentially be fulfilled by focusing on implementing market-based policy instruments that incentivise emissions reductions and by recognising low cost abatement methods to meet the emissions targets. For this purpose, the EU has introduced its Emission Trading System (ETS), which is the largest carbon trading system in the world and covers basic industries, electricity producers and the aviation sector. With regard to abatement methods, carbon emissions can be reduced in the EU by reductions in fossil fuel consumption (coal, oil and natural gas), increases in renewable energies (*e.g.* hydro, wind and solar power), energy-saving technologies and carbon capture and storage techniques (CCS).

Forest carbon sequestration (FCS), which involves forests capturing and storing carbon from the atmosphere via photosynthesis, is an alternative abatement measure that can be used to reduce carbon emissions. However, FCS has not yet been accepted as an abatement method to meet the carbon emissions targets within the EU, despite being viewed as a comparatively inexpensive method with great potential world-wide (Sohngen, 2009; Bosetti *et al.*, 2009; Murray *et al.*, 2009). The reasons for this non-acceptance relate to the uncertainty in FCS, which mainly stems from difficulties in measuring additionality[1], permanence[2] and leakage[3] (European Commission, 2015a). However, discussions are ongoing within the EU institutions on whether to accept emissions and sinks within the land use sector in climate policy in the future (European Commission, 2012).

Much research to date within the field of climate change economics has focused on calculating the cost of damage caused by climate change and the associated cost of climate change policy (*e.g.* Stern, 2006; Tol, 2009; Weitzman, 2009; Nordhaus, 2014). A number of studies have also calculated the cost of carbon sequestration in the land use sector (see reviews by Sedjo *et al.*, 1995; Richards & Stokes, 2004; van Kooten *et al.*, 2004; 2009; Phan *et al.*, 2014). In addition, forest and agriculture sector models have been developed to study the markets in the USA (*e.g.* Alig *et al.*, 2010) and the EU (Schneider *et al.*, 2008). The model for the USA also calculates the cost and potential of sequestration in these sectors (*e.g.* Adams *et al.*, 1999). There are some integrated assessment models that cover FCS (*e.g.* Eriksson, 2015). Some country-specific forest sector models also address sequestration (*e.g.* Sjølie *et al.*, 2011). However, FCS in the EU and its member states has not been widely studied. The reasons for this may be related to the lack of political interest until recently in including this abatement option in EU climate policy. Empirical

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[1] Additionality in relation to FCS implies that a project carried out in order to be credited must be in addition to projects that would happen without climate policy incentives.

[2] Permanence refers to the permanence of carbon storage. Carbon storage in forests is not permanent and hence it is difficult to measure the amount that is stored in each period.

[3] Leakage refers to a situation where forests are harvested to a larger extent in parts of the world where there are no incentives to store carbon because of the crediting in some other parts of the world.

results and associated conclusions from other continents regarding FSC are not necessarily applicable to the EU. The main reason why results are not transferable between countries is that FCS is largely determined by local climate conditions in terms of rainfall/precipitation, temperature and soil fertility conditions. Hence, it is not suitable to base the development of EU climate policy on overseas results and thus a research gap exists.

The overall aim of this thesis was to help close this research gap by analysing four main research questions relating to the cost efficiency and potential of different abatement methods to meet future EU climate policy targets, with specific focus on FCS. The outcome of the explicit empirical research questions posed is of specific relevance for EU climate policy makers.

This introductory chapter of the thesis is organised as follows. First, sources and sinks of carbon emissions are described. Next, there is a short outline of the environmental and human consequences of climate change. This is followed by a presentation of the economics of climate change and an introduction to the research question(s) addressed in Papers I-IV of the thesis. Finally, the main contributions of the thesis are discussed, together with policy recommendations following on from the results presented.

2 Sources and sinks of carbon emissions

Carbon dioxide is the GHG that constitutes the largest contributor to climate change (IPCC, 2014). It occurs naturally in the atmosphere through plant and animal decay as microorganisms break down the dead material. Other naturally occurring sources include forest fires and volcanoes. The level of atmospheric carbon is also influenced by man, in particular through the burning of fossil fuels, but also as a result of certain chemical reactions *e.g.* manufacturing of cement and certain metals. These man-made emissions are termed anthropogenic. Forest clearing, including deforestation and forest degradation, and the burning of solid waste, wood and wood products are all sources of atmospheric carbon dioxide.

Forests and vegetation constitute a sink for carbon dioxide as they grow. A sink is a reservoir or a stock that takes up a chemical element or compound from another part of its natural cycle (IPCC, 2015). The carbon cycle is one of the Earth's major biogeochemical cycles, where vast amounts of carbon continuously cycle between the Earth's atmosphere, oceans and land surfaces in both short-term and long-term cycles (IPCC, 2015). During photosynthesis, trees and vegetation absorb carbon dioxide from the air and emit oxygen. This process or flow is referred to as forest carbon sequestration. Humans can add to the carbon sink through forest management changes in the form of prolonged rotation periods, intensive forest management, reforestation and conversion of land into forestry.

The fifth assessment report of the IPCC states that the amount of anthropogenic greenhouse gas emissions has increased since the pre-industrial era and that this increase is driven in particular by economic and population growth. The level of greenhouse gases in the atmosphere is hence higher today than ever before. Emissions of carbon dioxide from fossil fuel combustion and industrial processes contributed about 78% of the total increase in greenhouse gas emissions between 1970 and 2010. The effects of all greenhouse gases and other anthropogenic drivers are extremely likely to have been the dominant cause of the observed global warming since the mid-20th century (IPCC, 2014)[4].

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[4] The IPCC gathers climate scientists from around the world to review scientific articles on the subject and then produce a common status report on climate change. This process makes the assessment reports issued by the IPCC trustworthy. However, some scientists do not agree with the content and conclusions of these reports (*e.g.* Dunlap & McCright, 2011).

3 Environmental and human effects of carbon emissions

Climate change in terms of higher GHG concentrations and changes in temperature and precipitation levels have the strongest and most comprehensive impacts on the natural system (IPCC, 2014). The effects on the environment in turn have consequences for humans. The negative effects for people, according to the most recent IPCC report (2014), are essentially related to access to water, food production, health and use of land and the environment. There are large variations in these effects across the globe. In Europe, the known effects of climate change vary along the north-south divide. Northern Europe has experienced effects on glaciers, snow, ice and/or permafrost, as well as on terrestrial, marine and food production systems. In Southern Europe the effects have largely been on rivers, lakes, floods and/or droughts, and on marine ecosystems and livelihoods, health and/or economics. In Central Europe, people have recently been affected by wildfires associated with climate change (IPCC, 2014).

As the world becomes warmer in the future, the damage caused by climate change is expected to accelerate. For Europe, this implies that there will be increased damage due to flooding, wildfires and extreme heat events, as well as increased water restrictions. These risks can be reduced by various adaptation and mitigation measures (IPCC, 2014). In this context, adaptation measures are actions taken in society to respond to the adverse impacts of climate change and mitigation measures refer to efforts taken to reduce emissions.

4 The economics of climate change

Economists, and also scientists from other disciplines, are seeking explanations and solutions for the problem of climate change. The main contribution from economists to understanding the climate change problem is based on the connection between the choices made by societies, individuals and companies and the consequences of GHG emissions for the environment and hence for humans. In terms of solutions to the problem, economists suggest different kinds of policy instruments that can reduce the negative effects.

4.1 Public goods, externalities and market-based solutions

The atmosphere, or the air, is defined within economics as a ‘public good’, meaning that it is both non-excludable and non-rival. Non-excludable means that a person cannot be excluded from using the good, while non-rival means that the use by one person does not reduce the availability to others (Varian, 1992). Public goods tend to be overexploited and hence damaged. In economics, this damage is referred to as a ‘negative externality’ and it affects all users. An externality is defined as a cost or a benefit that affects third parties without compensating them for it (Varian, 1992). Climate change is an example of a negative externality. Externalities are due to market failure, which means that the cost to society of an activity is not covered by the private cost of this activity. In such cases, the market outcome is not efficient. In economics, the term ’pareto efficient’ is used as a definition of efficiency. It means that efficient allocation is achieved when no one can be made better off without making someone else worse off (Varian, 1992).

According to the well-known Stern Report (2006), climate change has a number of features that together distinguish it from other externalities. First of all, it is global in its causes and consequences. Second, the impacts of climate change are persistent and develop over long periods of time. Third, there are a range of uncertainties related to climate change that prevent precise quantification of the impacts. Finally, there is a risk of major, irreversible change with great environmental and economic consequences. These aspects make climate change a more difficult externality to solve than others.

A number of solutions have been suggested to solve externality problems in general. These include allocation of property rights (Coase, 1960), introduction of (Pigouvian) taxes or markets for trading emission allowances and initiation of cooperation among users. For natural reasons, the allocation of property rights with respect to the atmosphere or the air is not an appropriate way forward for solving the climate change problem. Cooperation among users is also not ideal, due to the size of the world's population. Instead, different kinds of market instruments, including pollution taxes or emissions trading markets, are useful methods for coming to terms with the problem of climate change. These instruments aim to internalise the externality cost and hence make it more costly to pollute. Environmental or pollution taxes were first introduced by Pigou (1920), hence the name Pigouvian taxes, and comprise taxes on the externality imposed to achieve efficient allocation of the resource. The tax is intended to correct an inefficient resource allocation, which it does by being set at the level where the marginal abatement cost intersects with the marginal cost of pollution. The polluter then pays the tax if that is less costly than reducing the quantity of emissions. In this case the cost of the emissions reduction is known, but the magnitude of the reduction is not.

An alternative or additional market instrument is emissions trading, whereby an overall cap on emissions is set and rights to emit are distributed to participants (Tietenberg, 2006). These pollution rights are either allocated free of charge to participants according to specific rules, or by auctioning the rights to the highest bidder. Internal trade in emissions permits then allows parties to achieve the emissions reduction at the lowest cost. This is done through parties with a high marginal cost of reducing emissions buying permits from those with a low marginal cost of reducing emissions. Hence, the emissions target is achieved cost-efficiently. In this case the magnitude of the emissions reduction is known, but the cost of reaching it is not.

The EU introduced emissions trading in 2005 in the form of the EU ETS. This is a trading system that includes all basic industries, the energy sector and the aviation sector and covers 45% of the greenhouse gases in 31 countries (European Commission, 2015b). Allowances are partly distributed free of charge and partly auctioned to the participants depending on their industry group.

Abatement methods are closely connected to policy instruments, since the instruments aim to incentivise the use of different abatement options. Papers I-IV in this thesis all analyse the cost-efficiency of different abatement methods used to tackle climate change in the EU. This analysis is based on an economic model developed for the purpose in Papers I-IV. The model is briefly described below.

4.2 Theoretical framework - the economic model

The economic model developed to answer the research questions is based on abatement cost minimisation, subject to some specific conditions. More specifically, the objective of the social planner is to minimise the overall cost of achieving an EU emissions target in a specific year or annually. The date by which the target should be met or whether there should be yearly targets is determined by the research question in each individual study. The cost-efficient solution is obtained using mathematical optimisation, where a number of different abatement methods are available. The abatement methods include fossil fuel reductions and forest carbon sequestration to start with, while renewable energies and carbon storage in forest products are added in later versions of the model. Each abatement method is associated with a specific cost, which varies according to country, utilisation and time period. The amount of carbon emissions released to the atmosphere in any year depends on the amount of fossil fuels consumed within the EU.

The model used in Paper I is static and stochastic, which means that it is assumed that policy makers want to achieve the EU carbon reduction target with, at least, a subjectively chosen probability. A reliability constraint is therefore introduced in the model, which means that the expected emissions reductions plus a risk premium should be less than the stipulated emissions target. The size of the risk premium is determined by the decision maker’s subjectively chosen probability and the variance of carbon sequestration. The model in Paper I is set up to accommodate both the EU ETS target to 2020 and the national commitments that focus on emission reductions in sectors not covered by the ETS. The model used in Paper II-IV is dynamic and covers several decades. The dynamic nature of the model means that it can accommodate variations in forest biomass volumes over the forest’s lifetime. This is an important aspect when the analysis covers several decades and is due to the fact that individual forests grow at different rates, depending in particular on forest age. The dynamic model is an advantage compared with most existing models in the field of carbon abatement, since those are generally static and hence cannot accommodate variations over time.

The strength of the model relates in particular to its coverage. The EU-27 member states are included and the forest sector is modelled in some detail through country-specific forest growth functions and associated cost functions in Paper II-IV. The model set-up is based on some important assumptions. These are in particular: 1) The definition of Business-As-Usual (BAU) or baseline levels; 2) the use of linear demand and supply functions in both the fossil fuel and forest sectors; and 3) endogenously determined overall energy demand.

With regard to the BAU/baseline determination, this is modelled as a constant amount throughout the policy period. This amount is the same as the level in the first model year for the fossil fuels and forest sectors. The reason for having a constant BAU is in particular the lack of forecast data for each EU country's abatement method/s (fossil fuel, forest products, bioenergy) over several decades into the future. This assumption means that the model may underestimate the abatement cost associated with these abatement methods if the consumption and production of these products are likely to increase over time. This can happen if there is comparatively high economic and population growth, for example. However, there are also aspects that can work in the opposite direction and reduce the consumption/production, such as energy efficiency, alternative consumption patterns explained in particular by technological development and a general drive for sustainability in society.

The assumption on linear supply and demand functions in the fossil fuel and forest sectors is made because it is comparatively easy for the model to calculate the cost of abatement in these sectors. The cost of abatement is based on reductions or changes in consumer and producer surpluses, which are determined by the shape of the supply and demand curves. An alternative assumption would be to use iso-elastic curves, which would mean that the function has constant elasticity. However, such curves may be very steep at low/high levels of demand/supply, which means that it may be difficult to find an optimal solution for the model. The implication of the linearity assumption may be that the cost is underestimated compared with a situation with iso-elastic cost curves.

The assumption of modelling energy demand endogenously is taken in order to analyse what happens in the fossil fuel sector if there is hardly any restriction on the overall amount of energy consumed. Since the purpose is to find the most cost-efficient abatement methods and to analyse abatement in the forest sector in particular, meeting the energy demand is secondary in this kind of model. Furthermore, the model does not cover all energy sources, which is essential if the energy sector is the focus and if demand should be met by different sources. The endogenous approach differs to that taken when setting up an energy sector model, where the overall demand is usually exogenously given based on some previous model forecast.

The main empirical questions analysed in Papers I-IV of the thesis, using the model described above, are: i) Can the cost of EU 2020 targets be reduced by the inclusion of FCS and what does this mean in terms of equity among the member states? ii) Is FCS at the expense of bioenergy and forest products cost-efficient in EU climate policy to 2050? iii) Can renewable energies with learning-by-doing compete with FCS to cost-efficiently achieve the EU carbon target to 2050? iv) What are the consequences of climate change on FCS in the EU and what does this mean for the cost of climate policy to 2100?

The main focus in Paper I is hence on fairness among member states in the division of the cost burden of achieving the overall emission targets, with and without the use of FCS as an abatement method. Equity is important for climate policy makers when considering the inclusion of a new abatement possibility in the current EU regulation to 2020. It is also of interest to analyse how the existing burden allocation turns out in terms of equity. If the majority of the overall cost is allocated to one or a few countries, it is important for the policy makers concerned to try to correct this unfairness. This can be done by reallocating the emissions allowances or changing targets set for the member states.

The key focus in Paper II is choosing between three abatement methods in the forest sector in terms of abatement potential and cost. The choice is between FCS on the one hand, and bioenergy or carbon storage in forest products on the other hand. A reduction in harvest for the production of forest products or bioenergy means that more trees are left in the forest to sequester carbon. The choice of abatement method in the forest sector is also important for climate and forest policy makers, since it indicates how the forest would be used over time if the focus were to reduce the amount of carbon in the atmosphere cost-efficiently.

Paper III analyses whether it is more cost-efficient to use FCS than renewable energies to reduce carbon emissions. Renewable energies are modelled with endogenous technological development in the form of learning-by-doing. This means that the cost of the abatement method is reduced with increased use of the technology and hence the cost generally decreases over time. For climate policy makers it is essential to know how the cost will develop for different abatement options, since this gives an indication of the optimal choice of abatement method in each period.

Paper IV investigates what climate change may mean for forest growth and land area use over the current century in the EU. The reason for investigating this is to learn more about the amount of carbon that can be sequestered via FCS in the future. If it turns out that climate change can have positive effects on forest growth and forest land use, it may be useful for climate policy makers to include FCS in EU climate policy if that is a low cost option.

5 Summary of Papers I-IV

5.1 An equity assessment of introducing uncertain FCS in EU climate policy

Forests can sequester large amounts of carbon every year through photosynthesis. The aim in Paper I is to assess whether the cost of EU carbon policies for 2020 can be reduced by including FCS as an alternative abatement option and what that means in terms of equity in burden sharing among EU member states. The analysis is based on numerical calculations using an optimisation model in which the abatement cost is minimised while the emissions reduction target of the EU Emissions Trading System and the national effort-sharing targets are met. In the model, FCS is introduced as an uncertain abatement option in the form of a reliability constraint. This means that the expected emissions reduction plus a risk premium should be less than the stipulated emissions target. This means in turn that policy-makers will want to achieve the EU carbon reduction target with, at least, a subjectively chosen probability. The fairness in the distribution of the cost of achieving the targets is evaluated using Gini-coefficients for six different equity criteria. The reason for using different criteria is that there is no single definition of equity in the literature. The value of the Gini-coefficient ranges from 0 to 1, where 0 represents perfect equality and 1 represents perfect inequality.

The results show that the cost of meeting the emissions targets is reduced by 53% when including uncertain FCS in EU climate policy and by as much as 85% when this sequestration is introduced with certainty. The estimated Gini-coefficients in Paper I range between 0.11 and 0.32 for the current policy. When FCS is included as a certain abatement method, the Gini-coefficients range from 0.16 to 0.66. The spread in the Gini-coefficients is narrowed to 0.19-0.38 when the uncertainty in FCS is taken into account and policy-makers wish to meet the targets with at least 90% probability. The overall results hence show that the lower cost comes at the expense of reduced fairness when sequestration is included and that the impact is larger when sequestration is treated as certain. The explanation for reduced fairness with FCS is that there is a large variation in forest area, and per hectare carbon sequestration, in the EU member states, so that the gains from inclusion of sequestration are unevenly distributed. The reason for improved equity with uncertain FCS is that the certain sequestration potential is more valuable than the uncertain potential and hence has a larger impact on meeting the emission targets, in combination with the unequal distribution of forest area. The policy conclusions that can be drawn from these results indicate that it would be cost-efficient to recognise FCS as an abatement method, but that the burden sharing would be less equal if FCS is included in climate policy. The unequal distribution of the emissions reduction burden could potentially be avoided by a different *ex ante* allocation of the emissions allowances or emissions reduction targets by the climate policy makers.

5.2 Is FCS at the expense of bioenergy and forest products cost-efficient in EU climate policy to 2050?

The quantity of CO_2 emissions in the atmosphere is affected by forest management through carbon sequestration in standing biomass, carbon storage in forest products and production of bioenergy. The main question examined in Paper II is whether FCS is worth increasing at the expense of bioenergy and forest products to achieve the EU emissions reduction target for 2050 in a cost-efficient manner. A dynamic optimisation model of cost-efficient abatement solutions is used. This model is a development of the static model described above. To capture the dynamics in FCS, a so-called Chapman-Richard natural growth function of forest is introduced. This function is exponential, indicating that growth is low at a young age, high in mid-age and slow in old age. The function is calibrated to European growth conditions for each EU member state and then used in the aggregated empirical model. The aggregation assumes that there is a representative stand in each country, which reflects the average age and volume of that country’s forest. The outcome of two different scenarios, with and without additional sequestration, is compared in Paper II. The additional sequestration is defined as the level of sequestration above the BAU level, where the production/consumption of bioenergy and forest products is assumed to be constant throughout the policy period.

The results indicate that FCS is cost-efficient compared with bioenergy in particular, but sometimes also compared with forest products. The latter is due to the decay of forest products and also the dynamics in forest sequestration, meaning that it can be cost-efficient to reduce the production of these products in order to increase the age of the forest and hence increase growth and thereby sequestration in the future. When forest abatement is considered, the net present costs for meeting EU carbon targets can be reduced by 23%. The policy-relevant conclusion from this relates in particular to the use of European forests, where it is most beneficial from a climate perspective to use the forest for FCS instead of bioenergy and to some extent also forest products.

5.3 Can renewable energies with learning-by-doing compete with FCS to cost-efficiently meet the EU carbon target for 2050?

Renewable energies have great potential to contribute to CO_2 emissions reductions by substituting for fossil fuels. Paper III examines whether renewable energies with learning-by-doing technical change can compete with FCS to cost-efficiently achieve the EU carbon target for 2050. Cost-efficient abatement solutions are obtained from a dynamic optimisation model which builds on that described in Paper II. Renewable energies are introduced dynamically and the cost of these energies falls with previous experience of using the technology. The empirical model focuses on abatement by use of wind power, hydro power and solar photovoltaics, as well as abatement in the forest and fossil fuel sectors. The results show a net present cost of reaching the target of approximately 286 billion Euros and a carbon price of 364 Euro/ton CO_2 in 2050. Furthermore, the stock of renewables in 2050 can deliver twice as much as the current electricity production from renewables, which represents a contribution of 8.7% to meeting the emissions target. However, the cost per unit emissions reduction is at least fifteen-fold higher for renewables than for FCS. Hence, for policy makers in the field of climate change, the results demonstrate that renewables are unable to compete with FCS unless they receive continued government support.

5.4 Consequences of climate change on European forests and associated implications on the cost of EU climate policy

Climate change affects the quantity of carbon dioxide emissions sequestered by forests, directly by changing tree growth and indirectly through management changes. The main question examined in Paper IV is what the cost-efficient level of FCS would be in Europe and how that affects the cost of achieving an annual emissions reduction target by 2100, when forests are affected by climate change. The assessment builds on the dynamic optimisation model described in Paper III and it computes the cost-efficient abatement solutions for four climate scenarios. These climate scenarios stem from the IPCC and the input data in terms of changing forest growth derive from a European forest model. The data used to project forest land changes are taken from an in-depth analysis of land use changes in Europe for the next century (Paper IV).

The results indicate that Europe will experience a higher level of FCS throughout the period in all scenarios, compared with a situation without climate change, although there are large differences between countries. This indicates that the cost of reaching the annual EU emissions target can be reduced by 15-19%, depending on the scenario and compared with a situation without climate change and induced changes in harvest levels. These findings suggest that FCS can be a cost-efficient abatement method in Europe.

6 Key results and recommendations for EU climate policy

The main contribution of this thesis is the provision of an alternative carbon abatement model that focuses on FCS. This model is used in Papers I-IV to answer four important and policy-relevant research questions related to FCS as an abatement method in EU climate policy. Technically, the model quantifies the most cost-efficient carbon abatement combination in the EU-27 member states. The focus on FCS in EU climate policy has not been analysed in any detail in previous research and hence the conclusions drawn in Papers I-IV can all contribute to the existing literature in the field.

The abatement potential in the forest covers the whole forest potential in Paper I, whereas in Paper II-IV it only refers to the additional amount. For FCS this is defined as the amount in excess of the BAU/baseline level, which is a constant amount based on the level in the first model year (2010). This limitation on FCS hence imposes an upper bound on the magnitude of this abatement method, meaning that FCS can only contribute a few per cent to reaching the different carbon emission targets.

The conclusions that can be drawn from Papers I-IV, and which contribute to closing the research gap in this specific field, are all relevant for EU climate policy makers. At least five policy-relevant contributions by these papers with respect to FCS can be highlighted. These are: 1) FCS seems to be a cost-efficient abatement method in the EU, but with rather limited potential when only considering the additional amount on existing forest land; 2) among the forest sector abatement methods, FCS seems to be the most preferable option in terms of cost and emissions reduction potential; 3) in comparison with renewable energies, FCS also seems to be the most cost-efficient abatement method; 4) the limited FCS potential can possibly increase in the future due to climate change, which appears to positively affect forest growth and land dedicated to forestry in the EU; and 5) the inclusion of FCS in EU climate policy could negatively affect the equity with respect to the allocation of the abatement burden. This can be corrected for *ex ante* by allocating targets or allowances in a manner that reduces inequality. These conclusions all point toward a positive outcome in terms of reduced costs of including FCS in EU climate policy. There could also be additional benefits, such as improvements in biodiversity and additional ecosystem services, through focusing more on FCS.

However, there are still some issues to be resolved with regard to the inclusion of FCS in climate policy. These relate in particular to the handling of uncertainty and non-permanence with respect to FCS. The uncertainty seems to be larger for FCS than for alternative abatement methods (Gren *et al.*, 2012). The main reason is that sequestration depends on the photosynthesis process, which varies depending on weather and climate. These are uncertain parameters that change over time and geographical location. There is also uncertainty related to the measuring and monitoring of changes in FCS. Historically, the methods used for these purposes have varied between EU countries. However, recently harmonised methods for assessing carbon sequestration in European forests have been suggested (JRC-IES, 2010). The uncertainty is also related to the issue of permanence. FCS is not a permanent method for storing carbon. At a certain age the forest cannot grow any further and hence cannot sequester additional amounts of carbon. The trees are then either harvested or left untouched in the forest. When trees are harvested or left to die naturally, the stored carbon is partly released back into the atmosphere. The amount that is continuously stored depends on what the biomass is used for, *e.g.* wooden houses that store carbon for centuries or paper and bioenergy that more or less instantly release the carbon back into the atmosphere.

The kind of policy measures and instruments that can optimally incentivise FCS are not analysed in this thesis. The academic literature in this area mainly focuses on solving the above-mentioned problems of uncertainty, additionality and permanence when including FCS in climate policies and measures (for a review see Abenezer & Gren, 2014).

Apart from analysing what the best policy design would be with regard to FCS in the EU, there are some additional interesting issues to focus on in future research related to FCS. One such issue is an analysis of the additional benefits that FCS can bring in the form of biodiversity and ecosystem services. Furthermore, for a substantial contribution from FCS, it could be useful to assess the potential when more land is dedicated to forestry. This requires a model that includes other land use sectors and their emissions and sinks. As a concluding remark, there are still issues related to FCS that could be interesting to analyse from a policy perspective in order to fully close the research gap.

7 Sammanfattning (Swedish Summary)

Skogen kan bidra på flera sätt till att minska mängden koldioxid i atmosfären. Dels genom att producera trä som kan användas till både bioenergi, som ersätter fossila bränslen, och träprodukter, som kan lagra koldioxid under en lång period. Dessutom kan skogen stå kvar som växande skog och ta upp koldioxid. Den utgör då en så kallad ”kolsänka”. Målet med denna avhandling är att kvantitativt analysera hur mycket skogen kan bidra till att minska koldioxidutsläppen inom EU och estimera vad det innebär för kostnaderna för att nå EUs koldioxidmål i framtiden. Detta görs utifrån fyra olika frågeställningar som var och en utgör en artikel. Analysen baseras på en ekonomisk modell som grundar sig på matematisk optimering där målet är att nå uppsatta klimatmål till lägsta möjliga kostnad. En rad åtgärder för att minska utsläppen i modellen finns tillgängliga och en kombination av dessa utgör den optimala strategin. De åtgärder som kan användas i den mest utvecklade modellen (i artikel III och IV) är minskning av fossila bränslen (kol, olja och gas), ökning av förnybar energi (vindkraft, vattenkraft och solenergi) samt nyttjande/åtgärder i skogen (bioenergi, träprodukter och kolsänka).

De fyra separata artiklar som ingår i avhandlingen behandlar varsin forskningsfråga. I det första pappret fokuseras analysen på att bestämma hur mycket kostnaden för att nå EUs klimatmål till 2020 kan minskas och hur detta förändrar rättvisan i den fördelning av kostnadsbördan som medlemsstaterna har kommit överens om. Resultatet i denna artikel visar att man kan göra stora kostnadsbesparingar om man använder den kolsänka som finns inom EU idag som en minskningsåtgärd. Samtidigt blir rättvisan i kostnadsfördelningen mellan medlemsstaterna sämre, vilket mäts i form av sex olika rättvisekriterier. Den mer orättvisa fördelningen kan åtgärdas på förhand genom att ändra nuvarande fördelning av de nationella målen och/eller allokeringen av utsläppsrätter. Slutsatsen blir att man bör ta med skogssänkan i klimatpolitiken för att det är en billig åtgärd och samtidigt justera rättvisan i bördefördelningen.

Slutsatsen i artikel I leder oss in på frågeställningen i den andra artikeln som behandlar frågan om det är ekonomiskt att öka andelen skogssänka på bekostnad av mindre produktion av bioenergi och träprodukter. Modellen i detta papper utvecklas till en dynamisk modell och körs fram till år 2050, framför allt för att skogen har en lång rotationsperiod då tillväxttakten varierar beroende på dess ålder. Resultaten visar att skogssänkan är ett bättre alternativ att satsa på i klimathänseende jämfört med framförallt bioenergi, men i vissa fall också träprodukter. Dessa resultat bygger på att bioenergi är modellerat med ett nettoutsläpp av koldioxid på kort sikt, vilket stöds av litteraturen, och att träprodukter kan lagra nästan lika mycket koldioxid som stående skog.

Slutsatsen i den andra artikeln leder till nästa fråga som analyserar om förnybar energi kan konkurrera med skogssänkan när förnybar energi sjunker i pris i takt med dess utveckling. Svaret på frågan tyder på att förnybar energi har svårt att konkurrera med skogssänkan på grund av dess höga initiala kostnader och att man därför behöver fortsätta stödja dessa energikällor om man vill se mer av dem i framtiden. Analysen i både den andra och tredje artikeln tar man bara hänsyn till den mängd skogssänka som tillkommer utöver vad som tillkommit med oförändrad skogsskötsel som under första året i modellen - 2010 (dvs. man jämför med ett ”business-as-usual” scenario). Den skogssänka man kan tillgodoräkna sig i klimatpolitiken kallas ”ytterligare skogssänka” (additional på engelska). Det innebär att mängden skogssänka inom EU är jämförelsevis liten och att andra åtgärder måste utgöra majoriteten av utsläppsminskningen.

I det fjärde pappret blir det därför intressant att analysera hur mycket skogssänkan förändras över det kommande seklet då klimatförändringarna leder till högre skogstillväxt och därmed sänka i vissa länder (Norden) och lägre skogstillväxt i andra delar av EU (Medelhavsländerna). Resultaten i denna studie som bygger på fyra olika klimatscenarier fram till 2100 tyder på att EU kommer få mer skogssänka över tid. Detta leder då till lägre kostnader för att nå klimatmålet eftersom skogssänkan är en relativt billig åtgärd för att minska koldioxidutsläppen.

De slutsatser som kan dras utifrån de kvantitativa resultaten i de fyra artiklarna kan vara intressanta för politikens utveckling och sammanfattas i följande fem punkter:

1) Skogssänkan tycks vara en relativt billig åtgärd för att minska klimatpåverkan och bör därför inkluderas i EUs klimatpolitik;

2) En inkludering av skogssänkan kan leda till en mindre rättvis fördelning av den kostnad som uppstår i samband med de åtgärder som används för att minska koldioxidutsläppen och bör åtgärdas i förhand från politiskt håll;
3) Skogssänkan tycks vara en mer kostnadseffektiv metod för att minska koldioxidutsläppen än bioenergi. Därför bör man eventuellt omprioritera dagens fokus inom EU från bioenergi till skogssänka;
4) Förnybar energi har svårt att konkurrera med billigare åtgärder såsom skogssänkan. Därför bör man se över stödet till dessa energikällor om man vill se mer av dem i framtiden;
5) Klimatpåverkan på skogen kan leda till mer skogssänka i framtiden på grund av en högre skogstillväxt och större arealer till skogsbruket. Detta leder till att skogssänkan blir en än mer intressant klimatåtgärd för EU att ta ställning till.

Givetvis finns det en rad svårigheter med att inkludera skogssänkan i EUs klimatpolitik som bör ses över innan en inkludering kan ske. Dessa svårigheter rör framförallt osäkerheten i denna åtgärd, det faktum att åtgärden inte är permanent och hur man ska beräkna den ytterligare (adderade) kvantiteten.

I framtida studier om skogssänkan i EU kan det vara intressant att fokusera på frågor som ännu inte har blivit ordentligt genomlysta. Till exempel vore det intressant att studera mer ingående vilket/vilka styrmedel som bäst lämpar sig för skogssänkan i EU, hur markanvändningen skulle ändras i en modell där andra markanvändningsområden också ingår såsom jordbruk, våtmarker etc. För detta krävs en mycket mer omfattande modell än den som ligger till grund för resultaten i ovanstående artiklar. Med andra ord är forskningsgapet ännu inte helt slutet. Det finns fortfarande intressanta frågor att fördjupa sig i för den som känner sig manad.

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9 Acknowledgements

Many people were involved in the process of completing this thesis. Some contributed actively to the work and many others provided support and encouragement during the past seven years. Without you it would not have been possible to complete this thesis! First of all, I would like to thank all my supervisors for their input into the work during the years. A special thank you goes to Carl-Johan Lagerkvist, who believed in my capacity to complete the thesis.

Other people involved in the work also deserve to be mentioned here. Thank you Torbjörn Jansson, for always being so helpful when I had problems with GAMS and for your useful comments on the work. Thank you Luca Di Corato, for comments and help with the maths, and Katarina Elofsson, for all the discussions we have had during these years. I also had the pleasure to work with and get input from Jeannette Eggers, Carina Ortis and Mats Olsson – thank you. Many other colleagues were also very important for me during my studies, especially my fellow doctoral students Marit, Martin, Karl-Anders, Suvi, Katarina and my roommate Maria, who always cheered me up. A big thank you also goes to Birgitta, Elizabeth and Anna, for administrative assistance and nice chats. Thank you also to my nice colleagues at the Department of Economics for interesting discussions and chats over lunches and coffee breaks.

A huge thank you is also dedicated to my extended family, which has encouraged me and believed in me during this process. First of all, the greatest thanks and love goes to my husband Andreas, who has always been by my side and supported me when needed and who gave me three wonderful children - Nils, Alice and Emilia - during this time. A very special thank you also goes to my mother, Gunilla, who throughout my life has been so positive and encouraging in the things that I wanted to pursue. With regard to my thesis work, you gave me much support and good practical guidance. In the same

vein, I want to thank my father, Ingvar, for all kinds of support and encouragement during the thesis work. Thank you for making me focus more on what is most important in life during times when I could only see work. Thank you also to my father’s wife, Eva, for encouragement and for the lovely photo on the cover page of this thesis. Similarly, I want to thank my brother, Mattias, and my sisters, Ylva and Karin, for being in my life together with their partners and lovely children. Last, but not least, I want to thank my grandmother Elsa, aunt Elizabeth, Ulf and mother-in-law Inger, for being in my life and supporting me in different ways.

Miriam Münnich Vass
Sigtuna, December 2015