Aalto University
School of Science
Degree Programme in Engineering Physics and Mathematics

Riikka Siljander

Energy-climate-forest modelling for integrated policy analysis

Master's Thesis
Espoo, March 22, 2016

Supervisor: Professor Ahti Salo
Advisor: Tommi Ekholm D.Sc. (Tech.)

Aalto University
School of Science
Degree Programme in Engineering Physics and Mathematics

ABSTRACT OF MASTER'S THESIS

Author:	Riikka Siljander		
Title:			
Energy-climate-forest modelling for integrated policy analysis			
Date:	March 22, 2016	**Pages:**	vii + 75
Major:	Systems and Operations Research	**Code:**	Mat-2
Supervisor:	Professor Ahti Salo		
Advisor:	Tommi Ekholm D.Sc. (Tech.)		

Increased concern about global warming has led to an intensified search for new and efficient means to reduce greenhouse gas emissions (GHG). So far, forests have been part of climate policies mainly as a source of bioenergy which can substitute for fossil fuels. However, forests constitute also significant sinks and sources of carbon dioxide, which affect the atmospheric carbon balance. This has led to an ongoing debate on whether and how the changes in forest carbon stocks should be taken into account in climate policies. This thesis studies how the inclusion of the carbon stock in the emission targets of Finland would affect the cost-effectiveness of emission reductions and the Finnish energy and forest sectors.

The TIMES model is used for creating scenarios of the future energy system and the related emissions. A simplified forest model describing forest growth and carbon sequestration in Finland is developed, and integrated into TIMES. Together they constitute the first model that covers energy and forest sectors and GHG emissions in a single model, enabling an integrated analysis and optimisation of the system. Scenarios with different emission targets are created and analysed.

The results indicate that substantial improvement in cost-effectiveness can be achieved if changes in the forest carbon stock are included in the emission targets. In the scenarios, forest carbon sink was used for substituting more expensive emission reduction measures, like rapid reductions in fossil fuel use and the use of carbon capture and storage technology. At the same time, less wood was harvested from forests, and the increase in bioenergy use was not as high as without including the changes in forest carbon stock.

This thesis shows that forest carbon sinks have a high potential in controlling the atmospheric CO_2 concentration, and achieving savings in emission reduction costs in Finland. However, many uncertainties are embedded in the estimation of forest growth and carbon stocks, and the forest model built in this thesis is only a simplified representation of their development. Nevertheless, it provides a starting point for a combined energy–climate–forest analysis by capturing the most essential interactions between these sectors. If developed further, the model may provide insights for the optimal utilisation of forests in climate change mitigation.

Keywords:	Climate change, bioenergy, forests, carbon sink, TIMES
Language:	English

Aalto-yliopisto
Perustieteiden korkeakoulu
Teknillisen fysiikan ja matematiikan koulutusohjelma

DIPLOMITYÖN TIIVISTELMÄ

Tekijä:	Riikka Siljander		
Työn nimi: Energia-ilmasto-metsä mallinnus kokonaisvaltaisen politiikka-analyysin tukena			
Päiväys:	22. maaliskuuta 2016	**Sivumäärä:**	vii + 75
Pääaine:	Systeemi- ja operaatiotutkimus	**Koodi:**	Mat-2
Valvoja:	Professori Ahti Salo		
Ohjaaja:	Tekniikan tohtori Tommi Ekholm		

Kasvava huoli ilmaston lämpenemisestä lisää paineita nopeisiin ja tehokkaisiin päästövähennyksiin. Tähän asti metsiä on hyödynnetty ilmastonmuutoksen hillinnässä lähinnä bioenergian lähteenä korvaamaan fossiilisia polttoaineita. Toisaalta metsät ovat myös merkittäviä hiilinieluja ja -lähteitä ja vaikuttavat siten ilmakehän hiilidioksidipitoisuuteen. Tämä on johtanut keskusteluun siitä, pitäisikö muutokset metsien hiilivarastoissa ottaa huomioon päästötavoitteissa. Tässä työssä tutkitaan, miten hiilivarastojen huomioiminen vaikuttaisi päästövähennysten kustannustehokkuuteen sekä metsä- ja energiasektoreihin Suomessa.

Työssä käytetään TIMES-mallia, jolla voidaan luoda ja analysoida erilaisia skenaarioita tulevaisuuden energiasysteemistä ja sen päästöistä. Mallia täydennetään yksinkertaisella metsämoduulilla, joka kuvaa metsien kasvua ja hiilivaraston kehitystä Suomen olosuhteissa. Täten saadaan ensimmäinen Suomen kattava malli, joka yhdistää metsä- ja energiasektorit sekä niiden ilmastovaikutukset samaan malliin mahdollistaen niiden muodostaman systeemin kokonaisvaltaisen tarkastelun ja optimoinnin. Työssä luodaan ja analysoidaan vaihtoehtoisia päästövähennysskenaarioita.

Tulosten perusteella päästötavoitteet voidaan saavuttaa huomattavasti kustannustehokkaammin, mikäli muutokset metsien hiilivarastossa huomioidaan. Skenaarioissa metsien hiilinielulla kompensoitiin muita päästöjä, jolloin tarve nopeisiin ja kalliisiin päästövähennyksiin väheni. Esimerkiksi tarve hiilidioksidin talteenottoon ja varastointiin väheni ja hiilen käyttö laski hitaammin. Samalla metsistä korjattavan puun määrä väheni ja bioenergian käyttö kasvoi hitaammin.

Tämän työn perusteella metsien hiilinieluilla voisi olla merkittävä rooli Suomen päästöjen ja päästövähennyskustannusten hillitsemisessä. Metsien kasvun ja hiilivarastojen arviointiin liittyy kuitenkin monia epävarmuustekijöitä, ja tässä työssä kehitetty malli on yksinkertaistettu kuvaus metsien ja hiilivarastojen kehityksestä. Malli tarjoaa kuitenkin lähtökohdan energia-, ilmasto - ja metsäpolitiikan kokonaisvaltaiselle tarkastelulle kuvaamalla merkittävimpiä vuorovaikutuksia sektoreiden välillä. Mikäli mallia jatkokehitetään, sitä voidaan käyttää apuna arvioitaessa erilaisia tapoja hyödyntää metsiä ilmastonmuutoksen hillinnässä.

Asiasanat:	Ilmastonmuutos, bioenergia, metsät, hiilinielu, TIMES
Kieli:	Englanti

Acknowledgements

This masters' thesis has been made at the VTT Energy Systems Research Team as a part of the project ECOSUS, funded by the Academy of Finland. I am very grateful for the opportunity to work in this interesting project and as a part of this great team.

I would like to thank my instructor Tommi Ekholm for his great guidance throughout this project and supervisor Ahti Salo for the comments and insights he provided for this thesis. I would also like to thank Antti Lehtilä for his assistance with the TIMES energy system model. In addition, I am grateful to everyone else who provided comments and assistance for this thesis.

Finally, I would like to thank all my friends at the Aalto University for the joyful student days in Otaniemi and my family for all the support I have got. Special thanks go to Mikko for his support and patience during this project. I also warmly thank everyone else who have supported me through my studies.

Espoo, March 22, 2016

Riikka Siljander

Abbreviations and Acronyms

BEF	Biomass expansion factor
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
EC	European Commission
GAMS	General Algebraic Modeling System for mathematical programming
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land-use change and forestry
NFI	National Forest Inventory
NPV	Net present value
TIMES	The Integrated MARKAL-EFOM System
UNFCCC	United Nations Framework Convention on Climate Change

Contents

Chapter 1

Introduction

1.1 Climate change

Global warming is one of the major threats that humankind is facing in the 21st century. The average global temperature has risen approximately 0.8 °C in 1880−2012, two thirds of which has occurred after 1975 (NASA Goddard Institute for Space Studies). There is a broad consensus that anthropogenic greenhouse gas (GHG) emissions are the major cause of global warming. They have been growing considerably during the last decades: the cumulative anthropogenic carbon dioxide (CO_2) emissions in 1750−2010 were about 2000 Gt, and more than half of that occurred in 1970−2010. In spite of the enhanced political efforts for climate change mitigation, the growth of GHG emissions accelerated in 2000−2010, being the highest in human history. Global temperature is estimated to rise further, and increase 3.7 to 4.8 °C compared with pre-industrial levels by 2100 if no additional efforts besides the current attempts to reduce GHG emissions are carried out. (IPCC, 2014)

The most considerable growth of greenhouse gas emissions in 2000−2010 came from energy production and consumption. During this period emissions in energy supply sector increased globally by 47 %, and constituted 35 %

of the total GHG emissions in 2010 (IPCC, 2014). If transport sector is added to these figures, the corresponding shares are 58 % and 49 %. In Finland, about 80 % of greenhouse gas emissions currently arise from the energy use (Parliamentary Committee on Energy and Climate Issues, 2014). U.S. Energy Information Administration (2013) has estimated that global energy consumption will still increase more than 50 % in 2010−2040. This will put an additional pressure on reducing emissions in the energy sector.

There is a political agreement that global temperature rise should be limited to 2 °C in order to avoid hazardous interference with the climate system (UNFCCC, 2009). Achieving this target requires political actions and global co-operation. The European Union (EU) has set a target to reduce GHG emissions at least 80 % by 2050 compared with the 1990 level, which is in accordance with the goal of limiting global warming below 2 °C (European Council, 2009). One of the key strategies for achieving this target is to increase the share of renewable energy. The target share is 20 % by 2020 and 27 % by 2030 (European Commission, 2014). Increasing the use of bioenergy is one of the key components in reaching of the renewable energy target. Wood-based bioenergy has an important role in achieving the climate and energy policy targets both in Finland and in the EU (European Parliament and Council of the European Union, 2009, Parliamentary Committee on Energy and Climate Issues, 2014).

1.2 Forests in climate change mitigation

Forests are an important part of the global carbon cycle, serving both as sinks and sources of atmospheric carbon dioxide. In climate change mitigation, forests have two main roles: (1) they can reduce the atmospheric CO_2 concentration by capturing and storing carbon in the biosphere through forest growth, or (2) act as a source of bioenergy which can substitute for fossil fuels. However, these two ways of using forests are in contradiction. Carbon accumulates to the forest biomass, and thus, carbon sinks can be enhanced by increasing the biomass. On the other hand, increased use of wood-based energy leads to intensified harvests of forest biomass, decreasing the carbon sinking capacity of forests.

Increasing the use of wood-based bioenergy is an attractive means for reducing GHG emissions because wood is often considered as a carbon neutral source of energy. This is based on the assumption that carbon released during biomass combustion is sequestered back to the forest during the regrowth, and therefore, the amount of carbon in circulation is not increased. However, the carbon neutrality and environmental sustainability of wood-based biomass has been increasingly challenged (see e.g. Gunn et al., 2012, McKechnie et al., 2010, Searchinger et al., 2009, Zanchi et al., 2012).

The emission benefits of wood-based biomass in comparison to fossil fuels depend on, for example, the source of biomass and the considered time horizon (see e.g. McKechnie et al., 2010, Zanchi et al., 2012). In short and medium term, the use of biomass does not necessarily reduce GHG emissions, and may even lead to negative climate impacts compared with fossil fuels (Kallio et al., 2013). This is based on the fact that harvesting and burning of wood-based biomass, which currently consists mainly of harvest residues, releases immediately carbon dioxide which would otherwise be stored in the biosphere, or released from decomposing biomass over a longer time period. A significant time delay exists before the released carbon is sequestered back to the re-growing biomass, and causes a temporary increase in CO_2 concentration in the atmosphere – referred as a carbon debt – even though forests would be managed sustainably. The amount of carbon debt depends on the type of harvest residues used. For example, the decomposition of stumps takes essentially longer compared with branches, and thus, collecting and burning of stumps causes more considerable carbon debt (Repo et al., 2011). In addition, the increased use of harvest residues increases the amount of outgoing nutrients from the forest site, which may affect the future growth of the forest (see e.g. Egnell and Valinger, 2003, Helmisaari et al., 2011).

If the use of wood-based bioenergy is increased, it may lead to a rise in the current harvest levels, and to a need to use also other sources than by-products of harvests, for example stem wood, in energy production. Harvesting of growing trees decreases the forest carbon stock. In addition, it causes indirect emissions because without harvests the trees would have continued growing and sequestering more carbon. On the other hand, the ability of forests to maintain growth is limited because the growth decelerates and natural mortality increases in ageing forests (Lippke et al., 2011). As a result, the forest volume and carbon stock eventually saturates, or may even decrease. Thus, intensive management can also help to maintain and enhance the growth and carbon sequestration of forests.

Because there are close linkages between energy, climate, and forest sectors, decisions in one sector have consequences in the others. For example, setting of emission targets affect the energy policy because energy sector is the main emitter of greenhouse gases. In addition, targets or subsidies for bioenergy affect the harvest decisions, and collecting of harvest residues. On the other hand, harvest decisions affect the carbon balance of forest, and thus, have direct climate effects. As long as bioenergy is produced mainly form harvest residues, the harvest decisions also determine how much biomass is available for energy procution.

1.3 Carbon stocks in emission targets

In international climate policies, the use of wood-based biomass for substituting fossil fuels is emphasised over the use of forests as a carbon sink. The current accounting systems for the emissions from the biomass combustion is based on the carbon neutrality assumption (IPCC, 2006). This is to avoid a double counting of emissions because the changes in national carbon stocks are already taken into account in the land use, land-use change and forestry sector (LULUCF). However, sinks and emissions from forest use have so far been ignored in the EU's emission targets, and carbon sinks cannot be utilised in achieving the targets. This creates an incentive for favouring the use of wood in energy production for fulfilling emission reduction commitments, regardless of whether it is truly reducing CO_2 emissions compared with fossil fuels within the timeframe considered. Favouring the use of wood-based bioenergy may be beneficial in long term, but might reduce the climate benefits in short term. Thus, the current accounting of the emissions is insufficient for estimating the total climatic effect of wood use and for guiding the optimal forest use in climate change mitigation.

There is an ongoing debate on whether and how carbon stocks should be taken into account in the EU climate policies (European Commission, 2012). Including of the forest-based sinks and emissions in the emission targets would give a more complete picture of the net GHG emissions and real climate impacts. This would have a significant effect on climate policy, for example, in Finland where forestland is estimated to sequester approximately 50-60 % of the national greenhouse gas emissions (Finnish Forest Research Institute, 2013). The current accounting of forest carbon stocks may change as a result of the Paris Agreement (UNFCCC, 2015). However, at the moment, the role of LULUCF sector in the international and EU's climate and energy policies remains open.

1.4 Research objectives

This thesis studies how the inclusion of the forest-based sinks and emissions in the emission targets would affect emission reduction strategies and reduction costs in Finland. If the cost-effectiveness is improved, the current emission targets could be achieved at lower costs, or greater emission reductions could be achieved with the same costs than are needed for reaching the current targets. In addition, this thesis studies the impacts on energy and forest sectors, like the effects on the energy production and consumption, use of bioenergy, and the total volume of harvested wood.

The approach is to create long-term scenarios by using the TIMES energy system model which contains a detailed description of the whole energy system and the related emissions. In order to incorporate the forest sector into analysis, a forest module is developed in this thesis and integrated into TIMES. The module is a simplified description of forest growth and carbon sequestration when forests are subjected to management. The most considerable simplification is the approximation of all forests in Finland with similar growth dynamics, and thus, ignoring regional and species-specific variations in forest growth. The forest module replaces the – earlier external – wood supply in TIMES. The inclusion of the forest module combines energy, climate, and forest sectors into a single model and allows to study their interactions. Since the focus of the study is these interactions, rather than detailed examination of forest growth dynamics, the simplified approach is sufficiently accurate for the purpose of the model, and no exact estimates, for example, of the future forest volume will be provided. Scenarios with different emission targets with or without including the changes in forest carbon stock are built to study the influences of different emission policies on the energy and forest sectors and the cost-effectiveness of the emission reductions.

A number of existing models already depict the forest growth, forest related emissions, and use of forests as an energy source. However, none of the existing models combine all these aspects. Thus, the novelty of the model created in this thesis is the integration of energy, climate, and forest sectors into a single model, enabling the examination and optimization of the system as a whole. Through this, it is possible to get new insights to the most efficient way of utilizing forests to achieve the highest benefit in terms of climate change mitigation and mitigation costs.

1.5 Structure of the thesis

The rest of the thesis is structured as follows: Chapter 2 gives a short introduction to the forest growth and yield dynamics. In addition, it presents a few modelling approaches which have been applied for Finnish forests earlier. Chapter 3 introduces the TIMES energy system model and the forest module which is integrated into TIMES. This is followed by an introduction to the research setup in Chapter 4. It includes an introduction to the scenarios analysed in this thesis and the objectives of the analysis. Results are presented in Chapter 5. Chapter 6 contains discussion about the results and concludes the thesis.

Chapter 2

Forest dynamics

Forests are dynamic systems, which means that the structure and development of a forest stand depends not only on the factors currently affecting – like weather, nutritions, and management decisions – but also on the history of the stand. The study of forest dynamics is interested in the changes in forest structure and composition as well as factors and conditions affecting these changes (Pretzsch, 2009). Forest growth and yield models can be used for predicting the future growth and yield, and studying the impacts of management activities like thinnings and final fellings, or changes in natural conditions like climate change, on the future development of forests (Vanclay, 1994). These models can be used for supporting decision making in forestry, for example planning and scheduling management activities.

2.1 Forest growth and yield

Forest growth refers to an increase in the size or weight of an individual tree or a stand within a certain time period, and yield refers to a size of tree or entire biomass accumulated within a stand at the end of a certain period (Vanclay, 1994). The growth of an individual tree is usually defined as an increase in the size of stem wood and quantified as an increase in the height, stem diameter at breast height, or stem volume. The growth of the forest stand refers to the increase in total biomass which is usually quantified as the total stem volume per unit area within the stand. The yield of the forest stand per unit area can be derived from the number of trees; and the diameter, height, or stem volume of the trees on the area. The forest growth and yield can be studied in the tree, stand, area, or country level. In this thesis, growth is considered as an increase in the average stem volume and yield as the total stem volume per unit area, and the stand development is studied in the forests of Finland.

The stand volume increases as forest grows and decreases as a result of management, natural mortality, and biomass decay. The growth of forests depends on several factors, like growing conditions, species, treatment, and age (Pretzsch, 2009). In addition, disturbances – like forest fires, weather conditions, and insects – affect the forest growth. Climate change has also potential effect because rising temperatures and increased atmospheric CO_2 concentration may enhance the forest growth (see e.g. Kellomäki and Väisänen, 1997, Matala et al., 2005). However, at the same time, natural mortality can increase due to the higher risk of extreme weather events, like drought, heat, and increased population of insects and fungis (Allen et al., 2010). Thus, the total impact of climate change on forest growth is still uncertain.

Forests have a limited ability to maintain growth as the growth decelerates and natural mortality increases in aging forests (Lippke et al., 2011). Thus, the stand volume achieves its maximum and yield saturates to a site-specific equilibrium, or may even decrease because of the increased risk of disturbances, like forest fires and storm damages, in old forests. A theoretical development of the total stem volume in unamaged forest can be described with an s-shaped function, where growth accelerates after the initiation of the stand and decelerates as the forest ages (see Figure 2.1).

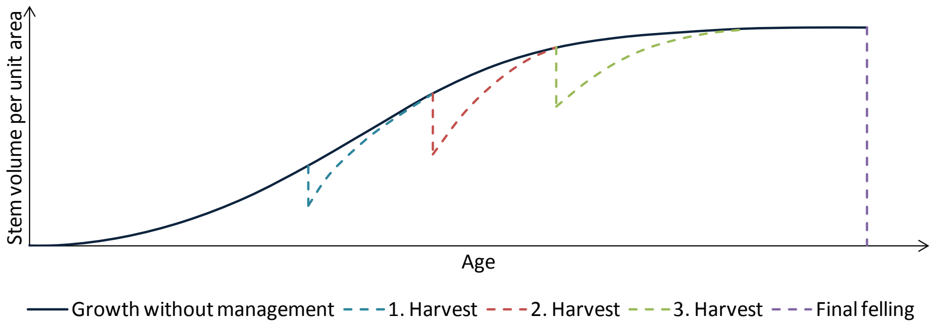


Figure 2.1: A theoretical development of the average stem volume of unmanaged forests and impact of thinnigs and final felling on the volume. The growth enhances after thinnings, and thus, the deficit in the stem volume caused by thinnings reduces in time.

In managed forests, the greatest impact on forest growth is caused by management activities. A forest management can be based on even-aged or uneven-aged management (Kuuluvainen et al., 2012). In even-aged management, a forest stand goes through a repetitive cycle which includes regeneration, growing and thinning, and final felling in which the stand is clear-cut. After final felling, a new forest is initiated, and the rotation of the stand starts from the beginning. In uneven-aged management, harvests are carried out by removing indiviadual trees, or small groups of trees. Thus, there is no clear regeneration phase, and the stand comprises of trees at different ages. Thinning influences the future medium and long-term development of the stand by changing the stand structure and density. Thinning enhances the growth of remaining trees because there is less competition for resources, like space and nutritions. Thus, the deficit in stand volume caused by thinning reduces in time (see Figure 2.1). Thinnings and final fellings may affect the future forest growth also through the outgoing nutritions from the stand. The nutrition content of the soil depends on whether harvest residues, like stumps and needles, are also collected from the thinning or felling site (see e.g. Asikainen et al., 2012, Egnell and Valinger, 2003, Helmisaari et al., 2011).

2.2 Estimation of biomass and carbon stock

Forests constitute a significant carbon stocks. Carbon is stored in living biomass and dead organic matter – both below and above ground – including trees, decomposing organic matter, litter, and soil. Carbon is exchanged between these systems and the atmosphere through photosynthesis, respiration, decay of dead organic matter, and biomass combustion. Growing forest absorbs CO_2 from the atmosphere to the trees and indirectly to the soil. If forest biomass increases, the amount of carbon stored in the forest increases, and the forest acts as a carbon sink. On the other hand, reduction in forest biomass reduces the carbon stock, and forest acts as a source of carbon dioxide increasing the atmospheric CO_2 concentration if it is released to the air. This temporary increase in CO_2 concentration is called carbon debt which is paid only when the forest stand has reached the same volume it had before removals.

National forest inventories (NFI) provide estimates of the national and regional forest resources, like area, stem volume, and forest growth. The data obtained from NFI is often used for measuring the total forest biomass and carbon stock (Löwe et al., 2000). The total biomass of a forest stand can be derived from the total stem volume with simple biomass expansion factors (BEFs) which converts the stem volume to a whole tree biomass. Often, constant values are used for BEFs, but some studies also suggest that biomass expansion factors should vary according to the species and the age of the stand (see e.g. Jalkanen et al., 2005, Lehtonen et al., 2004). The total biomass can be further converted to the total carbon stock if the carbon content of biomass is known. Often carbon content is assumed to be 50 % of the total dry biomass (IPCC, 2003). Therefore, estimates of carbon stocks can be derived by multiplying the total biomass by 0.5.

Because national forest inventories provide the most reliable information of the existing forest resources, the NFI data is often used as an input in the growth and yield models, and as an initial point in simulating the future development of forest resources (see e.g. Karjalainen et al., 2002). Reliable estimates of the forest resources are important if the forest carbon sinks are to be used as a means for mitigating climate change. In Finland, national forest inventories have been carried out regularly in 5−10 years cycles since 1920's. The NFI data has been used for estimating the forest carbon stock in Finland by using BEFs estimated for the main tree species (Tomppo, 2000).

2.3 Modelling of growth and yield

Several types of growth and yield models have been developed for predicting the changes in forest structure and its response to management activities. Forest models are often dynamic, but may differ substantially in the level of details they provide. Models can be divided, for example, to whole-stand models, size-class models, and single-tree models; or to statistical and process-based models (Vanclay, 1994).

In *whole-stand models*, stand-level parameters – like stand area, stand age, number of trees per unit area, and stand volume – are used for predicting the future growth and yield. The whole-stand models are based on the overall growth of the stand and includes no details of the individual trees. They are simple and require relatively little information for predicting the forest growth. On the other hand they provide only quite general information of the future stand.

In *size-class models*, trees are distributed to classes according to some criteria, like size, age, or species. The classes form the basic units for modelling. This approach is relatively simple and computationally efficient, but still offers information in sufficient detail for many forest management applications. This modelling approach is between the whole-stand and single-tree models.

Single-tree models are the most detailed approach for modelling the forest growth. They predict the growth and yield of individual trees by using input parameters like diameter, height, and crown height; which are estimated for each tree within the stand. In addition, the growth of individual tree is affected by competition between trees. The single-tree models can be further divided to distance-dependent and distance-independent models. In the distant-dependent models, the growth of individual tree depends on its relative position within the stand and the size of neighbouring trees. In the distance-independent models, the competition between trees is modelled through stand-level parameters, like basal area and number of trees per unit area.

2.3.1 Statistical models

Statistical (or emipirical) models are a traditional approach for modelling forest growth and yield and have been widely used in forest management because of their relative simplicity, but sufficient accuracy (Amaro et al., 2003). In statistical models, the predictions of the future growth and yield are based on historical data obtained from measurements in sample plots (Weiskittel et al., 2011). They provide quantitative information for management and planning, like information about log sizes and size distribution.

A weakness of the statistical models is that they can be reliably used only for predicting the growth and yield over short time periods for which the conditions and management activities are expected to stay similar as in the past (Peng, 2000). Thus, they are well suited for locally focused predictions in stable conditions but do not provide reliable predictions of forest development in changing conditions (Bossel, 1991).

2.3.2 Process-based models

In process-based models, forest growth is described through physiological processes, like photosynthesis and respiration (Matala et al., 2003). The processes and their interactions can be described at different levels, like at stand, tree, foliage or root levels (Mäkelä, 2007). The process-based models are mainly used for studying a forest productivity and changes in it (Landsberg and Waring, 1997). Because estimates are based on physiological processes, process-based models can provide estimates also for stands for which no measurements exist. They can be applied for studying the growth responses to management activities and changing environmental conditions, like predicting the impacts of climate change on forests (see e.g. Kellomäki et al., 1997, Kirschbaum, 2000).

Process-based models have been originally developed for research purposes and they attempt to represent the physiological processes with high accuracy (Landsberg, 2003). These models can enhance the understanding of forest growth and stand dynamics but are often complex and may require detailed data which includes high uncertainties. Because of the lack of adequate data, they are difficult to parameterise and validate, and thus, rarely used in forest management (Battaglia and Sands, 1998). However, the interest for applying process-based models in forest management has grown with the increased awareness of the influence that changing environmental conditions have on forests. There also exists models with characteristics from both statistical and process-based models, and in the future, the use of models with process-based components are expected to increase in the forest management (see e.g. Landsberg, 2003, Mäkelä et al., 2000).

2.4 Examples of models applied in Finland

2.4.1 MELA

MELA is a statistical forestry model designed in the 1970s for regional and national analyses of timber production in Finland (Siitonen et al., 1999). It has been used, for example, for assessing the regional felling possibilities (Nuutinen et al., 2005). The estimates of the model are based on the data obtained from the Finnish National Forest Inventories and forest stand compartment inventories. A stand compartment refers to a forest area in which the growing stock and habitat share similar characteristics and forest management requirements (Finnish Forest Centre, 2013).

MELA consists of two main parts: the stand simulator and the optimization package. The stand simulator predicts the stand development, basing on distance-independent single-tree models for regeneration, growth, and mortality (Hynynen et al., 2002). The growth of an individual tree is simulated in five-year time steps and depends on tree and stand characteristics, like species, age, tree diameter, height, stand type, and location. A stem volume is obtained from stem curve models as a function of tree species, diameter, and height. The development of the stand can be derived by aggregating the single-tree information.

The optimization package is designed for management planning. It creates several alternative management schedules for each forest stand. The schedules differ, for example, by timing and management activities. For a particular region, an optimal combination of schedules is chosen by using linear programming, while fulfilling the restrictions and objectives defined by the user (Lappi, 1992). The management schedules consist of the chains of states and events which can be natural processes – like the growth and mortality of trees – or human activities like thinning, final felling, and fertilization. The treatments are chosen on the basis of average characteristics of the management unit which may be a forest stand or a set of homogeneous stands. The simulations are based on the expected values, and no stochastic variations in natural processes – for example in the tree growth – is taken into account.

2.4.2 MOTTI forest stand simulator

MOTTI is a stand-level forest simulator developed for forestry planning in Finland. It is a statistical model that utilises the Finnish National Forest Inventory and forest stand compartment inventory data. MOTTI can be used for assessing the profitability of alternative forest management scenarios and the influence of the management on the growth and yield of a forest stand (Hynynen et al., 2005). In addition, features; that enable the prediction of biomass production, carbon sequestration, and biodiversity; have been added to the model.

MOTTI is developed on the basis of the MELA forestry model, and they share almost similar growth models (Salminen et al., 2005). The main difference between the models is that MOTTI simulates a predetermined management schedule for a given forest stand and calculates the influence of the management, whereas MELA chooses an optimal combination of the stand-specific management schedules for a given region. MOTTI is applicable to simulating the growth of all the major tree species and sites all around Finland.

In MOTTI, the biomass production of trees is predicted for the following compartments: foliage, branches, stems, stumps, coarse roots, and fine roots. The estimates for the different tree compartments are based on the tree-level biomass equations for the main species: Scots pine, spruce and birch. The equations use either tree diameter and height, or only diameter for predicting the biomass. The biomass of tree compartments, for which no biomass equations are available, is estimated by using other sources. The amount of carbon stored in the trees are received by multiplying the biomass by 0.5 which is the assumed carbon content of wood. In addition, the litter production of trees is estimated and the decomposition of litter and soil organic matter simulated in MOTTI. Thus, the model can also estimate the amount of soil carbon stock.

2.4.3 Finnish Forest and Energy Policy Model

Finnish Forest and Energy Policy Model (FinFEP) is a partial equilibrium model of the Finnish forest and energy sectors (Lintunen et al., 2015). FinFEP can be used for studying the cost-effectiveness of policy instruments, and their influence on the energy and forest sectors. However, it does not cover the whole energy sector: for example the emissions from transportation and households' energy use are outside of the scope of the model.

The model consists of forest resources and processing modules. The forest resources module consists a description of forest resources available for wood production in Finland. The state of the forest stand at a certain age is described through the number of trees in one-hectare area, the average volume of individual trees, and the width of volume distribution. The volume of the forest stand can be derived as a product of the average volume and the number of trees. Forests are managed by forest owners who maximize their utility which consist of the monetary and recreational values of the forest. Two types of management activities can be performed on the stand: thinnings and final fellings. After final felling, the stand is regenerated by planting a new forest. Dynamic optimization is used for determining the management behavior, and the thinnings and final fellings together determine the wood supply.

The processing module consists of the profit maximizing energy and forest sector firms in Finland. A competitive market is assumed, which means that all firms are price takers, and the prices are determined when the supply and demand are in equilibrium. The demand is partly exogenously determined by demand functions, and partly endogenously determined by the forest owner decisions and production decisions of the intermediate commodity producers.

The main motivations for building the model was to integrate the energy and forest sectors into a single model, link the forest industry and the private forest owners' objectives, and study the impacts of differrent policies. The policy instruments, that can be analysed, include, for example, feed-in tariffs for electricity produced form wood chips, carbon rentals for landowners, and forest taxation. Their impacts can be studied under different scenarios which vary according external variables, like oil and CO_2 prices, or demand for Finnish forest industry products.

Chapter 3

TIMES energy system model

3.1 Overview of TIMES

3.1.1 Introduction

TIMES (Integrated MARKAL-EFOM System) is a global energy system model (Loulou and Labriet, 2008, Loulou et al., 2005). It can be used for studying the future energy systems over a long time horizon by creating and analysing different scenarios. The model allows to study either the whole energy system or a single sector, like electricity or district heating sectors. Because the model represents also emissions related to the energy system, it is also well suited for analysing energy and environmental policies. The model runs usually in 10-year time steps up to the year 2100.

In the TIMES model, the global energy system is divided into 19 regions which represent both individual countries, as well as groups of countries, or even whole continents. For example, Europe is divided into the following regions; Finland, Sweden, Norway, Denmark, the rest of Western Europe, and Eastern Europe. Individual regions are connected to each other through trade in energy and materials, like crude oil, natural gas, coal, and wood.

Actions taken in one region affect other regions through the price elasticities of traded commodities. The model enables the examination of national, multi-regional, and global energy systems.

3.1.2 Basic structure

The inputs needed for construction of the scenarios consist of four components: demand, supply, policy, and techno-economic components. The demand trajectories are defined by the user and depend on demand drivers – like GDP and population growth – and the elasticities of the demands to their respective drivers. In addition, the demands are elastic to their own prices, which allows the demands to be affected by different assumptions and constraints of the scenarios. The supply curves for primary energy and materials represent the resources available in each region at a certain cost, including also trading possibilities. The policy component allows the user to create various policy scenarios by setting different constraints on the energy system, like emission limits or subsidies for certain technologies. The techno-economic component contains a description of the technologies that convert commodities – like fuels, materials, and emissions – into other commodities.

TIMES represents a bottom-up modelling approach where the base elements of the system are described with high detail, and linked to each other to form a larger system. TIMES consist of technologies (or processes), commodities, and commodity flows. Commodities include energy carriers, energy services, materials, monetary flows, and emissions. Technologies are activities that produce and/or consume commodities. They can be divided into following sectors: energy extraction (e.g. coal mining), energy trade, energy transformation (e.g. oil refinery), power generation (e.g. conversion plant producing electricity from primary resources) and energy consumption (e.g. heating systems). Each technology is described by a set of technical and economic parameters including, for example, its inputs, outputs and unit costs. The inputs and outputs of the technologies are referred as commodity flows. They

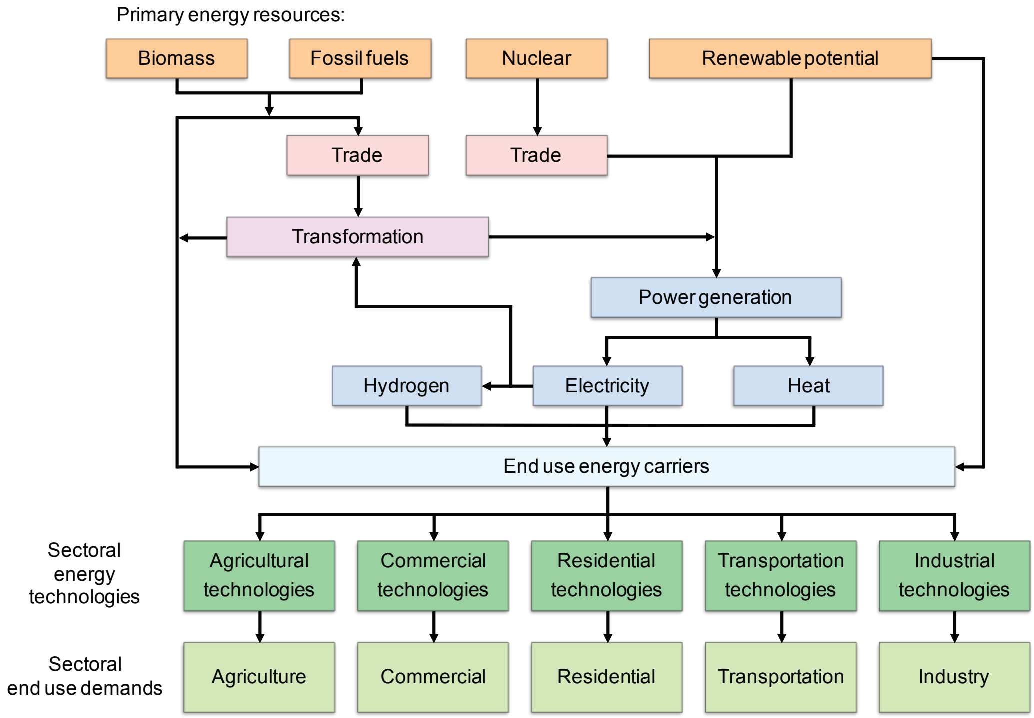


Figure 3.1: The basic structure of the TIMES energy system.

are of the same nature as commodities, but are attached to certain technologies, forming links between commodities and technologies. The current implementation of TIMES contains several thousand technologies and commodities. The basic structure of the TIMES energy system is presented in Figure 3.1.

The TIMES model is not used for forecasting the future energy system but for studying possible futures through alternative scenarios. First, a baseline scenario – describing the business as usual – is formed. Then, alternate policy scenarios which can differ in all or only some of their input components, are created. The effect of different policies can be studied by comparing the scenarios. Outputs of the scenario calculations include, for example, the investments on and operating levels of different technologies, imports and exports of energy and materials, flows of commodities in and out of each technology, and emissions by technology and sector.

The climate module in TIMES can be used for assessing the impacts of the decisions in energy sector on the climate. It calculates the changes in the athmospheric CO_2 concentration, radiative forcing, and temperature. TIMES includes all the greenhouse gases listed in the Kyoto Protocol (UNFCCC, 1998), as well as all the technologies available for emission reductions and their costs. TIMES includes also GHG emissions from other sectors than energy, like waste and agricultural emissions.

3.1.3 Economical approach

The TIMES is a linear, partial equilibrium model. The prices and quantities are in equilibrium at each time within the modelled sectors as competitive markets are assumed. This means that producers are willing to produce exactly the quantities that consumers are willing to buy at the equilibrium price. This supply-demand equilibrium maximizes the total economic surplus which is the sum of consumer and producer surplusses. In other words, the energy services are supplied at minimum global costs. The equilibrium is calculated by using linear programming, which require that all equations in TIMES in a linear form.

The model assumes price-elastic demand, competitive markets and perfect foresight. The demands are elastic to their own prices, except in the baseline scenario in which the demand is defined by the user. Perfect foresight means that each decision maker has a perfect knowledge of markets' parameters and future events; they know all the decisions made by themselves and others in the current and all the future periods. In the competitive market, none of the agents is able to exercise market power, which means that the market price of a commodity is equal to its marginal value in the economy, and no individual producer or consumer can affect it. In reality, markets are rarely fully competitive. For example, the existence of monopolies and oligopolies, such as large state-owned companies, prevent the emergence of perfectly competitive markets. However, the competitive-market approach serves as good approximation to real-world markets, and thus, is often used as a modelling approach. In TIMES deviations from perfectly competitive markets can occur as a consequence of user-defined constraits, like taxes, subsidies, or emission limits.

3.2 The forest module

In this thesis, the TIMES energy system model is supplemented with a simplified forest module which describes the growth and carbon sequestration of forests in Finland. The module enables to examine the development of forest carbon stock under different wood-use scenarios. The forest module is implemented with General Algebraic Modelling System (GAMS).

The forest module estimates the development of the total forest volume and carbon stock. The natural growth of forests is disturbed only by thinnings and final fellings. Other disturbances, like storm and insect damages as well as the possible effect of climate change, are omitted in this study. First, a stand-alone forest model is created. Then, the model is integrated into TIMES.

As TIMES is supplemented with the forest module, it provides a more comprehensive estimates of the net GHG emissions. In the earlier version, bioenergy was assumed to have zero emissions, and wood consumed by industry, and used for energy production had no direct connection to the existing forest resources and their development. Thus, the sinks and emissions from LULUCF sector were ignored. Through the forest module, the wood consumed by different technologies affect the total volume and the carbon stock of forests. This connects the energy, climate and forest sectors to each other, and allows to study their interactions. Other than forest-based sinks and emissions from LULUCF sector are still excluded from TIMES.

3.2.1 Stand-alone non-linear model

The forest model is a dynamic, discrete, whole-stand model based on age classes. All forests in Finland are approximated as a one averaged forest stand. Therefore, an average growth and yield is applied for all forests in Finland omitting the fact that forests are growing at different pace and the maximum stem volumes differ considerably, for example, between regions and tree species. In addtion, the wood obtained from harvests, are not distributed to sawlogs, pulpwood, and wood used for energy production but only the total volume is calculated. Forest management is based on even-aged stand management which is the primarily used practise in Finland (Kuuluvainen et al., 2012). The model runs in ten-year time steps, and the simulation period is 2010−2100; $t = 2010, 2020, ..., 2100$.

The total forest area at the time t, $A(t, \tau)$, is divided into 17 classes indexed with age τ. The age has a ten-year interval so that the first class includes the forests at the average age of 5 (all 0−10-year-old forests), and the last class includes all over 160-year-old forests; $\tau = 5, 15, ..., 155, 165$. The area in a certain age class shifts to the next age class in the following period. An area equal to $10H(t, \tau)$ is final felled from the forest at the age τ at the time t. $H(t, \tau)$ refers to the average final felling area per year. Final fellings are allowed only for forests older than 50 years. This corresponds to the current forest management practicies in Finland where forests reach regeneration maturity in the age of 40−60 depending on the location (Äijälä et al., 2014). Final felling of younger forests is not profitable because young trees are not suitable for sawnlogs. The forest area in a certain age class – except for the first and last age classes – is the area in the previous age class in the preceding period reduced by the area that is final felled. Thus, the area of the age class τ at the time t is

$$A(t, \tau) = A(t - 10, \tau - 10) - 10 \cdot H(t, \tau), \quad \text{if} \quad 15 \leq \tau \leq 155. \qquad (3.1)$$

The total forest area is assumed to stay constant during the whole simulation period. This is based on the fact that forest legislation obligates the owner to plant a new forest after final felling, and the total forest area has stayed relatively constant in Finland since 1944. Only minor changes have occurred, for example, due to clearing of the land for cultivation and construction, and reforestation of the cultivated area. The assumption of the constant area requires that a new forest is planted immediately after final felling. Thus the area of 5-year-old forest is equivalent to the total final felled area:

$$A(t, 5) = 10 \cdot \sum_{\tau} H(t, \tau). \tag{3.2}$$

Because the age class 165 includes all the forests more than 160 years old, the area of the age class 165 at the time t is equivalent to the area of forests at age classes 155 and 165 at the time $t - 1$ reduced by the final felled area:

$$A(t, 165) = A(t - 10, 155) + A(t - 10, 165) - 10 \cdot H(t, 165). \tag{3.3}$$

The area is converted to the stem volume of unmanaged forests, $V_{unman}(t, \tau)$, by multiplying the area by the average stem volume per unit area $\rho(\tau)$. Thus, the volume of the forests in the age class τ at the time t is

$$V_{unman}(t, \tau) = A(t, \tau) \cdot \rho(\tau). \tag{3.4}$$

The stem volume of unmanaged forests is further converted to the stem volume of managed forests by taking into account the deficit in the stand volume caused by thinnings. In this thesis, a term thinning deficit, $d(t, \tau)$, is used for describing the percentual decrease in the stem volume of the managed forest compared with the unmanaged forest. Thinning deficit at a given time depends on the thinnings performed at that time and before. Because of the accelerated growth after thinning in respond to additional space and resources available, the thinning deficit decreases in time. However, the stem volume of forests should not exceed the volume that would be achieved if no thinnings are carried out. Thus, the thinning deficit should approach zero. These characteristics apply, for example, with exponential decrease. In addition, it approximates the development of thinning deficit in the MOTTI model quite well (see Figure 3.2). Thus, exponentially decreasing thinning deficit is applied in this model. The thinning deficit of the forests at the age class τ at time t is

$$d(t,\tau) = d(t-10,\tau-10)\cdot e^{-10x} + p(t,\tau), \quad p(t,\tau)\epsilon[0,1], \tag{3.5}$$

where x is a constant, and $p(t,\tau)$ is the percentage of the total stem volume that is thinned from the age class τ at the time t. The thinning deficit from previous periods decreases by a factor e^{-x} per year. Thinnings are assumed to be distributed evenly across the country and carried out after final fellings. Under 20-year-old forests are left unthinned since the first commercial thinning is usually carried out only in forests older than 15−20 years (Äijälä et al., 2014). The stem volume of the managed forest, $V_{man}(t,\tau)$, is the stem volume of unmanaged forests reduced by the thinning deficit:

$$V_{man}(t,\tau) = V_{unman}(t,\tau)\cdot[1-d(t,\tau)] = A(t,\tau)\cdot\rho(\tau)\cdot[1-d(t,\tau)]. \tag{3.6}$$

The stem volume is converted to the total forest biomass by multiplying it by biomass expansion factor (BEF). This is further converted to the forest carbon stock by multiplying the total forest biomass by the carbon content of biomass c. Thus, the total carbon stock is

$$cs(t) = \sum_{\tau} V_{man}(t,\tau)\cdot BEF\cdot c. \tag{3.7}$$

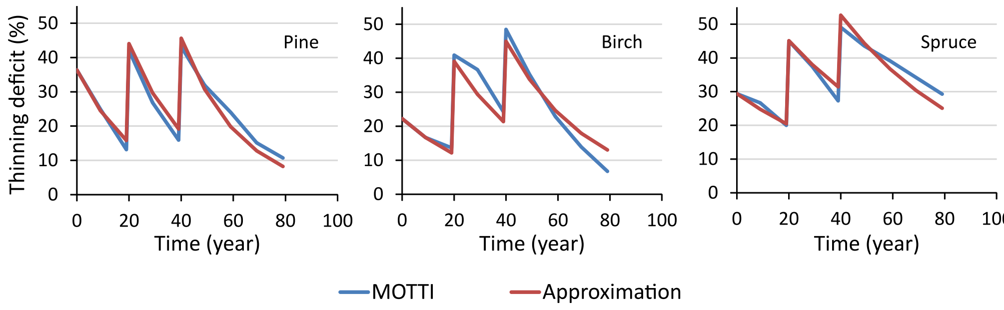


Figure 3.2: The evolution of thinning deficit in pine, birch and spruce stands in the MOTTI results (Matala et al., 2005), and a fitted approximation in which thinnig deficit decreases exponentially. The time series starts from the first thinning, and the following thinnings are carried out 20 and 40 years after the first thinning.

The quantity of the forest CO_2 sink or source is the change in the carbon stock between successive time steps. The mass of carbon is converted to the mass of carbon dioxide by multiplying it by the fraction of carbon and carbon dioxide molar masses. The molar mass of carbon is 12 g/mol, and the molar mass of carbon dioxide is 44 g/mol. The average CO_2 sink or source per year at the time t is

$$CO_2(t) = \frac{cs(t) - cs(t-10)}{10} \cdot \frac{44}{12}. \tag{3.8}$$

The carbon stock and sink represent only the carbon stored in the living trees. The model omits, for example, carbon stored in the soil, dead trees, as well as in stumps, and other harvest residues which are left on the forest site after final fellings. From now on, the forest carbon stock and sink refers in this thesis to the carbon stored in the living trees unless stated otherwise.

3.2.2 Linearization and integration into TIMES

TIMES is based on linear optimization, but the model described above is non-linear due to the equation (3.6). Thus, the forest model has to be linearized before its integration into TIMES. In order to convert the equation (3.6) to a linear form, the choice of thinning percentage is restricted to given discrete options instead of enabling the model to choose it freely between 0 and 1. Ten different options are set for the thinning percentage so that the minimum is zero and the maximum 0.2. The upper limit is set in order to keep the thinnings at a reasonable level and to prevent the thinning deficit to increase unrealisticly high. The forests are distributed to thinning intensity classes i for which the thinning percentage $p(i)$ is

$$p(i) = (i-1) \cdot 0.02, \quad i = 1, 2, ..., 10.$$

Now, the forest area at the time t, $A(t, \tau, i)$, is classified according to age and thinning intensity. As a new forest is initiated, the planted area is divided into the intensity classes and thinned similarly at every period, apart from the first two periods after the initiation of the stand. On other words, $p(i)$ percent of the volume of forest in thinning intensity class i is thinned at every time step until the final felling.

Because a certain forest stand is thinned similarly at every period, the thinning deficit at a certain age is known and can be stated in terms of age and thinning intensity. Because under 20-years-old forests are left unthinned, the thinning deficit is zero for the age classes 5 and 15. The thinning deficits of other age classes can be derived recursively by using the equation (3.5):

$$\begin{cases} d(25,i) = p(i) \\ d(35,i) = d(25,i) \cdot e^{-10x} + p(i) = p(i) \cdot e^{-10x} + p(i) \\ d(45,i) = d(35,i) \cdot e^{-10x} + p(i) = p(i)e^{-20x} + p(i) \cdot e^{-10x} + p(i) \\ \vdots \\ d(n,i) = p(i)e^{-(n-25)x} + p(i)e^{-(n-35)x} + \cdots + p(i) \cdot e^{-10x} + p(i). \end{cases}$$

By using the formula for a geometric sum

$$\sum_{k=0}^{n-1} aq^k = a \cdot \frac{1-q^n}{1-q}, \quad q \neq 1,$$

the thinning deficit can be expressed in the following form:

$$d(\tau, i) = \begin{cases} 0, & \text{if} \quad \tau \leq 15 \\ p(i) \cdot \frac{1-e^{(\tau-15)}}{1-e^{-10 \cdot x}}, & \text{if} \quad \tau > 15. \end{cases}$$

The total area and biomass of forests in each age class can be derived analogously to the linear model (see equations (3.1), (3.2), (3.3), and (3.6)), except that now they depend also on thinning intensity besides of time and age. The total area and biomass according to the age class and time can be derived by summing over the intensity classes

$$A(t, \tau) = \begin{cases} \sum_i A(t, 5, i) = \sum_{\tau, i} H(t, 5, i), & \text{if} \quad \tau = 5 \\ \sum_i [A(t-10, \tau-10, i) - 10H(t, \tau, i)], & \text{if} \quad 15 \leq \tau \leq 155 \\ \sum_i [A(t-10, 155, i) + A(t-10, 165, i) & \\ -10H(t, 165, i)], & \text{if} \quad \tau = 165 \end{cases}$$

$$V_{man}(t, \tau) = \sum_i V_{man}(t, \tau, i) = \sum_i A(t, \tau, i) \cdot \rho(\tau) \cdot [1 - d(\tau, i)].$$

The total forest carbon stock and the amount of CO_2 sink or source are calculated as earlier (see equations (3.7) and (3.8)).

The linearized forest module is integrated into TIMES by replacing the external wood supply by the module. The total volume of wood consumed by industry or used for energy production equals the total volume of harvested wood which denotes here to the combimed thinning and felling volumes. Therefore, all wood use affects the forest carbon stock and the quantity of CO_2 sink or source, and thus, have direct climatic effects. A simplified representation of the integration of the forest module and TIMES and links between energy, climate and forest sectors are presented in Figure 3.3. The upper limit for the total harvested volume is 81 million m^3 per year which is the maximum sustainable volume of removals – the highest level of removals which can be maintained without diminishing the future harvesting potentials – estimated by Natural Resources Institute Finland (2015c).

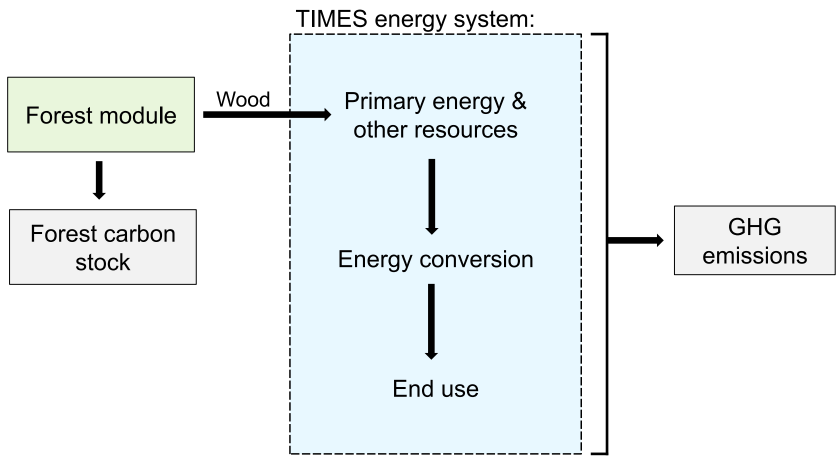


Figure 3.3: Integration of the forest module into TIMES, and a simplified representation of the interactions between energy, climate, and forest sectors in the model. The external wood supply is replaced by the forest module, and the climatic effect of wood use is taken into account through the changes in the forest carbon stock. In the earlier version of TIMES sinks and emissions from LULUCF sector were excluded.

3.2.3 Numerical assumptions

Data of the area and stem volume of managed forests at different ages is available in statistics of the 11th national forest inventory (NFI11) which was carried out in Finland 2009−2013. The initial forest age distribution in the model, $A(2010, \tau)$, is derived from the NFI11 data and is shown in Figure

3.4. Since data for unmanaged forests is not readily available, the average stem volume of unmanaged forest has to be estimated from the stem volume of managed forest and the thinning deficit (see equation (3.6)). The average stem volume of managed forest at different ages is derived from NFI11. The thinning deficit is estimated based on the study of Matala et al. (2003) and the share of thinned forests in different regions, which can be calculated from the NFI11 data.

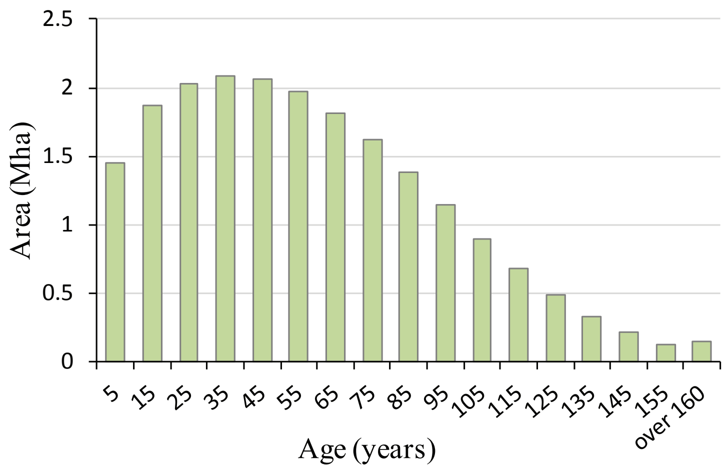


Figure 3.4: The age distribution of forests in Finland based on the NFI11. This is used as an initial age structure in the model.

The stem volume yield curve for unmanaged forest is derived by fitting a curve to the stem volume estimates. The yield curve is assumed to be s-shaped, go through origin and saturate at a reasonable level. The following function is used as an approximation

$$\rho(\tau) = e^{v_2 \cdot \tau} \cdot v_1 \cdot \left(-\frac{1}{v_2^2} + \frac{\tau}{v_2} \right) + e^{v_4 \cdot \tau} \cdot v_3 \cdot \left(\frac{-6}{v_4^4} + \frac{6 \cdot \tau}{v_4^3} - \frac{3 \cdot \tau^2}{v_4^2} + \frac{\tau^3}{v_4} \right) + \frac{v_1}{v_2^2} + \frac{6 \cdot v_3}{v_4^4}.$$

The parameter values v_i are estimated with the least squares method. The obtained yield curve is shown in Figure 3.5. It is assumed to stay unchanged during the whole simulation period.

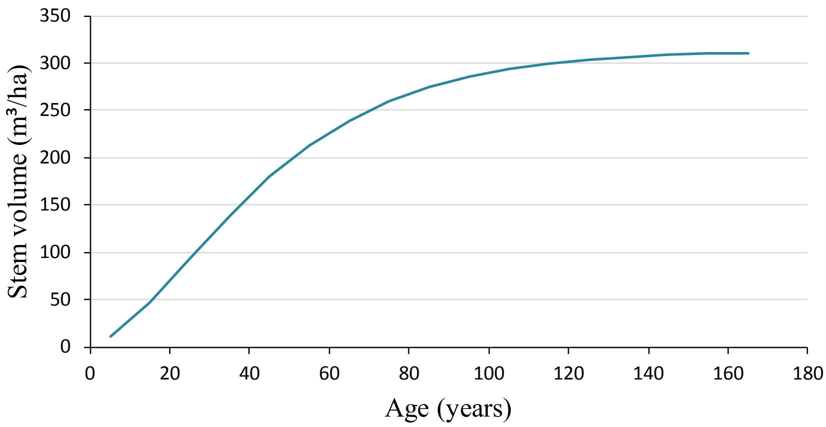


Figure 3.5: The stem volume yield curve which is used in the forest model. It represents the average stem volume per unit area in unmanaged forests.

A similar curve as above is fitted to the data of managed forests and the initial thinning deficit is approximated as a difference between the curves according to the equation (3.6). The model divides the initial forest area into the intensity classes so that the total thinning deficit in each age class equals to the initial thinning deficit. The constant x determines the decrease of the thinning deficit (see equation (3.5)). The value of x is estimated from the MOTTI model (see Figure 3.2) for the three main species, and weighted with the shares of each species in the forests of Finland. As a result, a national-level average, $x = 0.033$, is obtained.

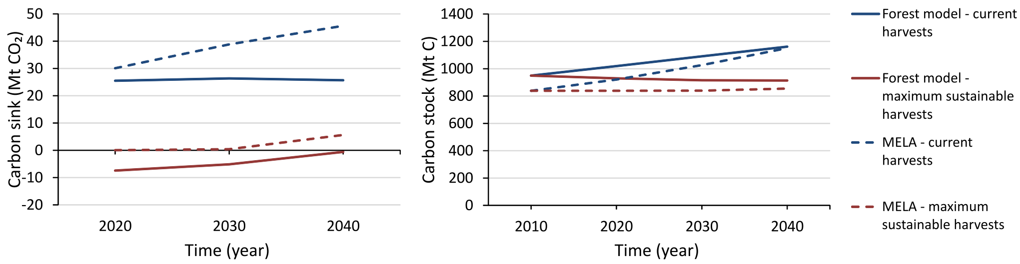
The total harvests in 2010 are fixed according to the realized harvests. A constant value 0.72 is used for biomass expansion factor which is obtained as area-weighted-average from the species specific BEFs estimated by Lehtonen et al. (2004). These BEF estimates include the biomass of stem, foliage, living and dead branches, bark, stump, and roots of pine and spruce; and stem, living and dead branches, and bark of broadleaved trees. The assumed carbon content of biomass is 50 %.

3.2.4 Evaluation

The linear stand-alone forest model is evaluated by creating two timber demand scenarios and comparing the results to those obtained from the MELA model (Natural Resources Institute Finland, 2015a). The demands for domestic timber in these scenarios are about 60 and 86 million m^3 per year in 2020−2040, which are used in the MELA scenarios as the average level of the past year's harvests and as a maximum sustainable harvest level, respectively. The development of the forest carbon sink and stock is compared between the models. The results from the MELA simulations include estimate of the total biomass of living trees at the different harvest levels. This is converted to the forest carbon stock by multiplying the biomass with 0.5 which is the assumed carbon content of biomass.

The development of the forest carbon sink and stock in these scenarios are presented in Figure 3.6. In both scenarios, the MELA model predicts a slightly larger carbon sink compared with the forest model (see Figure 3.6(a)). When current harvest level is used, the predictions of the carbon sink are relatively close to each other in 2020, but the carbon sink increases in MELA whereas it stays almost constant in the forest model. Thus, the difference is more significant in the estimates concerning the more distant future. When the maximum sustainable harvest level is used, the development of the carbon sink is similar in both models, but the amount of sink is systematically lower in the forest model.

The forest carbon stock increases in both models when the current harvest level is maintained (see Figure 3.6(b)). However, the growth rate is somewhat higher in MELA. At the maximum sustainable harvest level, the carbon stock stays relatively constant in MELA and decreases slightly in the forest model. In addition, the initial levels of the carbon stock differ between the models. Because the carbon stock is directly proportional to the forest biomass, the results indicate that the growth rate of forests is higher in MELA. This leads to the larger carbon sink and faster growth of the carbon stock.



(a) Carbon sink (b) Carbon stock

Figure 3.6: Development of the carbon sink and stock in the MELA and the forest models when harvests stay at current level (60 Mm^3 per year) or at the maximum sustainable level (86 Mm^3).

Altogether, the forest model seems to give more conservative estimates of the forest growth and development of the carbon sink. The differences may stem from the different assumptions and precision of the models. For example, the assumptions about the forest growth and the estimation of total biomass may vary between the models. The forest model is highly simplified and does not include as detailed description of the forest growth as MELA.

The actual forest carbon sink during the recent years falls between the sink estimates in the current harvest level scenarios of MELA and the forest model. During 1997 – 2014, the average harvests were 60 Mm^3 and carbon sink was 32 CO_2eq per year (Natural Resources Institute Finland, 2015b, Statistics Finland, 2015). Harvests varied between 57 – 65 Mm^3 and carbon sink between 22 – 42 Mt CO_2eq per year, apart from 2009 when harvests were 48 Mm^3 and the carbon sink was 51 Mt CO_2eq because the global recession reduced the demand for forest products. The carbon sink estimates of the forest model falls within this range of variations, but is slightly lower than the average sink in recent years.

The carbon sink estimates of the forest model seem to be of the right magnitude, but might be slightly underestimated. Nevertheless, high uncertainties are involved in predicting the forest growth and carbon sequestration (Kangas, 1997, Monni et al., 2007), and high variations in the carbon sink have occurred between years even at relatively constant harvest levels. Thus, the projections of the future carbon sink can in any case only be thought as indicative estimates. Given all the uncertainties related to the estimation of the carbon sink and the simplifications of the forest model, the estimates are accurate enough for the purpose of the model. Further sensitivity analyses on the model's assumptions are carried out in Section 5.5.

3.2.5 Limitations and further developments

The greatest simplification and probably the main source of error in the forest model is the applying of similar assumptions about the forest growth over different tree species and regions in Finland. In reality, the site conditions affect the forest growth significantly, and large differences occur, for example, between southern and northern Finland. In addition, the growth and maximum stem volume vary between different tree species. The model accuracy could be improved by dividing the forests into different classes according to the location and/or species and applying different assumptions to these classes.

A high uncertainty is also related to the stem volume yield curve which is a focal component in estimating the carbon balance of forests. Several assumptions were made in assessing the yield curve because there is no NFI data from which it could be directly estimated. In addition, the yield curve is assumed to stay unchanged during the whole simulation period 2010−2100, which supposes that forest growth does not change during this century. However, this assumption might be too simplistic because many natural factors affect the growth, and these factors may change during the century. For example, the average temperature is likely to increase due to global warming. The forest model could be improved by allowing the forest growth to vary over time, for example, by being responsive to the temperature.

The assumptions about the timing and intensity of thinnings are not entirely realistic. The assumption, that thinnings in a certain forest stand are carried out regularly in ten-year intervals and at the same intensity from the initiation of the stand until it is final felled, is made for linearizing the model and does not reflect the reality of forest management. In Finland, a forest stand is usually thinned two or three times before final fellings (Äijälä et al., 2014). In addition, determination of the initial thinning deficit influences the thinning intensity several periods onwards, and prevents the model to freely adjust the thinning levels. Thus, the initial stage may affect the results of the model.

The integration of the forest module and the TIMES model could also be improved. The wood supply in TIMES used to be external variable, and thus, the source of wood had no importance. As the forest module is integrated into TIMES, the total harvested volume (aggregate volume from thinnings and final fellings) replaces the external wood supply, and thus, the industrial and other processes in the model do not distinguish the wood that comes from thinnings and final fellings. However, for example, sawlogs used by the forest industry are received mainly from the final fellings. Also, in the perspective of practical forest management, it is not realistic that a forest stand is only thinned, but no final fellings and regeneration of the stand is performed or vice versa. The model could be improved in this respect, for example, by requiring that a certain amount of wood comes from thinnings and final fellings in each period, or by distinguishing sawlogs, pulp wood and wood for energy production and directing the wood flows to certain processes.

The effect of natural disturbances are omitted in the forest model. In reality, disturbances – like forest fires, storm damages, and insects – may significantly affect the forest growth and yield. However, because aggregate values are used for representing the forest growth and yield in the whole country, the effects of the possible natural disturbances are significantly smaller as they would be, for example, in a stand-level analyses. The possible changes in environmental conditions – like natural variation in the forest growth and the effect of the climate change – are also left outside of the model.

3.3 Decision variables and their constraints

In the TIMES model, the objective function describes the total costs of the energy system. It is minimised by using linear programming while all the constraints have to be satisfied. The objective function is expressed through decision variables which values are determined by the model during the optimization phase. TIMES includes thousands of variables which consists, for example, of the activity levels of different technologies, quantities of commodities produced and consumed by the technologies, investments to a new production capacity, and quantities of commodities exported or imported. These are further affecting the greenhouse gas emissions which are calculated by the climate module.

In the forest module, the quantities to optimise are the thinning and felling volumes at each time. Together they determine the total harvested volume of wood which is available for different processes, like bioenergy production and industrial processes. On the other hand, they affect the total forest biomass, and thus, the carbon stock. The decision variables are the final felled area of each age class at each time and the share of the newly planted forests placed at each thinning intensity class. The final fellings determine the age structure of the forests, and the thinning intensity class determine the share of the forest stand volume that is thinned at each period, which affects the future development of the total forest biomass.

Large number of constraints have to be satisfied as the total costs are minimised. They represent physical and logical constraints associated to the energy system. For example, the demand projections have to be satisfied; and production, consumption, imports, and exports of commodities have to be in balance; at each time and within each region. In addtion, constraints are imposed on the energy resources and technologies. For example, the use of a certain technology cannot be higher than its installed capacity. The deterioration of technologies is also described through constraints. In addition, the user may want to examine different policy scenarios, and thus, set additional constraints. Limiting the investments to a new nuclear capacity or imposing emission limits are examples of the possible user-defined constraints.

Constraints are also set on the forest module, and thus, the thinning and felling volumes cannot be determined entirely freely by the model. Because TIMES has a predetermined demand for the industrial output, a certain amount of wood is required by the forest industry. As the wood is supplied by the forest module, the wood demand places a lower limit for the total harvested volume. In addition, an upper limit is set in order to prevent the model to final fell and thin unsustainable amounts of the forest biomass even if it was economically feasible. The upper limit is set to 81 Mm^3 which corresponds to the maximum sustainable removals estimated by Natural Resources Institute Finland (2015c). In addition, the forest module includes restrictions for the timing of the thinnings and final fellings. Only forest over 50 years old can be final felled. The thinning intensity of a forest stand can be changed only when it is final felled and a new forest planted. Thinning can be performed as the forest reaches the age of 20 years, and every subsequent period a constant share of the total stand volume is thinned according to the thinning intensity class it belongs to.

Chapter 4

Research Setup

4.1 Low carbon roadmap

This thesis studies the effects the inclusion of forest carbon sinks and sources in emission targets would have on the energy and forest sectors in Finland. The analysis builds on European Commission (EC) low carbon roadmap 2050 (European Commission, 2011). The European Union has set a target of reducing greenhouse gas emissions by 80−95 % by 2050 compared with 1990 level, which is in accordance with the objective of restricting global warming below 2 °C. In the low carbon roadmap, European Commission has estimated that the cost-effective pathway for reaching this goal is 25 %, 40 % and 60 % below the 1990 level in 2020, 2030 and 2040, respectively. Sinks and emissions from the LULUCF sector are not taken into account in these targets but the emission reductions have to be achieved within other sectors.

Forest carbon sinks and sources could be included in the emission targets determined by the low carbon roadmap at least in two separate ways: by keeping either the percentual or net emission reductions constant. In the first case, the target for net emissions would change because the reference level is different when forest carbon sinks and sources are also included. In the second case, the target is set so that the reduced net emissions would remain equal. The net emissions refer here to the combined emissions from other than LULUCF sector supplemented by the change in the forest carbon stock. In both cases, the reductions can be achieved either by reducing the emissions from other than LULUCF sector (as is the case in the low carbon roadmap), or by increasing the forest carbon stock. Also other sinks and emissions from the LULUCF sector can be included in the targets, but they are not modelled explicitly in this study.

4.2 Scenario setup

Different emission reduction scenarios are created with the TIMES energy system model. Data on the emissions in 1990 and 2010 are used as a basis for the construction of the scenarios. The emission levels of Finland in 1990 and 2010 with and without emissions from land use, land-use change and forestry sector are represented in Table 4.1. Negative emissions in the LULUCF sector mean that more carbon was sequestered than emitted. The emissions from other than forestry in LULUCF sector have stayed relatively steady, being approximately 10 Mt CO_2eq between 1990 and 2010 (Statistics Finland, 2013). Thus, forests in Finland have been acting as a carbon sink sequestering approximately 25.8 and 36.7 Mt CO_2eq in 1990 and 2010, respectively. The total emissions excluding other than forest-based emissions from LULUCF sector were about 45.8 Mt CO_2eq in 1990 and 39.1 Mt CO_2eq in 2010.

The scenarios are run from 2010 to 2100. They differ in terms of emission targets and whether changes in the forest carbon stock and other sinks and emissions from the LULUCF sector are included in the emission reductions of Finland. In all scenarios, except in *Baseline scenario*, either percentual or net emission target is set for 2050. In subsequent periods, the emissions are limited to 2050 level or below. The 1990 reference level is 71.6, 55.8,

Table 4.1: Greenhouse gas emissions in Finland in 1990 and 2010 (Statistics Finland, 2013). Emissions are expressed in milloin tons of CO_2 equivalents. Negative quantities mean reductions of CO_2.

	1990	2010
Total emissions excluding LULUCF sector	71.6	75.8
Total emissions including LULUCF sector	55.8	49.1
LULUCF sector	-15.8	-26.7

or 45.8 Mt CO_2eq depending on whether changes in the forest carbon stock and other emissions from LULUCF sector are included. In scenarios, where a net emission target is set, a linear target pathway from 2010 to the 2050 is assumed. Emission targets for the rest of the world are kept constant across all scenarios; the targets for the European Union corresponds to the low carbon roadmap and for the rest of the world to the 2 °C global warming pathway.

Descriptions of the scenarios are provided below and summarised in Table 4.2. Scenarios 1 and 2 are the main point of interest in this study. They are based on a low carbon roadmap with and without including the changes in forest carbon stock, and their comparison forms the basis for analysing the impacts of including forest carbon sinks and sources in the emission targets. Scenarios 3−7 are ordered according to the stringency of their emission targets beginning with the loosest one. In scenarios 8 and 9, artificial targets are created in order to achieve a comprehensive set of scenarios. Net emissions in the scenario descriptions refer to the total emissions including changes in forest carbon stock, but excluding other emissions and sinks from LULUCF sector. A term *sink* is used in the scenario labels because forests of Finland have traditionally served as sinks rather than sources. However, reductions in carbon stock are also allowed, in which case forests act as a source of CO_2.

Table 4.2: The emission targets in different scenarios. The target level includes the net emissions excluding other than forest-based emissions from LULUCF sector.

Scenario	Percentual reduction from 1990	Changes in forest carbon stock included	Other LULUCF included	Target level in 2050 (Mt CO_2eq)	Notes
1: Low carbon roadmap	−80%*	-	-	14.3-sink**	*Reference level 71.6 Mt CO_2eq **No constraits for sink
2: Low carbon roadmap with sink	-	×	-	14.3 - sink*	*Target level will be set equal to *Low carbon roadmap* scenario
3: Baseline scenario	-	-	-	-	No emission target
4: Current policy	−40%*	×	-	27.5	*Reference level 45.8 Mt CO_2eq
5: Equal percentual reductions and sink included	−80%*	×	-	9.2	*Reference level 45.8 Mt CO_2eq
6: Emission neutrality – sink included	-	×	-	0.0	
7: Emission neutrality – all emissions included	-	×	×	-10.0*	*Other than forest-based emissions from LULUCF assumed 10 Mt CO_2eq
8: Emissios -5 Mt CO_2eq by 2050	-	×	×	-5.0*	*Other than forest-based emissions from LULUCF assumed 10 Mt CO_2eq
9: Emissios 20 Mt CO_2eq by 2050	-	×	-	20.0	

Scenario 1: Low carbon roadmap

The emissions target is −80 % compared with the 1990 level, excluding the LULUCF sector. The 2050 target level is 14.3 Mt CO_2eq. The scenario is based on the European Commission low carbon roadmap and used as the reference case of the analysis.

Scenario 2: Low carbon roadmap with sink

The emission target is determined according to the net emissions reached in the *Low carbon roadmap* scenario. Thus, equal net emissions are achieved in both scenarios, but in this one, the changes in forest carbon stock are also included, and the forest carbon sink can be utilised in achieving the emission target.

Scenario 3: Baseline scenario

In this scenario, no emission target is set. It provides a baseline against which the other scenarios can be compared in order to study the effects of imposing different emission targets.

Scenario 4: Current policy

The current policies are fully implemented, but no new efforts for reducing emissions are carried out. The EC estimates that this would reduce emissions 20 % by 2020, 30 % by 2030 and 40 % by 2050 compared with 1990 levels (European Commission, 2011). Changes in the forest carbon stock are included, and the 2050 target is 27.5 Mt CO_2 eq.

Scenario 5: Equal percentual reductions with sink

The same percentual emission target is applied as in the *Low carbon roadmap* scenario, but changes in the forest carbon stock are also included. The 2050 target level is 9.2 Mt CO_2 eq.

Scenario 6: Emission neutrality – sink included

The target is to achieve zero emissions by 2050 when changes in the forest carbon stock is included in the emission target. Other sinks and emissions from LULUCF sector are excluded.

Scenario 7: Emission neutrality – all emissions included

The target is to achieve zero emissions by 2050 when whole LULUCF sector is included in the emission targets. Other than forest-based emissions and sinks in LULUCF sector are assumed to stay constant, 10 Mt CO_2eq per year, during the whole simulation period. Thus, emissions from other sources should consist -10 Mt CO_2eq 2050 onwards.

Scenario 8 and 9: Emissions -5 and 20 Mt CO_2eq by 2050

The 2050 target levels are -5 and 20 Mt CO_2eq. These scenarios are created to provide intermediate points between scenarios 4, 5 and 6.

4.3 Ojectives of the study

4.3.1 Cost-effective achievement of emission targets

The cost-effective achievement of emission targets is the focal point of this study. It is examined whether the emission target of Finland could be achieved more cost-effectively if the changes in forest carbon stock are included in the target. Inclusion of the carbon stock would provide alternative means for reducing emissions because part of the emission reductions can be offset by with the forest carbon sink. The hypothesis is stated as follows:

Hypothesis: The same net emission level can be achieved more cost-effectively if forest carbon stock is included in the emission targets.

The hypothesis is based on the rationale that an objective can be reached more cost-effectively or at least with the same cost if more means are available for achieving the objective. The hypothetical effect of the inclusion of the forest carbon stock in the emission targets is presented in Figure 4.1. The relation between emissions and emission reduction costs is presented as a descending curve because the less reduction measures are realized, the lower the costs and the higher the cumulative emissions. If increasing the

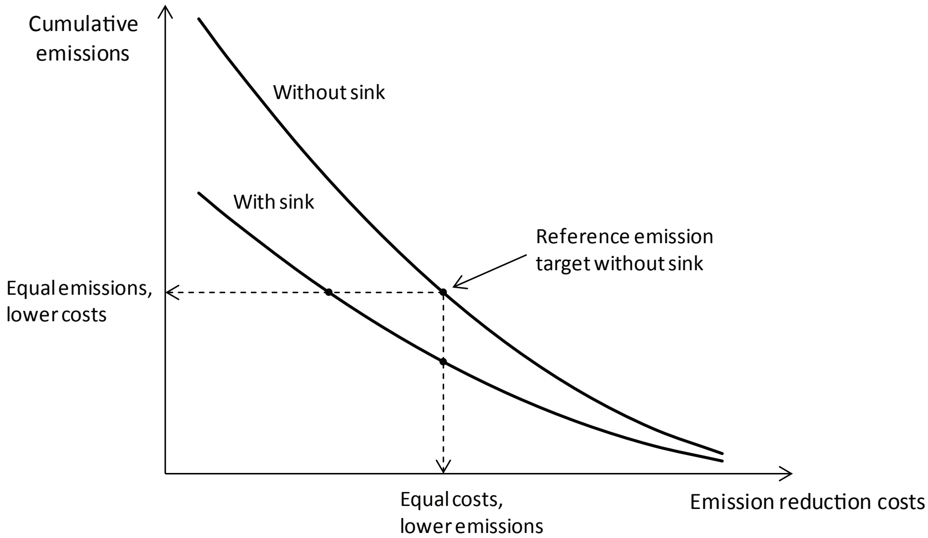


Figure 4.1: The relation between emission reduction costs and cumulative emissions with and without including the changes in the forest carbon stock in the emission targets.

forest carbon stock is added as a means to reduce emissions, the curve shifts downwards, meaning that more emissions can be reduced at the same costs or the same emission reductions can be carried out with lower costs.

4.3.2 Other objectives

This thesis studies also other influences of the inclusion of forest carbon stock in the emission targets. The effect on the following aspects in the forest and energy sectors are studied:

- Development of forest carbon sink
- Total harvested volume wood
- Development of GHG emissions
- Primary energy supply
- Bioenergy use

The effects on the forest and energy sectors are studied by comparing the results of the scenarios *Low carbon roadmap* and *Low carbon roadmap with sink*.

In the *Low carbon roadmap* scenario, forest carbon stock is not included in the emission target, resulting with no incentive to increase the forest carbon sink. Thus, it is expected that the carbon sink is higher in the *Low carbon roadmap with sink* scenario where sink can be used as a means to reduce emissions and substitute emission reductions in other than LULUCF sector. On the other hand, GHG emissions in other sectors are expected to be higher because the scenarios have equal net emission targets.

It is also studied whether and how the inclusion of the forest carbon stock affects energy primary energy supply, especially bioenergy use. Inclusion of the stock in the emission targets places an incentive to utilize forests in the emission reductions not only as a source of bioenergy but also as a carbon sink. Thus, it is expected that bioenergy use is lower in the *Low carbon roadmap with sink* scenario. In addition, slower reductions are expected in the use of more emission intensive energy sources, like coal and oil, because part of these emissions can be offset by the forest carbon sink.

4.4 Sensitivity analysis

A sensitivity analysis is carried out in order to assess the uncertainties of the model. The sensitivity of the emission reduction costs to the model assumptions about the total forest area, the stem volume yield curve, and the initial thinning deficit, are examined. The *Low carbon roadmap with sink* scenario is used in the sensitivity analysis.

4.4.1 Yield curve

The derived yield curve describes the average stem volume per unit area across whole Finland and is assumed to stay constant during the whole simulation period from 2010 to 2100. The yield curve contains large uncertainties because no data is available of the average stem volumes of unmanaged forests. Thus, several assumptions had to be made in estimating the yield curve. The sensitivity of the model to the following possible errors related to the yield curve is assessed:

- The yield curve contains a systematic error; the stem volume estimates are throughout too high or low.
- The assumption about the saturation of stem volume does not hold.

The first point refers to the possibility that the made assumptions cause systematic error to the yield curve. The effect on the emission reduction cost is tested if the yield is 20 % higher or lower than assumed. It is expected that increase in the yield curve leads to lower emission reduction costs in the scenarios where forest carbon sink is included in the emission reduction targets. This is based on the fact that changes in the yield curve ultimately affect to the total stem volume of the forest and thereby to the total carbon stock. Thus, the accelerated growth reduces the effort needed for achieving the emission reduction targets. Conversely, reduction in the yield curve is assumed to increase the emission reduction costs.

The second point relates to the uncertainty regarding the assumption that stem volume saturates to a certain level in old forests. Based on the derived yield curve, this is assumed to happen after forest has achieved the age of 100 years. The effects on emission reduction costs is analysed in a case where stem volume continues to increase until the age 160. The yield curve is kept unchanged for the young age classes, but the upper end of the yield curve is lifted. This affects the total stem volume of forests, and the expected consequences to emission reduction costs are as described above.

4.4.2 Total forest area

The total forest area is assumed to stay constant during the whole simulation period from 2010 to 2100. However, it is possible that the total forest area changes during the century. For example, increasing temperatures may turn cultivation more profitable in the Northern parts of Finland, turning some forest area to a cultivated area. On the other hand, the increasing competition may decrease the profitability of cultivation in Finland leading to reforestation of the cultivated area, which increases the total forest area.

The effect of the total forest area is studied by increasing or decreasing the forest area by 2 % in every period compared to initial area in 2010. Changes in the total forest area affect the total volume of the forest. If the stem volume yield curve is fixed, an increase or a reduction in forest area increases or reduces the total stem volume respectively. The assumed effects on the emission reduction costs are as described in previous section.

4.4.3 Initial thinning deficit

The assumption on initial thinning deficit affects the thinnings and thinning deficit in the subsequent periods. The model has freedom to place the initial forest area into thinning intensity classes which determine the percentage of the volume that is thinned in each period until the forest stand is clear-cut. The only restriction is that the total thinning deficit in each age group has to be equal to the initial thinning deficit. The influence of the initial thinning deficit diminishes over time.

The sensitivity of the model to the initial thinnings deficit is tested by modifying the initial deficit by ± 15 %. The lower the initial thinnings deficit, the less the future thinnings are restricted. Thus, it is expected that the emission reduction costs are lower when initial thinnings deficit is reduced because degrees of freedom in the model are increased. In addition, lower thinning deficit means larger total stem volume of forests in the first period and in all the subsequent periods where this deficit still occurs. A larger total stem volume is also expected to contribute to the reduction of the costs as reasoned earlier. On the contrary, a higher initial thinnings deficit is assumed to increase the emission reduction costs.

Chapter 5

Results

Emission reduction pathways in the different scenarios are presented in Figure 5.1. The Figure illustrates the development of net emissions which mean here the total GHG emissions including changes in the forest carbon stock, but omitting other sinks and sources from LULUCF sector. All but two scenarios have a 2050 net emission target which is achieved through a linear target pathway. After 2050, the net emissions have to stay at the 2050 level or below. In *Baseline scenario*, no emission target; and in *Low carbon roadmap*, no constraint for the forest carbon sink; is set. Thus, they have no exact emission targets, and the net emission levels can vary also after 2050. The emission target in the *Low carbon roadmap with sink* scenario was set so that the net emissions are equal to *Low carbon roadmap* scenario. Thus, they share the same emission reduction pathway.

The results concentrate on the scenarios *Low carbon roadmap* and *Low carbon roadmap with sink* which have the same net emission levels, but only in the latter, the forest carbon sink can be utilized in achieving the emission target. These scenarios are used for studying the changes in the energy and forest sectors caused by the inclusion of the carbon stocks in the emission policies. The cost-effectiveness is analysed by examining the relation of the cumulated

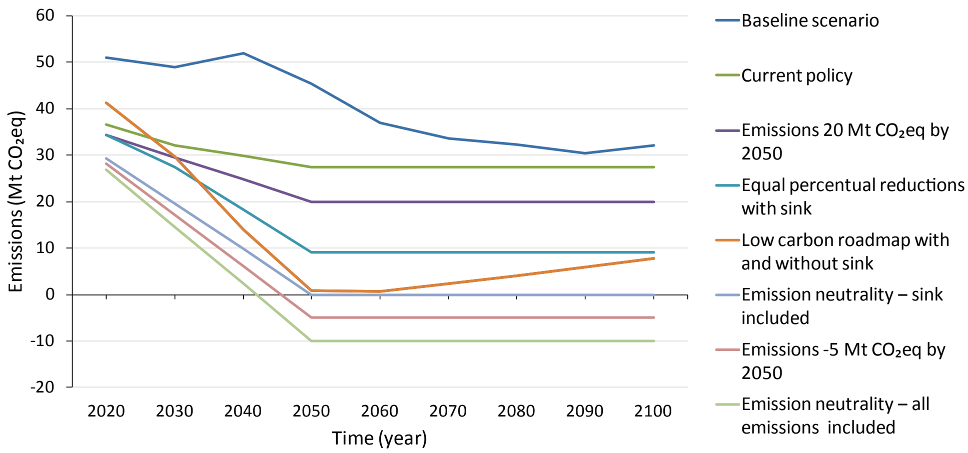


Figure 5.1: The emission reduction pathways in different scenarios. The figures consist of the total GHG emissions including the forest carbon sink, but exluding other emissions from LULUCF sector.

emissions and the costs caused by emission reduction measures in 2010−2100. All scenarios are included in the analysis.

5.1 Forest carbon sink and GHG emissions

Development of the forest carbon sink and stock and the total volume of harvested wood in the scenarios *Low carbon roadmap* and *Low carbon roadmap with sink* are presented in Figure 5.2. In both scenarios, forests act as a carbon sink in 2010−2100 (see Figure 5.2(a)), but the sink is larger in the *Low carbon roadmap with sink* scenario during the whole period. The largest difference between the scenarios occurs in 2050 when the quantity of the carbon sink peaks in the *Low carbon roadmap with sink* scenario, after which it decreases steadily. In the *Low carbon roadmap* scenario, the carbon sink stays relatively steady in 2020−2060 and slowly declines 2060 onwards. In 2090−2100 only a small difference exists between the scenarios. Due to the higher carbon sink, especially between 2040 and 2060, about 16 % larger carbon stock is achieved by 2100 in the *Low carbon roadmap with sink* scenario (see Figure 5.2(b)). The larger carbon sink and stock is a consequence of lower harvest levels (see Figure 5.2(c)). However, though the harvest level is systematicly higher in the *Low carbon roadmap* scenario during the last half of the century, the difference between the carbon sinks diminishes. The probable reason is that the lower harvest levels lead to an older age structure of forests in the *Low carbon roadmap with sink* scenario. Thus, forest growth slows down and the carbon sink decreases at the end of the simulation period.

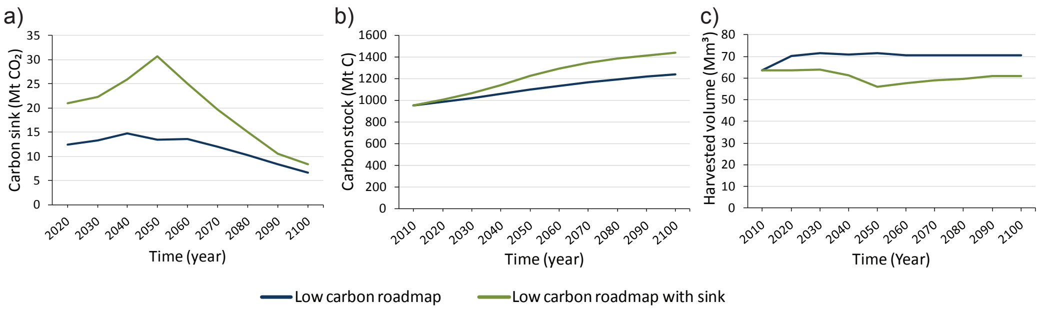
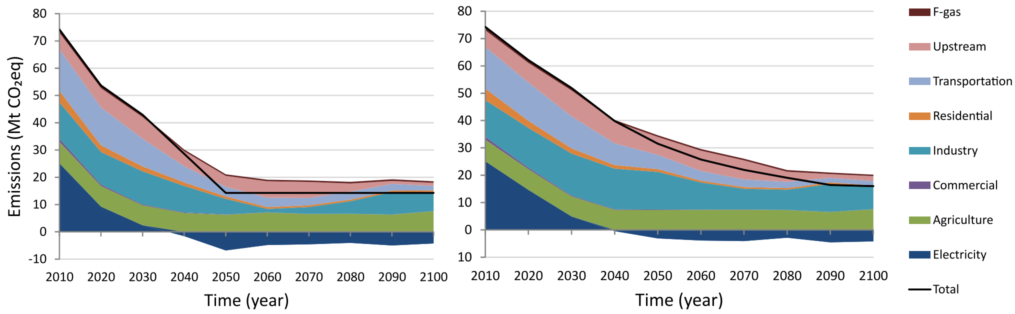


Figure 5.2: Development of the forest carbon sink (a) and stock (b) and the total volume of harvested wood (c) in the scenarios *Low carbon roadmap* and *Low carbon roadmap with sink*.

Greenhouse gas emissions by sector, excluding the LULUCF sector, in the *Low carbon roadmap* and *Low carbon roadmap with sink* scenarios are presented in Figure 5.3. When forest carbon sink cannot be utilised as a means for achieving the emission target, the total GHG emissions from other sectors decrease steeply between 2010 and 2050 (see Figure 5.3(a)). In the *Low carbon roadmap with sink* scenario, GHG emissions from other than LULUCF secrtor are decreasing more steadily and stay at a higher level during the whole period 2010−2100. This is possible because part of the emissions is offset by the forest carbon sink. Therefore, achieving the same net emissions does not require as significant and fast emission reductions in other than LULUCF sector as in the *Low carbon roadmap* scenario.

The most considerable differences between the scenarios occur in the emissions of the industry and electricity sectors. Emissions from electricity sector decrease faster in the *Low carbon roadmap* scenario. In addition, greater



(a) Low carbon roadmap (b) Low carbon roadmap with sink

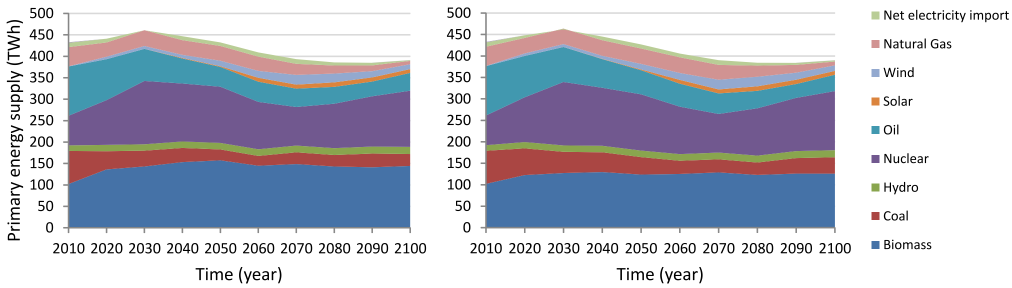
Figure 5.3: The development of greenhouse gas emissions by sector, excluding the LULUCF sector. Negative emissions can be achieved due to the expected development of carbon capture and storage technology in the model.

negative emissions are achieved from 2040 onwards due to combined use of bioenergy, and carbon capture and storage (CCS) technology. Emissions from the industry sector are also lower in the *Low carbon roadmap* scenario – especially between 2040 and 2070 – because less emission intensive energy sources and CCS technology are used more.

5.2 Primary energy supply

Only minor differences occur in total primary energy supply between the scenarios *Low carbon roadmap* and *Low carbon roadmap with sink*, as shown in Figure 5.4. However, some variations can be identified in the source-specific supply. The main difference is that biomass supply is higher and coal supply lower in the *Low carbon roadmap* scenario. The primary energy supply from other sources is relatively similar in both scenarios.

The coal supply decreases and the biomass supply increases from the 2010 level in both scenarios. The combined coal and biomass supply is relatively equal in the scenarios, suggesting that part of the coal is replaced by biomass in order to reach the emission target. However, not all coal supply is replaced in either scenario because it is relatively cheap form of energy, and emissions from coal combustion can be limited by using CCS technology which commercialisation is assumed in the coming decades in the model. In addition, total emission neutrality is not required in these scenarios. In the *Low carbon roadmap with sink* scenario, coal consumption is higher because the forest carbon sink can be used for offsetting emissions from coal use. As a result, less bioenergy is used for replacing coal.



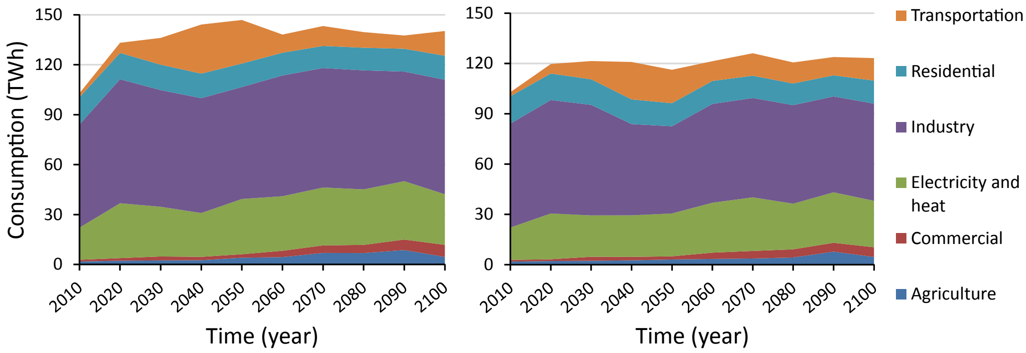
(a) Low carbon roadmap (b) Low carbon roadmap with sink

Figure 5.4: Primary energy supply by source.

5.3 Bioenergy consumption

A more detailed presentation of the bioenergy use is provided in Figure 5.5 which shows the consumption by sector. Bioenergy consumption is 11−26 % higher in the *Low carbon roadmap* scenario compared with the *Low carbon roadmap with sink*. The difference is highest in 2050 when the biomass use reaches its highest level in the *Low carbon roadmap* scenario. In the *Low carbon roadmap with sink* scenario, consumption stays relatively constant between 2020 and 2100.

The largest differences in bioenergy consumption appear in industry, and electricity and heat sectors. In 2050, bioenergy consumption in both sectors is almost 30 % higher in the *Low carbon roadmap* scenario. In the transportation sector, bioenergy consumption is higher between 2020 and 2050, implying a more extensive use of biofuels to reach the emission target by 2050. Only minor differences occur in other sectors.



(a) Low carbon roadmap (b) Low carbon roadmap with sink

Figure 5.5: Bioenergy consumption by sector.

5.4 Emission reduction costs

The relations between emission reduction costs and cumulative emissions in all scenarios, except in the *Baseline scenario*, are presented in Figure 5.6. Cumulative emissions are calculated as a sum of the annual net emissions 2010−2100. Changes in the forest carbon stock are included in the emission figures, but other sinks and emissions from LULUCF sector are excluded. Emission reduction costs represent the net present value of the total costs caused by emission reduction measures in 2010 – 2100. They are calculated as a difference in the total costs compared to the *Baseline scenario* in which no emission target is set, and thus, the total costs are minimised without a need to restrict GHG emissions. Other scenarios differ from the *Baseline scenario* only in terms of emission targets which place additional constraints on the system, leading to the higher total costs.

In the scenarios, where the changes in the forest carbon stock are included in the emission targets, the emission reduction costs increase as the cumulative

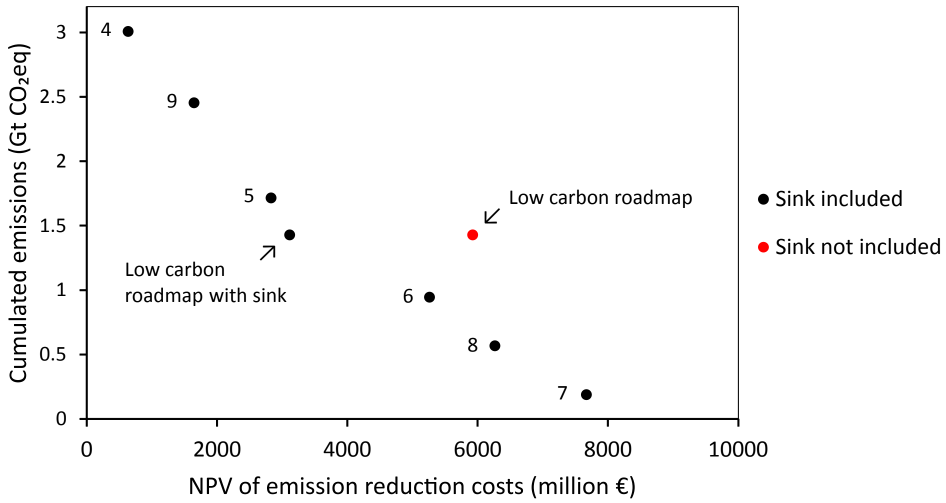


Figure 5.6: Cumulated emissions and the net present value (NVP) of emission reduction costs when the forest carbon sink is or is not included to in emission targets. The scenarios *Low carbon roadmap* and *Low carbon roadmap with sink* are named in the Figure, and the numbers refer to the scenarios $4 - 9$ as described in the section 4.2.

emissions decrease. In the *Low carbon roadmap* and *Low carbon roadmap with sink* scenarios, exactly the same net emission levels are achieved. However, as shown in the Figure 5.6, the emission reduction costs between these scenarios differ substantially: the costs are almost halved when the forest carbon sink can be utilised in achieving the target. The emission reduction costs in *Low carbon roadmap* scenario are between the costs in the scenarios *Emission neutrality - sink included* and *Emissions -5 Mt CO_2 eq by 2050* (scenarios 6 and 8 in the Figure 5.6). Their cumulative emissions are about two thirds and one third of the cumulative emissions in the *Low carbon roadmap* scenario.

According to the results, cost-effectiveness of emission reductions is improved when the changes in the forest carbon stock are included in the emission targets. In the *Low carbon roadmap with sink* scenario, forest carbon sink provides an alternate means for reducing emissions, replacing more expensive options. For example, achieving the emission target does not require as extensive use of CCS, and less emission intensive, but more expensive energy sources. As a result, lower emission reduction costs are achieved compared with the *Low carbon roadmap* scenario.

5.5 Sensitivity of costs to assumptions

The sensitivity of the emission reduction costs to the model assumptions were examined by modifying the stem volume yield curve, the total forest area and the initial thinning deficit in the *Low carbon roadmap with sink* scenario. Altogether, seven different cases were examined:

- Higher yield curve: +20 %
- Lower yield curve: −20 %
- No saturation in the yield curve before the age of 160
- Increasing forest area: +2 % in each period (compared to the initial area)
- Decreasing forest area: −2 % in each period (compared to the initial area)
- Higher initial thinning deficit: +15 %
- Lower initial thinning deficit: −15 %

The yield curves for the first three cases are presented in Figure 5.7.

The emission reduction costs are very sensitive to the changes in the assumptions related to the yield curve and the total forest area, as shown in Figure 5.8. If the yield curve or the total forest area is increased, the costs are reduced and vice versa. The rationale for this is that other things being equal, increase in stem volume or area increases the total forest volume and carbon stock, which reduces the effort to achieve the emission target. The model is

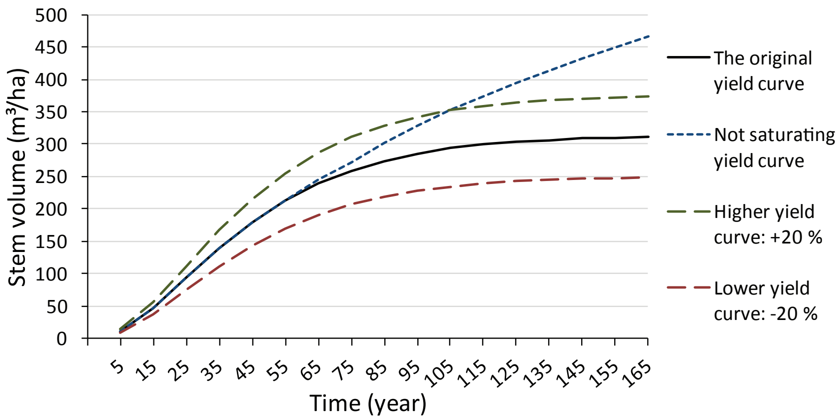


Figure 5.7: The original yield curve and the modified yield curves which are used in the sensitivity analysis.

most sensitive to the changes in the yield curve: the 20 % increase decreases the costs to a less than half, and the 20 % reduction more than doubles the costs.

As expected, lower emission reduction costs are attained as the yield curve does not saturate before the age of 160. Furthermore, emissions are reduced even more than required in this case (see Figure 5.8). This is because a larger carbon sink is attained as the growth of forests continue longer. As a result, the emission target does not restrict the system, and the target is achieved without any additional effort in some of the calculation periods. However, as the emission reduction costs are not zero, this is not the case in all the periods.

The model did not respond to the changes in the initial thinning deficit as assumed. The emission reduction costs were expected to increase as the initial thinning deficit is increased because more constraints are imposed on the system. The opposite was assumed as the initial thinning deficit is reduced. However, increase in the initial thinning deficit decreases the emission reduction costs and vice versa (see Figure 5.8). The reason is that the increased initial thinning deficit increases the forest growth, and thus, the carbon sink, in the following periods. The initial thinning deficit also affects the future thinnings through the determination of the thinning intensity classes, which might lead to more intensive thinnings and accelerated growth also in the future periods.

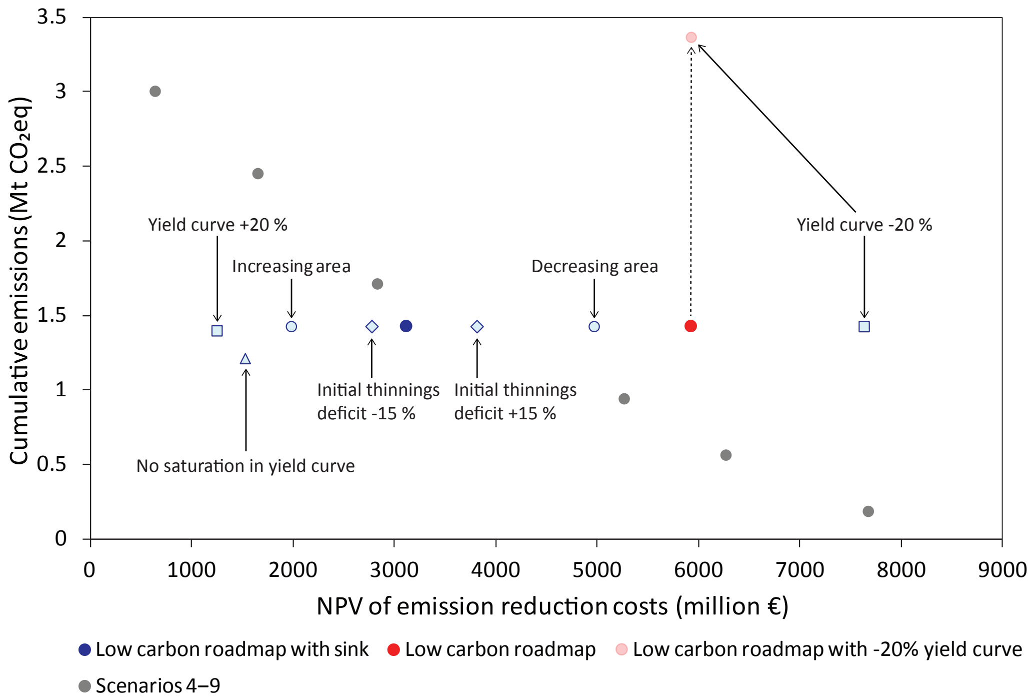


Figure 5.8: Sensitivity analysis of the net present value of emission reduction costs and the cumulative emissions. The light blue marks denote the sensitivity cases of the *Low carbon roadmap with sink* scenario as the yield curve, the total area, and the initial thinning deficit are modified. The pink mark denotes the change in the cumulative emissions in the *Low carbon roadmap* scenario as the original yield curve is reduced by 20 %.

As the yield curve is decreased by 20 %, the emission reduction costs in the *Low carbon roadmap with sink* scenario exceed the costs of *Low carbon roadmap* scenario, which indicates that cost-effectiveness is not always increased though the forest carbon sink could be utilised for achieving the emission target. However, the comparison is not straightforward. The 20 % reduction in the yield curve would also increase the cumulative emissions in the *Low carbon roadmap* scenario – in which the changes in the forest carbon stock are not included in the emission target – because the emissions from other than LULUCF sector would stay constant, but the carbon sink would be smaller. The change in the cumulative emissions would be remarkable as demonstrated in Figure 5.8. At the same time, emission reduction costs would stay constant because the same reduction measures would be carried out. The increase in the cumulative emissions in the *Low carbon roadmap* scenario should be considered when comparing the cost-effectiveness of the emission reductions between the scenarios. Thus, this result does not necessarily reverse the finding that emissions can be reduced more cost-effectively if the changes in the forest carbon stock are included in the emission target.

The results of the sensitivity analysis suggest that the cost-effectiveness of the emission reductions is highly influenced by the model assumptions. The emission target in the *Low carbon roadmap with sink* scenario is based on the assumed development of the forest carbon sink when it is not part of the emission target. However, if the assumptions, and thus, the development carbon sink deviates from the supposed, emission reduction costs may change significantly. In all sensitivity cases, reductions in the parameter values have a more significant influence to the emission reduction costs than the corresponding increases because of a highly convex cost curve. In addition, reductions in the costs are not as much of concern because it means that less effort is needed for achieving the emission target. Instead, an unexpected increase in the costs is a more severe risk. However, only one case resulted in higher emission reduction costs compared with the *Low carbon roadmap* scenario.

If the forest-based carbon sinks and sources would be included to the emission policies, there are various ways to determine the emission targets – not only the one used here – and different risks and benefits are related to them. If the net emissions are kept constant, lower costs are achieved, but not as ambitious emission reductions are attained than would be cost-effectively possible if the same investments were made than without including the changes in the forest carbon stock. Furthermore, there is a risk that the overall emission reductions are dimished if the utilisation of the forest carbon sink in emission reductions delays the implementation of other reduction efforts, and the sink does not develop as expected. If improved cost-effectiveness was taken into account, and tighter targets would be set, a higher benefit in terms of climate change mitigation would be achieved. However, the cost risk would increase because deviations from the assumed development of the carbon stock could lead to high additional costs. Thus, a careful consideration is needed to determine the targets and managing the risks in predicting of the forest growth and development of the carbon stock. New mechanisms would probably be needed for reducing the risks because it is impossible to eliminate all the uncertainties that are involved in these predictions.

Chapter 6

Discussion and conclusions

This thesis examined the cost-effectiveness of emission reductions and the effects on the forest and energy sectors if forest carbon stock is included in the climate policies and purposefully used as a means for reducing greenhouse gas emissions in Finland. The study was carried out by creating and analysing different emission reduction scenarios by using the TIMES energy system model. In order to conduct integrated energy–climate–forest analysis, a forest module was build, and integrated into TIMES.

The results of this thesis indicate that the cost-effectiveness of emission reductions could be improved if forest carbon stocs were included in the climate policies. This means that the current emission targets could be achieved with less financial effort, or more significant emission reductions could be achieved at the same costs than is needed to fulfil the current targets. When forest carbon stocks are included in the emission policies, the value of forests is not restricted to the wood that they provide for industry and energy production but a value is placed also for the standing forests and the carbon stored in them. This had a direct effect on the energy and forest sectors in the model. Less intensive harvests were performed, the larger forest carbon stock was achieved, and the forets carbon sink was used for substituting some of the more expensive means to reduce emissions, like rapid reductions in fossil fuel consumption and intensive utilisation of CCS technology. As a result, GHG emissions from other than LULUCF sector stayed at a higher level for many decades, especially in the industry and electricity sectors which are highly energy intensive.

The use of bioenergy was slightly lower when the changes in the forest carbon stock was taken into account in the emission targets. This suggests that it is better – at least to some extent – to leave forest to grow for a longer period instead of cutting it for bioenergy production if the objective is a cost-effective climate change mitigation. However, the relative reduction in bioenergy use was not as significant as the achieved savings in the emission reduction costs. Thus, utilising forest carbon sink in reducing GHG emissions does not necessarily obviate the value of bioenergy in the climate policies. They might both benefit the climate change mitigation, but the challenge is finding an optimal balance.

The inclusion of the carbon stock decreased also the use of carbon capture and storage technology. At present, CCS technology is too expensive and immature for large-scale use, and many uncertainties are related to its commercialisation in the future (see e.g. Pires et al., 2011). However, in the model, CCS technology is assumed to evolve and provide a means for reducing emissions in the future decades. If this assumption does not hold, the role of forest carbon sink could be even more important in achieving the emission reduction targets. On the other hand, the role of forest carbon sink may be less significant if efficient and inexpensive CCS technologies will be commercialised.

Other uncertainties are also contained in forecasting the distant future. For example, the future energy demand, prices and availability of different energy sources, and the development of renewable energy and storage technologies affect the emission reduction potential and costs. Also, changes in real-world climate policies, for example, in the emission targets or emission trading schemes, could alter the cost-effectiveness of emission reductions. In addition, the changes in the timber demand can affect both the bioenergy use and the development of the forest carbon stock. The volume of Finnish forest industry has been declining in the last decade as a result of decreasing demand for paper products. Bioenergy is often produced from harvest residues which are obtained as the by-products of fellings. Thus, a decrease in the timber demand can reduce the bioenergy supply if no shift from harvest residues to a whole tree utilisation occurs. On the other hand, decreased harvest levels increase the forest carbon stock. Though high uncertainties are embedded in long-term forecasting, and many assumptions about the future have to be made; long time spans are essential for the examination of the topics related to the forest management and climate change.

Models are simplifications of the reality and cannot capture all aspects of real-world systems. The forest model build in this thesis is a simplified representation of the complex dynamics involved in the growth and carbon sequestration of forests. Uncertainties in the accuracy and reliability of the model should be considered in evaluating the results before doing any far-reaching conclusions. When forest carbon stock was included in the emission targets, the emission reduction costs were highly sensitive to the assumptions of the stem volume yield curve and the total forest area. However, it does not seem likely that significant reductions in the total forest area in Finland will occur during this century because it has remained relatively stable since 1940s and is regulated by forest legislation. Thus, a greater uncertainty is associated to the yield curve because there is no NFI data of the stem volume in unmanaged forests and no straightforward means for estimating it. At the same time, the changes in the yield curve had the greatest impact on the emission reduction costs. When the yield curve was decreased by 20 %, the costs even exceeded the costs achieved without including the forest carbon stock in the emission targets. However, also the cumulative emissions in the case, where the carbon sink is not included to the emission targets, would be significantly higher if the yield curve is reduced. Thus, the result do not necessarily imply that emission reductions are in some cases more cost-efficient without utilising forest carbon sink. In addition, the model evaluation imply that the carbon sink is rather underestimated than over-estimated in the model (see section 3.2.4). In any case, the high sensitivity indicates that large cost risks are involved if forest carbon stocks are included in the emission targets.

It should be noted that the results of this thesis represent the situation where all the resources are optimally utilised considering the whole energy system. This is not the case in reality where markets may be imperfect, and different actors do not always act rationally or under perfect information. For example, the decision makers do not really have perfect foresight of the future, and forest owners do not necessarily manage their forests optimally. Thus, the results represent the best-case scenarios at the given constraints, which cannot be achieved in reality, but form a basis for the comparison of the consequences of different policies.

If forest carbon stocks were to be included to the emission targets, a careful consideration would be needed in defining the targets. In this thesis, the comparison was made with scenarios which had an equal limit for the net emissions. The limit was based on the estimate of the future development of the forest carbon stock in the case where it is not included to the emission target. However, in reality the estimation of the future development of the forest carbon sink is extremely difficult because many uncertainties and natural variations are involved. These uncertainties should be taken into account in setting the emission targets and in managing the risks related to them. In addition, different countries have unequal forest resources. If carbon stocks are included to the emission policies, the accounting rules are likely based international agreements, and are also a question of equality.

Although significant uncertainties are involved in the estimation of the the changes in the forest carbon stocks, the potential of forests in climate change mitigation is evident. Forests constitute a substantial carbon sink at some parts of the world whereas they are significant sources of atmospheric carbon dioxide in others (Pan et al., 2011). Better understanding and utilisation of the carbon sink capacity of forests could provide an important tool for climate policies. Despite of the uncertainties related to the accuracy of the model developed in this thesis, it gives a starting point for a combined energy–climate–forestry analysis. The purpose of the model was not to provide detailed and exact numbers of emission reduction costs or other quantities but to catch the most important interactions between the sectors and to provide a simple tool for assessing the role of forests in climate change mitigation. It may provide a valuable tool for analysing optimal forest use if further developments are performed to improve the reliability of the model. If forest carbon sinks are to be used as a means for mitigating climates change, reliable estimates of the forest growth and carbon sinks, as well as the interactions between different sectors, are needed in planning and evaluating forests' mitigation potential.

Bibliography

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., ..., and Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259(4):660–684.

Amaro, A., Reed, D., and Soares, P. (2003). *Modelling forest systems*. CABI Publishing: Wallingford, United Kingdom.

Asikainen, A., Ilvesniemi, H., Sievänen, R., Vapaavuori, E., and Muhonen, T. (2012). Bioenergia, ilmastonmuutos ja suomen metsät. *Working Papers of the Finnish Forest Research Institute*, 240.

Battaglia, M. and Sands, P. (1998). Process-based forest productivity models and their application in forest management. *Forest Ecology and Management*, 102(1):13–32.

Bossel, H. (1991). Modelling forest dynamics: moving from description to explanation. *Forest Ecology and Management*, 42(1):129–142.

Egnell, G. and Valinger, E. (2003). Survival, growth, and growth allocation of planted scots pine trees after different levels of biomass removal in clear-felling. *Forest Ecology and Management*, 177(1):65–74.

European Commission (2011). Communication from the Commission to the European Parliament, the Council, the European Economic and Social

Committee and the Committee of the Regions - A Roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 final.

European Commission (2012). Commission staff working document - Impact Assessment on the role of land use, land use change and forestry (LULUCF) in the EU's climate change commitments. SWD(2012) 41 final.

European Commission (2014). Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - A Policy framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final/2.

European Council (2009). Brussels European Council 29/30 October 2009 - presidency conclusions. 15265/1/09 REV 1.

European Parliament and Council of the European Union (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 - on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*, 58(L 140):16–62.

Finnish Forest Centre (2013). Suomen metsäkeskuksen metsävaratiedon laatuseloste. Available at http://www.metsakeskus.fi/sites/default/files/metsavaratiedon_laatuseloste.pdf.

Finnish Forest Research Institute (2013). *Finnish statistical yearbook of forestry 2013*. Vammalan Kirjapaino Oy: Sastamala, Finland. In Finnish.

Gunn, J. S., Ganz, D. J., and Keeton, W. S. (2012). Biogenic vs. geologic carbon emissions and forest biomass energy production. *GCB Bioenergy*, 4(3):239–242.

Helmisaari, H.-S., Hanssen, K. H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P., and Tveite, B. (2011). Logging residue removal after thinning in Nordic boreal forests: long-term impact on tree growth. *Forest Ecology and Management*, 261(11):1919–1927.

Hynynen, J., Ahtikoski, A., Siitonen, J., Sievänen, R., and Liski, J. (2005). Applying the motti simulator to analyse the effects of alternative management schedules on timber and non-timber production. *Forest Ecology and Management*, 207(1):5–18.

Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen, H., and Haapala, P. (2002). Models for predicting stand development in MELA System. The Finnish Forest Research Institute. Research papers 835.

IPCC (2003). *Good practice guidance for land use, land-use change and forestry* [Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., and Wagner, F. (eds)]. IGES: Hayama, Japan.

IPCC (2006). *2006 IPCC guidelines for national greenhouse gas inventories* [Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds)]. IGES: Hayama, Japan.

IPCC (2014). *Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel T., and Minx, J.C. (eds.)]. Cambridge University Press: Cambridge, Unted Kingdom and New York, NY, USA.

Jalkanen, A., Mäkipää, R., Ståhl, G., Lehtonen, A., and Petersson, H. (2005). Estimation of the biomass stock of trees in sweden: comparison of biomass equations and age-dependent biomass expansion factors. *Annals of Forest Science*, 62(8):845–851.

Kallio, A., Salminen, O., and Sievänen, R. (2013). Sequester or substitute - consequenses of incresed production of wood based energy on the carbon balance in finland. *Journal of Forest Economics*, 19:402–415.

Kangas, A. S. (1997). On the prediction bias and variance in long-term growth projections. *Forest Ecology and Management*, 96(3):207–216.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.-J., Erhard, M., Eggers, T., Sonntag, M., and Mohren, G. (2002). An approach towards an estimate of the impact of forest management and climate change on the european forest sector carbon budget: Germany as a case study. *Forest ecology and management*, 162(1):87–103.

Kellomäki, S., Karjalainen, T., and Väisänen, H. (1997). More timber from boreal forests under changing climate? *Forest ecology and Management*, 94(1):195–208.

Kellomäki, S. and Väisänen, H. (1997). Modelling the dynamics of the forest ecosystem for climate change studies in the boreal conditions. *Ecological modelling*, 97(1):121–140.

Kirschbaum, M. U. (2000). Forest growth and species distribution in a changing climate. *Tree physiology*, 20(5-6):309–322.

Kuuluvainen, T., Tahvonen, O., and Aakala, T. (2012). Even-aged and uneven-aged forest management in boreal fennoscandia: a review. *Ambio*, 41(7):720–737.

Landsberg, J. (2003). Physiology in forest models: history and the future. *FBMIS*, 1:49–63.

Landsberg, J. and Waring, R. (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management*, 95(3):209–228.

Lappi, J. (1992). JLP: A linear programming package for management planning. The Finnish Forest Research Institute. Research papers 414.

Lehtonen, A., Mäkipää, R., Heikkinen, J., Sievänen, R., and Liski, J. (2004). Biomass expansion factors (BEFs) for scots pine, norway spruce and birch according to stand age for boreal forests. *Forest Ecology and Management*, 188(1):211–224.

Lintunen, J., Laturi, J., and Uusivuori, J. (2015). Finnish Forest and Energy Policy model (FinFEP): a model description. Natural Resources Institute Finland (LUKE). Natural resources and bioeconomy studies 59/2015.

Lippke, B., Oneil, E., Harrison, R., Skog, K., Gustavsson, L., and Sathre, R. (2011). Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Management*, 2(3):303–333.

Loulou, R. and Labriet, M. (2008). ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. *Computational Management Science*, 5(1-2):7–40.

Loulou, R., Remme, U., Kanudia, A., Lehtilä, A., and Goldstein, G. (2005). Documentation for the TIMES Model - Part I. *Energy Technology Systems Analysis Programme* (IEA-ETSAP). Available at http://www. iea-etsap. org/documentation. asp.

Löwe, H., Seufert, G., and Raes, F. (2000). Comparison of methods used within member states for estimating CO_2 emissions and sinks according to UNFCCC and EU monitoring mechanism: forest and other wooded land. *Biotechnologie, agronomie, société et environnement*, 4(4):315–319.

Mäkelä, A. (2007). Mallien käytöstä metsän kasvun ennustami-seen ja käsittelyjen suunnitteluun. *Metsätieteen aikakauskirja 2007: 1*.

Mäkelä, A., Landsberg, J., Ek, A. R., Burk, T. E., Ter-Mikaelian, M., Ågren, G. I., Oliver, C. D., and Puttonen, P. (2000). Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiology*, 20(5-6):289–298.

Matala, J., Hynynen, J., Miina, J., Ojansuu, R., Peltola, H., Sievänen, R., Väisänen, H., and Kellomäki, S. (2003). Comparison of a physiological model and a statistical model for prediction of growth and yield in boreal forests. *Ecological Modelling*, 161(1):95–116.

Matala, J., Ojansuu, R., Peltola, H., Sievänen, R., and Kellomäki, S. (2005). Introducing effects of temperature and CO_2 elevation on tree growth into a statistical growth and yield model. *Ecological Modelling*, 181(2):173–190.

McKechnie, J., Colombo, S., Chen, J., Mabee, W., and MacLean, H. L. (2010). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental science & technology*, 45(2):789–795.

Monni, S., Peltoniemi, M., Palosuo, T., Lehtonen, A., Mäkipää, R., and Savolainen, I. (2007). Uncertainty of forest carbon stock changes–implications to the total uncertainty of ghg inventory of finland. *Climatic Change*, 81(3-4):391–413.

NASA Goddard Institute for Space Studies (n.d.). GISS Surface Temperature Analysis. Retrieved January 24, 2016 from http://data.giss.nasa.gov/gistemp/.

Natural Resources Institute Finland (2015a). MELA Tulospalvelu [TuPa hakupalvelu - VMI11 (mittausvuodet 2009-2013)]. Retrieved February 11, 2016 from http://mela2.metla.fi/mela/tupa/index.php.

Natural Resources Institute Finland (2015b). Statisticts database [Total roundwood removals]. Retrieved February 12, 2016 from http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__04%20Metsa__02%20Rakenne%20ja%20tuotanto__10%20Hakkuukertyma%20ja%20puuston%20poistuma/01_Hakkuukertyma.px/?rxid=8f94b4b4-2407-4210-8de5-68e808f11d94.

Natural Resources Institute Finland (2015c). Valtakunnan metsien inventointi: Puuvarat mahdollistavat hakkuiden lisäyksen. Available at http://www.luke.fi/tiedote/valtakunnan-metsien-inventointi-puuvarat-mahdollistavat-hakkuiden-lisayksen/.

Nuutinen, T., Hirvelä, H., and Salminen, O. (2005). Alueelliset hakkuumahdollisuudet Suomessa. The Finnish Forest Research Institute. Working papers 13.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., et al. (2011). A large and persistent carbon sink in the world's forests. *Science*, 333(6045):988–993.

Parliamentary Committee on Energy and Climate Issues (2014). Energy and climate roadmap 2050 - Report of the Parliamentary Committee on Energy and Climate Issues on 16 October 2014. Publications of the Ministry of Employment and the Economy - Energy and the climate 50/2014.

Peng, C. (2000). Understanding the role of forest simulation models in sustainable forest management. *Environmental Impact Assessment Review*, 20(4):481–501.

Pires, J., Martins, F., Alvim-Ferraz, M., and Simões, M. (2011). Recent developments on carbon capture and storage: an overview. *Chemical Engineering Research and Design*, 89(9):1446–1460.

Pretzsch, H. (2009). *Forest dynamics, growth, and yield.* Springer: Berlin, Germany.

Repo, A., Tuomi, M., and Liski, J. (2011). Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *GCB Bioenergy*, 3(2):107–115.

Salminen, H., Lehtonen, M., and Hynynen, J. (2005). Reusing legacy FORTRAN in the MOTTI growth and yield simulator. *Computers and electronics in agriculture*, 49(1):103–113.

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., Likens, G. E., Lubowski, R. N., Obersteiner, M., Oppenheimer, M., et al. (2009). Fixing a critical climate accounting error. *Science*, 326(5952):527.

Siitonen, M., Härkönen, K., Kilpeläinen, H., and Salminen, O. (1999). *MELA Handbook - 1999 Edition.* The Finnish Forest Research Institute.

Statistics Finland (2013). Suomen kasvihuonekasupäästöt 2013. Official statistic of Finland. Ympäristö ja luonnonvarat 2015. Available at http://tilastokeskus.fi/til/khki/2013/khki_2013_2015-04-15_fi.pdf.

Statistics Finland (2015). Statisticts Finland's PX-Web databases [Greenhouse gas emissions in Finland]. Retrieved February 12, 2016 from http://pxnet2.stat.fi/PXWeb/pxweb/en/StatFin/StatFin__ymp__khki/010_khki_tau_101.px/?rxid=5b3acd25-a776-47b7-91eb-4f2dd268649e.

Tomppo, E. (2000). National forest inventory of finland and its role estimating the carbon balance of forests. *Biotechnologie, Agronomie, Société et Environnement*, 4(4):281–284.

UNFCCC (1998). Kyoto Protocol to the United Nations framework convention on climate change. Available at http://unfccc.int/resource/docs/convkp/kpeng.pdf.

UNFCCC (2009). Decision 2/CP.5 – Copenhagen Accord. In *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009.* FCCC/CP/2009/11/Add.1.

UNFCCC (2015). Adoption of the Paris Agreement – Proposal by the President – Draft decision -/CP.21.

U.S. Energy Information Administration (2013). International energy outlook 2013 – with projections to 2040. U.S. Energy Information Administration, U.S. Department of Energy: Washington, DC, USA.

Vanclay, J. K. (1994). Modelling forest growth and yield: applications to mixed tropical forests. *School of Environmental Science and Management Papers*, page 537.

Weiskittel, A. R., Hann, D. W., Kershaw Jr, J. A., and Vanclay, J. K. (2011). *Forest growth and yield modeling.* John Wiley & Sons: Chichester, United Kingdom.

Zanchi, G., Pena, N., and Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, 4(6):761–772.

Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K., and Väisänen, P. (eds.) (2014). Metsänhoidon suositukset. Metsätalouden kehittämiskeskus Tapion julkaisuja.