# Forest management strategies for $CO_2$ mitigation

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## Abstract

The concentration of greenhouse gases in the atmosphere has increased since pre-industrial time and a further increase is expected to lead to profound global climate change. Forests can play an important role in counteracting green house gas emissions as they are ubiquitous and are one of the currently available mechanisms for mitigating the increase of atmospheric $CO_2$.

This thesis focuses on how carbon sequestration considerations can be incorporated in forest management analysis and planning.

In Paper I the carbon status of forest biomass and soil in forest stands in southern Sweden were scrutinized under various thinning regimes and fertilization programmes. Biofuel production was also considered. Thinning and biofuel harvest decreased on-site carbon sequestration. Off-site forest carbon storage in products and fossil fuel substitution were, however, not considered.

In Paper II an optimizing model that could handle a large forest area and the monetary value for carbon sequestration was presented. The objective was to maximize the net present value of harvested timber, biofuel production and carbon sequestration. The model was applied to the county of Västerbotten (3.2 million hectares) in northern Sweden using Swedish National Forest Inventory data. Applying a monetary value to carbon sequestration increased carbon storage and decreased harvest levels.

In Paper III the model developed in the previous paper was used to model short- and long-term potential carbon sequestration together with timber and biofuel production. In-depth analyses of the same data set as in Paper II, i.e., the county of Västerbotten, were performed. Carbon prices ranged from zero up to the same level as the Swedish carbon dioxide tax (2310 SEK per tonne C). Harvest levels ceased at about 1000 SEK per tonne C. The decrease in harvest was more pronounced in the western low productive areas of the county.

The focus in Paper IV was to investigate the impacts of climate change uncertainty in solutions to forest management problems for typical Swedish stands. Only the effect of raised temperature was considered. The economic value increased almost 5 % when the maximum temperature trend (+6.0°C) was applied, compared to the value under the minimum trend (+2.5°C). However, the economic importance of optimizing management plans according to the correct temperature scenario appeared to be limited.



*Keywords:* Boreal forest, Carbon, Carbon price, Climate change, Fertilization, Thinning, Forest biofuel, Forest management planning, Optimization, Uncertainty



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# Dedication

To Alva and Fanny

# Contents

# List of Publications

This thesis is based on the work presented in the following papers, which are referred to by the corresponding Roman numerals in the text:

I Backéus S., Lämås T. and Wikström P. Carbon sequestration in Swedish forest stands under various management regimes. (manuscript).

II Backéus S., Lämås T. and Wikström P. (2005). A model for regional analysis of carbon sequestration and timber production. *Forest Ecology and Management* 216(1-3), 28-40.

III Backéus, S., Wikström, P. and Lämås, T. (2006). Modeling carbon sequestration and timber production in a regional case study. *Silva Fennica* 40(4), 615-629.

IV Eriksson, O., Backéus S. and Garcia F. The effects on stand management of growth uncertainty caused by climate change. (manuscript).

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# Abbreviations

| | |
|---|---|
| BEF | Biomass Expansion Factor |
| C | Carbon |
| $CO_2$ | Carbon Dioxide |
| COP | Conference of the Parties |
| DOC | Dissolved Organic Carbon |
| GHG | Greenhouse Gases |
| IPCC | Intergovernmental Panel on Climate Change |
| LULUCF | Land Use, Land Use Change and Forestry |
| MABH | Mean Annual Biofuel Harvest |
| MACS | Mean Annual Carbon Sequestration |
| MATH | Mean Annual Timber Harvest |
| NFI | National Forest Inventory |
| NPV | Net Present Value |
| SEV | Soil Expectation Value |
| SI | Site Index. The expected mean height of the largest diameter trees at age 100 years (H100) |
| UNFCCC | United Nations Framework Convention on Climate Change |

# 1 Introduction

## 1.1 Forests in the carbon cycle

The emissions of greenhouse gases (GHG) due to human activities have increased considerably since preindustrial times (IPCC, 2007b). The most important greenhouse gas is carbon dioxide ($CO_2$), which accounts for 77 % of the emissions. GHG emissions are expected to lead to profound global climate changes. To avoid serious damage to both ecosystems and the human population temperatures should not be allowed to increase more than 2 – 2.5°C (Seppälä *et al.,* 2009) compared to preindustrial times. The current $CO_2$-concentration is 380 ppm, compared to 270 ppm in preindustrial times, and an increase in GHG-concentrations to 400-450 ppm corresponds to a 2°C temperature increase (IPCC, 2007d). However, many studies suggest that forest ecosystems will suffer serious damage if the temperature increases more than 2–2.5°C (IPCC, 2007c). This could lead to large $CO_2$ losses if ecosystems collapse (Denman *et al.*, 2007). There is therefore an urgent need to counteract these emissions. The only long-term solution is to reduce the emissions, but meanwhile mitigation of emissions and adaption to a warmer climate are essential. An example of a mitigating factor – and the focus of this thesis – is the fact that carbon fixed by photosynthesis is taken from the atmosphere and sequestered for some time (of varying duration) in forests and forest products. This is the only active and currently practical measure to remove $CO_2$ from the atmosphere. Forests cover 30 % of the world's land area and have enormous potential to sequester carbon and mitigate the increase of atmospheric $CO_2$, provided that they are maintained and managed in an appropriate manner. There are essentially two principally different ways whereby forests can mitigate atmospheric $CO_2$: by substitution of fossil fuel and non-biomass materials, and by sequestering $CO_2$ in the forest ecosystem. On a global scale three main activities govern the effect of forests as sequestering agents: deforestation (the transfer of managed forest land to other non-tree covered managed land use classes), reforestation (planting and thus transforming former forest land back to forest land[1]) and afforestation (planting of non-forest land and thereby changing land use to forest). The net effect of those activities has resulted in reductions in the global forest carbon stock of about 4000 MtC per year between 1990 and 2005. Even though there was a decrease in the amount of global terrestrial ecosystems (vegetation, soil and detritus) they acted as a carbon sink in the years 2000 – 2005, sequestering an estimated 0.9 Gt C per year, while the total atmospheric increase of GHG was estimated to be 4.1 Gt C per year. The emissions from fossil fuel combustion and cement production amounted to circa 7.2 GtC per year (Denman *et al.*, 2007). The sizes of the sources and sinks associated with land use changes are very diverse, and the land use carbon source has the largest uncertainty in the global budget (Denman *et al.*, 2007). Deforestation in tropical areas is the largest source of carbon fluxes caused by land use changes, and it exceeds forest regrowth (afforestration and reforestration), thus the observed net uptake of $CO_2$ must take place somewhere else. It has been suggested that the still remote and untouched tropical forest might have sequestered large amounts of carbon. Highly productive forest under management in high and mid-latitude regions can also sequester considerable amounts of carbon since they are relatively young and fast growing.

## 1.2 Kyoto/Copenhagen

Under the United Nations Framework Convention on Climate Change (UNFCCC) the Kyoto Protocol was adopted in 1997 (UNFCCC, 1997) and entered into force in 2005. The Kyoto Protocol is legally binding (unlike the UNFCCC, which merely encourages industrialized countries to stabilise GHG emissions) and states that the industrialized countries should decrease their GHG emissions in the first commitment period (2008-2012) by 5.2 %, in total, relative to 1990 levels. In total 37 countries and the EU have ratified the protocol. The EU countries must reduce their emissions by 8 % in 2012 compared to 1990 levels. Within the EU-commitment Sweden was allowed to increase national emissions by 4 % but took its own decision to set a national goal to reduce emissions by 4 %. In a subsequent step the countries within the EU have agreed to decrease their emissions by 20 % by 2020 compared to 1990 levels, and by 30 % if other industrialized countries

[1] According to the IPCC, post-harvest regeneration is not included in reforestation

make comparable commitments in a new global agreement. As a means to reduce emissions the EU introduced an emission trade system (EU ETS), under which the price of one tonne of $CO_2$ has varied between circa 8.2 and 16.6 EUR in the last year (Nordpool, 2009). Under the Kyoto Protocol it is possible to include sinks in forests when calculating national carbon budgets. The sinks that should be included are carefully stipulated in article 3.3 (afforestration, reforestation and deforestration) and in article 3.4 (forest management). Article 3.3 is mandatory while article 3.4 is voluntary. The maximum total sink in forests that can be included is 15 % of the total sink, and for countries with large forest sinks like Sweden and Finland, the maximum limit is set to 3 % of total emissions. In the Swedish case this amounts to 2.13 Mton $CO_2$-eq (circa 10 % of a potential sink originating from forest management to fulfil the commitment under the Kyoto Protocol). Sweden's ambition is to not have to use forest management.

One major problem with these goals is that they are not sufficient. Realistically, to limit the maximal temperature to 2°C, the industrialized countries must lower their emissions by 25 to 40 % in 2020 and 80 to 95 % in 2050 compared to 1990 levels (IPCC, 2007a). Another obstacle is that the GHG emissions have increased by 24 % globally since 1990 (IPCC, 2007a). However, the emissions from EU countries (old member states, EU15) have deceased by 2.2 % in that time (EEA, 2008).

What will happen after the timeframe of the Kyoto Protocol is still under negotiation at the time of writing and the outcome is not yet clear. In December 2009 COP[2] 15 will meet in Copenhagen and hopefully the Kyoto Protocol will be followed up with a new agreement. The role of forests as a carbon sink will certainly be included in one way or another, but some central issues need to be considered, including: *i*) if forest-based sequestration is included in an emission trading system we risk losing focus on reducing emissions and $CO_2$ prices in cap-and-trade systems might fall, *ii*) the permanence of the sink (e.g. risks for damage by wind, insect pests etc), *iii*) optimal ways to monitor the sink, and *iv*) "leaks" arising when an action taken to increase the sink in one region of the world leads to carbon losses in another region.

## 1.3 Different pools in a carbon budget

The forest carbon cycle is driven by the trees' uptake of atmospheric $CO_2$ and subsequent production of sugar through photosynthesis. The only other inputs (in the simplest possible model) needed in the photosynthesis process

[2] Conference of the parties, the main decision body under UNFCCC, which meets annually.

are solar energy and water. The trees grow, respire and thus release some $CO_2$ back to the atmosphere. $CO_2$ is also emitted when litter from the trees decomposes on the ground. Some of the partly decomposed material (also called Dissolved Organic Carbon, DOC) is transported with water into the soil profile where it stays as a rather stable carbon pool. Some of the DOC is also transported with runoff water into lakes and streams. At final felling a major part of the biomass is taken out of the forest. The harvested stem wood is converted into forest products from pulpwood and sawn timber. Forest products have two major climate benefits. Firstly, carbon is stored outside the forest. The longer the lifetime of a forest product the longer the carbon is kept out of the atmosphere. Secondly, forest products can replace more energy-demanding materials like cement, steel and plastics made from fossil oil. After the lifetime of the products, wood can be recycled, burned for energy or placed in landfills. Carbon stored in landfills can be a potential important sink (Micales & Skog, 1997; Pingoud *et al.*, 1996) but the uncertainty regarding deacay rates, disposal systems and climate are large, making the size of the carbon sink in landfills hard to estimate (Lim *et al.*, 1999).

Logging residues (tops and branches) can be extracted and used as biofuel, thereby replacing fossil fuel. If the logging residues are left in the forest they decompose eventually and emit $CO_2$. In a long time perspective the same amount of $CO_2$ is released in both cases. However, for technical and other reasons some of the carbon in logging residues ends up in the soil carbon pool, where it can stay for a long time. Needles and stumps are normally left, but stump extraction has been tested in Sweden and is practised in Finland.

An alternative to timber and biofuel production is to leave forests unmanaged as carbon sinks/stores. However, there are two problems with leaving the forest to develop freely. Firstly, forests' growth rates decline with age and they will eventually reach a climax stage in which they will not sequester more carbon (at least in theory). Secondly, there is the risk of severe damage by fire, wind, or pests destroying the forest and releasing large amounts of $CO_2$ into the atmosphere. This has, for example been a major problem in Canada, where insects have turned the forest into a carbon source (Kurz *et al.*, 2008). The first problem might not be serious since carbon-dense forest might have other values and thus may be preserved anyway, leading to a win-win situation. Further, some forest types, (mainly in the tropics but also some, for instance, in the Pacific North West region of the USA (Van Tuyl *et al.,* 2005)) contain so much carbon in tree biomass that a final felling followed by regeneration will not compensate for the large loss of carbon at harvest. In some cases it has also been shown that old forests can sequester carbon (Jonsson & Wardle, 2009; Luyssaert *et al.,* 2008; Smithwick *et al.*, 2002). When harvesting old forests there is always an associated risk of losing large amounts of carbon from the soil. The damage risk factors are more complex, since they affect both managed and unmanaged forests, albeit to varying degrees.

## 1.4 The role of forests in Swedish GHG emissions and uptake

In 2008 the total reported emissions of GHG from Sweden amounted to 65.4 Mton $CO_2$-eq (excluding the LULUCF sector) and most of the emissions originated from combustion of fossil fuel (Swedish Environmental Protection Agency, 2009). In Sweden the below and above ground forest biomass make up a huge carbon pool (1125 million tonnes of carbon in 2008), and flows to and from this pool are important components of the Swedish carbon budget. In 2008 the LULUCF sector was a net sink, with an uptake of 20.2 Mton $CO_2$-eq, to which LUC (Land Use Change) made a negligible contribution. Forest biomass contributed as a net sink of 20.3 Mton $CO_2$-eq. The soil carbon pool is, in contrast, a net source since organic soils (especially those affected by drainage) emit methane, nitrogen dioxide and $CO_2$ (7.6 Mton $CO_2$-eq) while mineral soils comprise a smaller sink (-5.5 Mton $CO_2$-eq). Managed forests are currently a large net sink of GHG, but given today's harvest levels (95 million $m^3$ per year) it is not clear if the managed forest will continue to be a sink in the next three decades. The change is in the range of -4 to 7 million tonnes $CO_2$ per year (Skogsstyrelsen, 2008). In a longer perspective, the managed forest will probably be a carbon sink as a consequence of increased growth following climate changes. The sequestration in protected forest will continue, at rates in the range of 7-15 million tonnes $CO_2$ per year for several decades (Ingemarson & Nordin, 2008).

## 1.5 Forest management and forest carbon sequestration in Scandinavia

Forest management regimes in Scandinavian countries are traditionally based on production in even-aged stands, with planting, pre-commercial thinning, a number of thinnings and final felling. Sometimes fertilization is also applied. Besides supporting the forest industry with raw material, the forest supplies other social and ecological services, like recreation opportunities, high maintained biodiversity, and biofuel production. The importance of forests in the mitigation of GHG highlights the need to also consider carbon sequestration among these services. Modelling studies at stand level have shown that prolonging the rotation period can increase carbon sequestration (Kaipainen *et al.* 2004; Liski *et al.* 2001). Carbon sequestration can also be enhanced by changing the thinning regime, but findings in this respect are somewhat ambiguous. Several simulation studies have suggested that reducing the intensity of the thinning regime leads to higher stocking levels in forests, and may increase carbon sequestration (Briceno-Elizondo *et al.*, 2006; Kellomäki & Leinonen, 2005; Pohjola *et al.*, 2004). However, other studies have suggested that changing the thinning regime has only a minor effect on the carbon stock (Kaipainen *et al.*, 2004). Changing the thinning regime and rotation length in most cases affects both the available amount of timber for harvest and the economic outcome of forestry (Alam *et al.*, 2008; Garcia-Gonzalo *et al.*, 2007; Eriksson, 1994). Fertilization is usually a cost-effective way to increase forest production, and as forest production is increased, carbon sequestration in both above and below ground biomass also increases (Olsson *et al.*, 2005; Johnson & Curtis, 2001). Some studies also suggest that supplying nitrogen will retard soil processes, and thus increase the soil carbon stock (Hyvönen *et al.*, 2007).

## 1.6 Models of analysis

To predict the effects of specific policies and management actions on carbon sequestration, and their relation to forest composition and other goods and services, various approaches and tools are available. We can measure the actual forest state and its biomass, take samples of forest soils and set up eddy flux towers to measure the gas exchange over a forest area. We can also estimate past and present carbon stocks using national forest inventories. In addition, to draw general conclusions regarding likely changes over time chronosequences can be used (Wang *et al.*, 2003; Mund *et al.*, 2002), by examining plots with similar properties in different successional stages. However, the most common and most flexible method is modeling. A vast number of models have been developed for diverse purposes, which therefore have diverging course of actions and limits. The models can be categorized according to the way they describe basic growth dynamics, the unit of analysis, and the analysis method.

Growth models can be divided into two general groups: process-based models and empirical models (Korzukhin *et al.*, 1996). The former describe physical processes within plants and work with short time steps (days or hours). These models are mainly developed to investigate cause-and-effect problems, and thus elucidate relationships, while the other group of models – empirical models – focus on predicting the effects of certain factors. The empirical models are based on statistical relationships between/among datasets without considering the inner structure of a process unit, e.g. a tree. The time steps in empirical forest growth models are normally five to ten years. Traditionally, process-based models have mainly been used in research while empirical models have been used both in research and practical forest management. Both model types are developed to simulate phenomena at a range of spatial scales, from tree level up to landscape level. This process-based vs. empirical division of models is not rigid, since most models include some aspects of both types. Both model types have potential uses for addressing carbon and climate change issues, since both can predict carbon contents quite well. Empirical models use biomass functions or biomass expansion factors (BEF) while process-based models already have biomass included. However, when climate change is incorporated there is a significant difference between these types of models. Most process-based models use climate data as input data while empirical models only have geographical location, and perhaps site factors, such as vegetation and moisture, as climate-related inputs. Therefore, effects of climate change are easily incorporated in process-based models while empirical models have difficulties handling them. Since empirical models are widely used both in research and practical management methods there is need for solutions to this problem.

The analysis may focus on the stand level or the forest level. The distinction is that in the former case only one unit that is homogenous in some respects is analyzed, whereas the latter considers several units. The forest could consist of stands belonging to a small forest owner, or all the forested land in a landscape, or the entire nation or continent. The most appropriate level depends on the questions being addressed. Effects of specific management actions can be studied at stand level for representative stands, but if more comprehensive issues are considered, e.g. ways to combine carbon sequestration with harvest activities that support industrial or other uses, larger region-scale analyses are required. To address policy questions and issues related to national goals the analyses might need to be done for a whole country, or even many countries (e.g. the EU). Reviews of models, with an emphasis on forest level models, have been conducted by Eriksson *et al.* (2009) for Europe and by Johnson *et al.* (2007) for North America. Process-based models, such as FinnFor (Kellomäki & Väisänen, 1997), 4C (Lasch *et al.*, 2005) and BIOMASS (Bergh *et al.*, 1998; McMurtrie *et al.*, 1990), are typically confined to stand level analysis.

EFISCEN and MELA are two systems that employ empirical models for climate change analyses at the forest level – see, for instance, Karjalainen *et al.* (2003) and Karjalainen *et al.* (2002) for details regarding EFISCEN and Matala *et al.*, (2009) for details regarding use of MELA. Heureka is a new analysis and planning tool for multi-purpose forestry (Heureka, 2009; Lämås & Eriksson, 2003) incorporating empirical models amended with climate change response functions and a soil carbon and nitrogen model. The Hugin system (Lundström & Söderberg, 1996) developed in the 1970's, uses empirical models for long-term harvest projections at regional and national levels, and has also recently been used for carbon assessment studies (Skogsstyrelsen, 2008; Ericsson, 2003). Other examples of empirical models used for carbon accounting/assessment include CBM-CFS3 (Kurz *et al.*, 2009) from Canada and CO2-FIX from Europe (Schelhaas *et al.*, 2004; Masera *et al.*, 2003).

The results from stand- and forest level studies can be used as input in the standards for various carbon projects. A carbon project aims at mitigating GHG emission for a specific action. Several carbon project standards exist but in general they include routines for monitoring, evaluating, documenting, verifying and certifying the carbon offsets (Greig & Bull, 2009). Examples of carbon projects are found within the Clean Development Mechanism (CDM) and Joint Implementation (JI) projects under the Kyoto Protcol (UNFCCC, 1997) or for state or national level.

Analyses can be based on optimization or elaboration of scenarios (scenario analysis). Scenario analysis is appropriate when evaluating a few specific scenarios, such as the effects of varying the rotation period (e.g. Kaipainen *et al.*, 2004; Liski *et al.*, 2001) or thinning (e.g. Alam *et al.*, 2008; Briceno-Elizondo *et al.*, 2006) on carbon sequestration. When there are explicit goals for the analysis, e.g. identifying the maximum value of different outcomes and utilities from a forest, optimization gives the opportunity to explore a much larger number of alternatives than scenario analyses.

In Scandinavia several studies have been done at the landscape/regional forest level (e.g. Alam *et al.*, 2008; de Wit *et al.*, 2006; Ericsson, 2003; Ågren & Hyvönen, 2003), but only Hoen and Solberg (1994), Raymer *et al.* (2009), Matala *et al.*, (2009) and Nuutinen *et al.* (2006) have used optimization and considered economic factors in analyses of $CO_2$ mitigation. At the stand level many studies have been done (e.g. Eriksson & Berg, 2007; Briceno-Elizondo, 2006) but only Pohjola & Valsta (2007) have considered economic outcomes and used optimization as a solution method. There is therefore a need to study effects of forest management practice in combination with carbon sequestration and economic aspects. Some Scandinavian studies have included the effects of climate change on growth of trees (e.g. Garcia-Gonzalo *et al.*, 2007; Briceño-Elizondo *et al.*, 2006; Bergh *et al.*, 2003), but no previous studies have attempted to incorporate the uncertainty associated with climate change patterns.

## 1.7 Objective of the thesis

The objective of the work underlying this thesis was to incorporate carbon sequestration considerations in forest management analysis and planning. The results from this work will hopefully provide guidance for decision-makers as well as other researchers. The methods applied for this purpose were based on modelling of forest stands (Papers I and IV) and a region (Papers II-III) in Sweden. Economic considerations for management solutions were essential. Both deterministic and stochastic optimization methods were applied. The specific objectives of Papers I-IV were:

Paper I: To study the effects of various thinning regimes and fertilization programs on the carbon status of forest biomass and soil and biofuel production for forest stands in southern Sweden. The stand management problem was based on a strategy oriented towards optimising timber production and economic returns.

Paper II: To develop a model that could handle a large regional dataset from the Swedish National Forest Inventory and find optimal solutions when a monetary value for carbon sequestration was added to the standard forest incomes from timber and biofuel production.

Paper III: To model the short- and long-term potential carbon offsets and carbon sequestration, together with timber and biofuel production, within a region in northern Sweden. In the analysis the model developed in Paper II was used.

Paper IV: To investigate the impact of climate change uncertainty on solutions to forest management problems for typical Swedish stands. It is intended to serve as a basis for discussions regarding ways to optimize the stand management problem under growth uncertainty caused by climatic change.

# 2 Summary of papers

## 2.1 Carbon sequestration in Swedish forest stands under various management regimes (Paper I)

The aim of this study was to analyse effects of the number of thinnings on the carbon sequestration, harvest levels and economic outcomes for four typical forest stands in southern Sweden. Fertilization and biofuel extraction scenarios were evaluated.

### 2.1.1 Material and Methods

Stand data were simulated for four stands in southern Sweden: two Scots pine (*Pinus sylvestris*) stands and two Norway spruce (*Picea abies*) stands, in each case one of high productivity and one of low productivity (Table 1). The site indices (SI, H100 m) were 18 and 28 meters for the low and high productivity stands, respectively. At the start of the simulation the stands were medium-aged (between 20 and 42 years) and assumed not to have been thinned before.

Table 1. *Characteristics of the Scots pine and Norway spruce stands in southern Sweden (latitude 58° N) simulated in Paper I. High and low refers to site index (SI).*

| | | Initial conditions: | | | |
|---|---|---|---|---|---|
| Stand | SI (H100) | Age (years) | Stems (stems $ha^{-1}$) | Basal area ($m^2$ $ha^{-1}$) | Stem volume ($m^3$ $ha^{-1}$) |
| Norway spruce, high | 28 | 24 | 2101 | 13 | 62 |
| Scots pine, high | 28 | 20 | 2600 | 18 | 80 |
| Norway spruce, low | 18 | 42 | 1500 | 12 | 61 |
| Scots pine, low | 18 | 38 | 1850 | 15 | 63 |

For modelling stand development, carbon sequestration in biomass and soil, management actions and economic outcome the Heureka analysis and planning system (Heureka, 2009) was used. Heureka has been developed at SLU and is designed to be used in multiple-purpose forest analysis. The tool is built around a common core of models projecting individual tree and stand development. In addition, the carbon and nitrogen status of the soil, biofuel production, habitat availability and recreation potential can be projected. The biomass contents in trees and their roots were calculated with the functions of Petersson (1999). For young stands were the biomass assessed by the functions of Claesson *et al.* (2001). The carbon in soil was modelled with the Q-model (Ågren & Bosatta, 1998) which is incorporated in the Heureka system together with a litter model (Ågren *et al.*, 2007).

The influence of thinnings was examined by varying the number of thinnings from zero to two. For the stated number of thinnings, the time points for thinning and final felling were chosen to find the highest Soil Expectation Value (SEV). In simulations with two thinnings the effects of biofuel harvesting and fertilization were also tested in two separate scenarios, in which neither the thinning practices (intensity and timing), nor final felling, was changed. Biofuel harvesting was assumed to occur after both thinning and final felling, while fertilization was applied ten years before final felling. These five scenarios were analysed for all four stands and the real interest rate was set to 3 %.

### 2.1.2 Results and Discussion

SEV increased when thinnings (one or two) were applied to the high productivity stands of both spruce and pine (Table 2). Otherwise SEV decreased when thinning was applied. Biofuel harvesting increased SEV compared to the scenario with two thinnings, and the same was true for the fertilization scenario.

Table 2. *Soil expectation values (3 % real interest rate; SEK). High and low refer to site productivity.*

| | Stand management regime | | | | |
|---|---|---|---|---|---|
| Stand | No thinning | One thinning | Two thinnings | Two thinnings and biofuel | Two thinnings and fertilization |
| Norway spruce, high | 15553 | 16746 | 16950 | 19798 | 20863 |
| Scots pine, high | 14024 | 17165 | 16959 | 20997 | 24747 |
| Norway spruce, low | 4014 | –143 | –1599 | –1077 | –931 |
| Scots pine, low | –1872 | –3198 | –3471 | –2474 | –1468 |

The scenario with no thinning was the best for sequestering carbon for all stands. In the following text the no-thinning scenario is regarded as the base scenario and all comparisons are made relative to this scenario, if not otherwise stated. Increasing the number of thinnings decreased the mean annual carbon sequestration (MACS) by up to 25 % (Table 3). However, for all stands and scenarios the MACS was always positive for any rotation period, implying that the stands were always a carbon sink. Biofuel harvesting decreased MACS by 3 to 9 % compared to the scenario with two thinnings. The decrease was solely related to the soil carbon pool because less harvest residues were left on the forest floor. Fertilization increased MACS by 1 to 24 % for all stands.

The mean annual timber harvest (MATH) increased with the number of thinnings for all stands. Biofuel harvesting did not affect MATH since the management regime was unchanged. Fertilization increased MATH slightly (by 1 to 5 %).

The best alternative for sequestering carbon seems to be to avoid thinnings, but the best alternative for producing timber was to thin twice times and fertilize ten years before final felling. Other studies (Eriksson *et al.*, 2007; Jandl *et al.*, 2007; Olsson *et al.*, 2005; Franklin, 2004) suggest that fertilization can improve carbon sequestration. The results presented in Paper I support this conclusion. In the future it would be interesting to investigate the effects of considering the total carbon sequestration in terms of MATH, MACS and biofuel harvests, since we have not as yet considered the substitution effects of products and biofuel.

Table 3. *Mean timber harvest (MATH; $m^3$ $ha^{-1}$ $year^{-1}$), mean carbon sequestration (MACS; tonne C $ha^{-1}$ $year^{-1}$) and mean biofuel harvest (MABH; tonne dry weight $ha^{-1}$ $year^{-1}$) for all stands and scenarios (real interest rate = 3 %). High and low refer to site productivity.*

| Stand and quantity | | Stand management regime | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | No thinning | One thinning | | Two thinnings | | Two thinnings and biofuel | | Two thinnings and fertilization | |
| | | | | %* | | %* | | %** | | %** |
| Norway spruce, high | MATH | 7.72 | 8.10 | 5 | 8.29 | 7 | 8.29 | 0 | 8.66 | 4 |
| | MACS | 0.959 | 0.880 | −8 | 0.825 | −14 | 0.760 | −8 | 0.891 | 8 |
| | MABH | | | | | | 0.97 | | | |
| Scots pine, high | MATH | 7.68 | 8.12 | 6 | 8.21 | 7 | 8.21 | 0 | 8.26 | 1 |
| | MACS | 1.253 | 1.253 | 0 | 1.072 | −14 | 0.977 | −9 | 1.129 | 5 |
| | MABH | | | | | | 1.05 | | | |
| Norway spruce, low | MATH | 3.49 | 3.55 | 2 | 3.79 | 9 | 3.79 | 0 | 3.98 | 5 |
| | MACS | 0.456 | 0.452 | −1 | 0.370 | −19 | 0.358 | −3 | 0.372 | 1 |
| | MABH | | | | | | 0.47 | | | |
| Scots pine, low | MATH | 3.00 | 3.08 | 3 | 3.17 | 6 | 3.17 | 0 | 3.24 | 2 |
| | MACS | 0.326 | 0.270 | −17 | 0.244 | −25 | 0.226 | −7 | 0.302 | 24 |
| | MABH | | | | | | 0.43 | | | |

*Percentage change relative to the no-thinning scenario.
**Percentage change relative to the two-thinnings scenario.

## 2.2 Modelling carbon sequestration and forest management in a regional case study (Papers II and III)

Papers I and IV address carbon (Paper I) and climate (Paper IV) issues at stand level, however Papers II and III addressed probable effects on timber and biofuel production in a region of adding a monetary value to carbon sequestration. Carbon sequestration and forest management assessment studies have been previously performed at country level (Ågren & Hyvönen, 2003; Karjalainen *et al.*, 2002; Karjalainen *et al.*, 1995) and at regional level within a country (Ericsson, 2003; Hoen & Solberg, 1994). Most such studies have been simulation studies incorporating only a few management alternatives and no economic value of carbon sequestration, except for the study published by Hoen & Solberg (1994), who used an optimizing model for a region in Norway and ranked the most cost-effective ways to sequester carbon. The studies reported in Papers II and III had two main goals. The first was to develop a model that could handle a large dataset from the

National Forest Inventory (NFI) and find optimal solutions when a monetary value for carbon sequestration was added to the standard forest incomes from harvesting. The second was to model the potential of carbon offsets and carbon sequestration together with timber and biofuel production within a region in northern Sweden.

### 2.2.1 Materials and Methods

The county of Västerbotten in northern Sweden (Figure 1) was chosen as the study area. Västerbotten is a county dominated by boreal forest, in which Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula pendula* and *B. pubescens*) are the most common species, representing 45 %, 36 % and 15 %, respectively, of the total wood volume (SLU, 2004). The forest industries are concentrated towards the coast, where the forest production potential is highest. The production potential declines towards the mountains in the west.

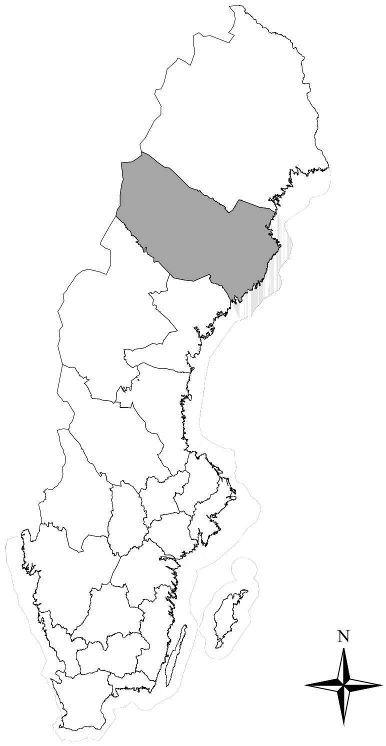


*Figure 1.* Map of Sweden, showing the county of Västerbotten (shaded area).

Detailed forest data for the county were available through the NFI. The whole county was covered by 3308 plots on productive land (productivity

> 1 $m^3$ $ha^{-1}$ $year^{-1}$) inventoried between 1996 and 2000. The total area of forest land represented by these plots was 3.2 million hectares. The model optimized NPV of wood production and carbon sequestration. Included components were harvests of wood, harvests of forest biofuel, transportation costs of timber, pulpwood and biofuel, the value of carbon storage and cost of carbon emissions (Equation 1). The time horizon was 100 years, divided into 20 five-year long periods. Actual local prices were used for timber, pulpwood and biofuel. The real interest rate was set to 3 % and the harvest level was allowed to vary by up to 1 % between periods. The objective function of the stated problem was as follows:

$$Maximize\ Z = NPV^{wood} + NPV^{bio\ fuel} + PV^{C-storage} - PV^{transport} - PV^{C-emissions} \quad (1)$$

where: $NPV^{wood}$ = NPV of timber and pulpwood production, including silvicultural costs; $NPV^{biofuel}$ = NPV from extracted harvest residues (for biofuel), including transportation costs; $PV^{C\text{-}storage}$ = present value of carbon storage; $PV^{transport}$ = present value of transportation costs for timber and pulpwood; and $PV^{C\text{-}emmsions}$ = present value of the cost of carbon emissions from products.

For each treatment unit (plot) a management program was searched such that the objective function was maximized subject to a set of constraints. A stand-level management model (Wikström, 2001; Wikström & Eriksson, 2000) was used to generate management alternatives for each plot. The stand level model included models for generation, growth, thinning response, mortality, biomass production and harvest value. The biomass change in every period was calculated as the sum of growth of living biomass minus the decay of dead biomass, harvested wood and natural mortality. The conversion factor from dry weight biomass to carbon content was 0.49. A positive net carbon change in a 5-year period was multiplied by a carbon price, thus giving carbon sequestration an economic value. Harvested products were divided into the product groups timber and pulpwood, where carbon was assumed to be released more rapidly from pulpwood than from timber. Emissions were treated as a cost that was discounted to the start of the planning horizon. The cost was the same as the carbon price. Carbon in mineral soil and humus was not accounted for since no suitable model was available. Carbon dioxide emissions from transport and harvesting were not included either.

### 2.2.2 Results and Discussion

In 2002 the Swedish rate of $CO_2$-tax was 630 SEK per tonne of $CO_2$. This corresponds to a carbon price of 2310 SEK per tonne C. Using this carbon price led to no harvest at all in the region. Therefore, carbon prices from zero up to 1200 SEK per tonne were entered in the model. The harvest ceased at values higher than about 1200 SEK. In accordance with expectations, carbon sequestration showed corresponding increases along with an increasing carbon price (Figure 2). The average carbon increase for the county was 1.48 million tonnes per year for no carbon price and 2.05 million tonnes per year for the highest carbon price. Carbon storage in living and dead biomass increased over time (Figure 3).

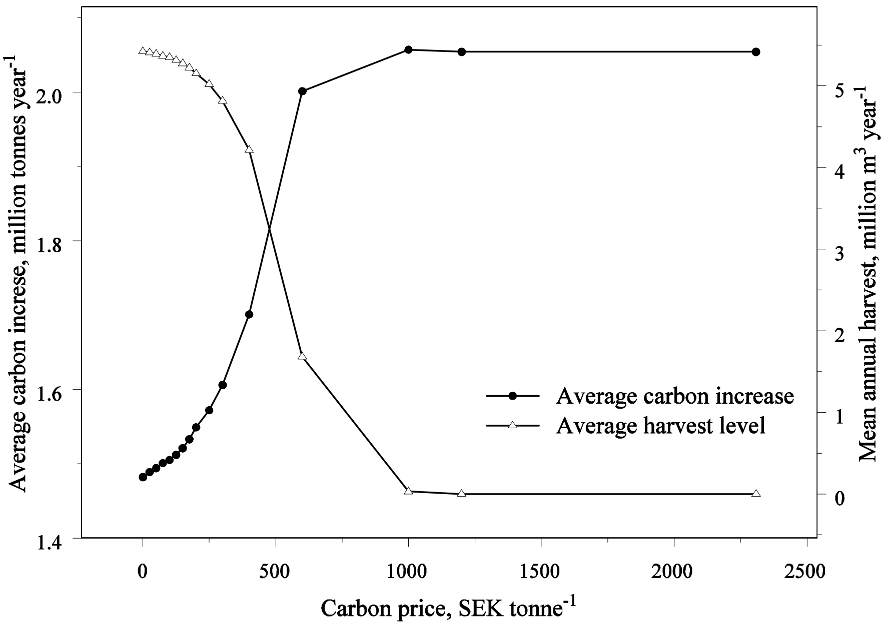


*Figure 2.* Average increase in stored forest carbon and mean annual harvest for a 100-year period in the 3.2 million hectare case study area.

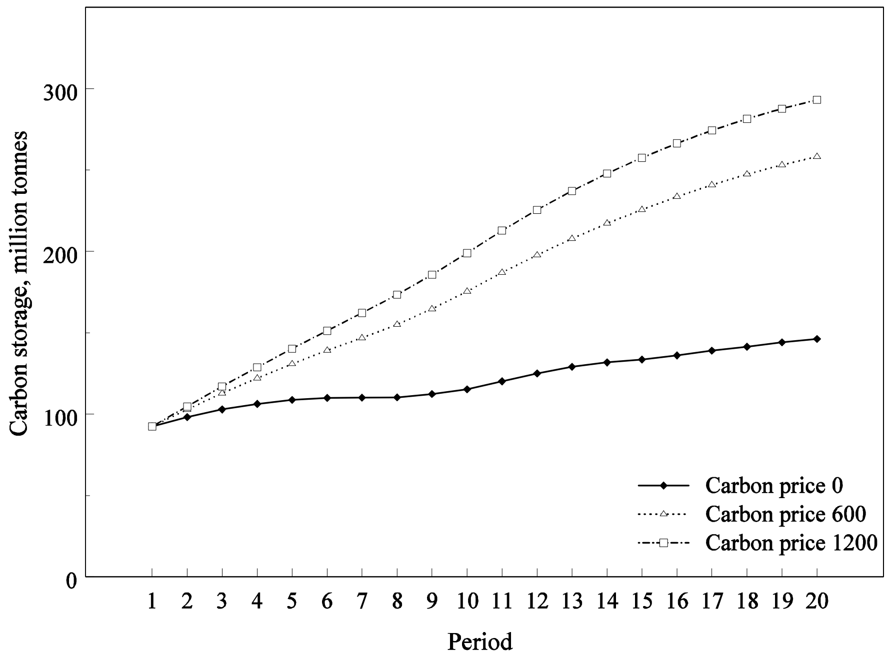


*Figure 3.* Total carbon storage (million tonnes) in living and dead forest biomass in each five-year period for carbon prices of zero, 600 and 1200 SEK per tonne.

The carbon storage did not reach a steady state-after 100 years with any of the tested carbon prices, but the curve was leveling out at the end of the planning horizon, indicating that the carbon flux into the standing forest was decreasing. A problem when building up large carbon stores in forest biomass is the risk of sudden catastrophic events like fire, strong winds or insect outbreaks causing large emissions of $CO_2$. When no carbon price was applied (i.e. today's situation) the harvest levels varied depending on the location within the region, with the highest harvest levels in the eastern parts near the coast where the productivity is highest and most of the industries are located. The average net carbon sequestration was also highest in the coastal area. When the carbon price increased the harvest levels decreased relatively more in the eastern parts. However, the relative carbon sequestration increase was similar for almost the whole county. This indicates that it is possible to both produce timber and store carbon when the productivity is high. The proportion of thinning of the total harvested volume decreased as the carbon price increased, and again the decrease was largest in the western parts. Excluding the thinnings increased the standing volume and thereby increased the carbon storage in the forest. This effect was also shown in Paper I.

Since biofuel harvests were only possible after final felling the biofuel harvest also decreased when the carbon price increased. It seemed however that our restrictions regarding price were too narrow since the biofuel harvest was small. We only applied current prices and costs for biofuel extraction, but prices might very well increase if the demand for biofuel rises, which would lead to higher biofuel extraction levels. When the total mitigation effect (i.e. carbon sequestered in forest biomass plus substitution of carbon from fossil fuel) was calculated, only 4 % originated from biofuel, the remaining part was due to sequestration in forest biomass. Although its contribution was not large in this study, biofuel extraction is potentially very important, since it is a permanent sink when replacing fossil carbon.

The lack of soil carbon in our model gives a limited picture of the problem, since the soil carbon pool is more than five times larger than the carbon pool in biomass in the boreal forest (IPCC, 2000). The soil carbon content in productive forest land in Sweden is approximately 74 tonne C per hectare (Lilliesköld & Nilsson, 1997). Simulation studies of forest soils in Nordic countries indicate that soil carbon sinks take up between 0.08 tonne C per hectare per year (de Wit *et al.*, 2006) and 0.25 tonne C per hectare per year (Liski *et al.*, 2005; Ericsson, 2003; Ågren & Hyvönen, 2003). Including soil carbon in the model applied in Papers II and III would probably strengthen the carbon sequestration value of the forest, assuming that low harvest levels lead to increasing soil carbon storage.

## 2.3 The effects on stand management of growth uncertainty caused by climate change (Paper IV)

Forest management is classically modeled as a deterministic planning problem in which decisions are determined in advance unconditionally with respect to future events. This approach has led to the development of efficient optimization methods based on linear programming, which can solve large forest management problems generally encountered in Scandinavian countries. Several studies have, nevertheless, established that it could be essential from an economic perspective to consider stochastic phenomena, such as natural hazards and market uncertainties, in the definition of long-term forest management problems (Lohmander, 2001; Valsta, 1992).

Climate change will almost certainly have important effects on forest ecosystems in the long term. According to the last scenarios published by IPCC, the average temperature increase in the world might be in the range of 1.1°C to 6.4°C by the year 2100 (IPCC, 2007). At regional level, a model developed by SWECLIM for Sweden predicts an increase between 2.5°C to 4.5°C by 2100 (Persson *et al.*, 2007), but there is also considerable uncertainty regarding the future climate trajectory. Hence, there is a need to apply more than merely deterministic planning approaches in forest management to assess (and counter) effects of climate change.

The objective in this study was to find out whether incorporating climate change uncertainty would substantially change the optimal management of stands and (if so) the implications for solving the stand management problem.

### 2.3.1 Material and methods

In the study 29 hypothetical forests stands in northern and southern Sweden were used. The stands contained one, two or three of the following species: Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula spp*). The stands were established, 27 to 50 years old and had not been thinned previously. The forest stand dynamics were influenced by the choice of thinning actions and final felling age over a finite time horizon. Management programs for the stands were generated by the GAYA stand simulation system (Hoen & Eid, 1990; Eriksson, 1983) with empirical growth functions developed by Ekö, (1985). In each five-year period four different management actions were considered for each species: 1) Do nothing, 2) Remove all trees, 3) Light thinning, or 4) Heavy thinning. We assumed that the climate change only affected the temperature.

The objective of the planning problem was to maximize the sum of future discounted rewards. Since we do not know the average observed temperature in advance we have an optimization problem under uncertainty. Thus, we need to consider the expected value of the sum of all discounted rewards based on the probability distribution of the temperature increase. The optimal plan to this problem is denoted $\tilde{P}^*$. However, to find solutions to $\tilde{P}^*$ is generally costly and, instead, approximate optimal plans can be found for a series of fixed temperatures over the planning horizon. The stand management problem was solved using simulated annealing.

To predict the temperature increase in each period a stochastic climate model was developed. It was assumed that the temperature increase in 100 years time would be in the range of 2.5°C to 6°C. The interperiodic variation was based on Sweden's past climate variation. Temperature changes were assumed to affect only basal area growth (*BI*) for each period (*t*) and species (*i*) and was calculated as:

$$BI_{ti} = B0_{ti}\left(1 + T_t * GE_i\right) \quad (2)$$

where $B0_{ti}$ is the calculated basal area growth over the five-year period, $t$, for species $i$ when temperature change is not accounted for, and $GE_i$ is the growth effect per degree of temperature change. We followed Bergh *et al.* (2003) by setting $GE_i$ to 0.065 for pine and birch, and to 0.05 for spruce.

### 2.3.2 Results and Discussion

The problem was first solved for all stands as a deterministic optimization problem, with three different temperature scenarios in each of which a linear increase of the temperature per 5-year period was applied, corresponding to a temperature increase of $T_{min}$ (2.5°C), $\bar{T}$ (4.25°C) and $T_{max}$ (6.0°C) degrees over 100 years, respectively. This resulted in a deterministic optimal plan $P^*$ for each scenario. The optimal plans associated with the three temperature scenarios are referred to as $P^*_{\min}, \bar{P}^*$ and $P^*_{\max}$, respectively. The sensitivity of the plans was tested by evaluating each plan in the other two temperature scenarios. Table 4 shows the relative loss when a plan for one of the three temperature scenarios ($P^*_{\min}, \bar{P}^*$, and $P^*_{\max}$) was applied in another of the temperature scenarios. The loss in most cases was around 1 %, but larger losses occurred in some cases when the $P^*_{\max}$ plan was used under temperature scenario $T_{min}$. The reason for the larger losses seems to be due to effects of the pricelist design.

*Table 4. Relative net present value loss (%) incurred from applying a plan (P) for a temperature scenario (T) for which it was not developed (real interest rate 3 %).*

| | Temperature scenarios and plans | | | | | |
|---|---|---|---|---|---|---|
| | $T_{min}$ | | $\bar{T}$ | | $T_{max}$ | |
| | $\bar{P}^*$ | $P^*_{\max}$ | $P^*_{\min}$ | $P^*_{\max}$ | $P^*_{\min}$ | $\bar{P}^*$ |
| Average | 1.0 | 2.1 | 0.4 | 1.1 | 1.1 | 0.5 |
| Min | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -0.3 |
| Max | 4.3 | 8.9 | 2.8 | 3.5 | 3.5 | 2.3 |

For the three stands that showed the largest losses we also solved them for $\tilde{P}^*$, i.e. considering the expected value. The expected values were similar for both $\tilde{P}^*$ and $\bar{P}^*$, but the standard variation was smaller for the $\tilde{P}^*$ plans (Table 5). $\tilde{P}^*$ plans seem to be more robust than $\bar{P}^*$ plans, but $\tilde{P}^*$ plans took in this case about 40 times longer to develop than $\bar{P}^*$ plans.

*Table 5. The expected net present value and its standard deviation for $\overline{P}^*$ and $\widetilde{P}^*$ plans for three stands.*

| Stand | Expected net present value | | | Standard deviation | | |
|---|---|---|---|---|---|---|
| | $\overline{P}^*$ | $\widetilde{P}^*$ | Rel diff | $\overline{P}^*$ | $\widetilde{P}^*$ | Rel diff |
| 23 | 31654 | 31630 | 1.001 | 1079 | 1029 | 1.049 |
| 27 | 41464 | 41959 | 0.988 | 1267 | 776 | 1.633 |
| 28 | 35788 | 36102 | 0.991 | 1444 | 886 | 1.630 |

The loss of value due to a non-adaptive plan appears to be limited. The worst cases, i.e. cases in which the plan was constructed based on one extreme temperature trend and then applied to a realisation of the opposite extreme temperature trend incurred losses of, on average, 1 to 2 %. The value of forming the plan based on the expected value to derive plan $\widetilde{P}^*$ also appears limited. The cases where it proved to yield more robust plans were largely due to model artifacts, such as the form of the price list, than the actual influence of climate change. The underlying basis for these conclusions, or at least one important reason, is that the change in temperature is relatively modest over the next few decades whereas discounting reduces the values in the more distant future.

# 3 Discussion and Conclusions

## 3.1 How important is it to include all components in a carbon budget?

A forest-related carbon budget may consist of many components, the main constituents being the carbon stored in forest biomass (living and dead), forest soil carbon, carbon stored in products and landfills. The first two are on-site and the latter two off-site storage pools. Clearly, in cases where carbon sequestration/storage must be considered in addition to traditional forest management goals, the most relevant carbon components should be considered in the analysis. Ideally, therefore, all components should be included, but that is not normally possible due to a lack of data or models, or both. However, if we do not consider all components there is a risk for misinterpretation of results. For example in an optimization study for a 30 000 ha hypothetical forest in New Brunswick, Canada, Hennigar *et al.* (2008) found that optimizing for carbon storage in only the forest (including soil) or in the forest and forest product pools (including landfills) resulted in similar levels of carbon storage. However, less wood was harvested in the first alternative (considering carbon storage in forests only) compared to the second (considering carbon storage in forests and forest products). When they also considered the replacement effect of the products, the management became more intense with shorter rotations, and timber yields were also higher. Neither economic factors, nor the possibility to use forest biofuel, were considered. An optimization study in a 1.342 million hectare region in Norway also considered the replacement effect of use of forest biofuel and incorporated economic factors (Raymer *et al.*, 2009). The cited authors found that NPV and thinning decreased, and planting increased, when maximizing carbon benefits and keeping the harvest at present levels. When the substitution effect of forest products was also included, planting and thinnings increased, thus management regimes changed depending on the included carbon compartments. In the study at stand level considering thinning and fertilization presented in Paper I, it was found that mean annual carbon sequestration decreased when forest biofuel was extracted. If the soil carbon pool had been excluded the biofuel harvest alternative would have been more attractive, but inaccurate. On the other hand, the effect of biofuel substituting fossil fuel was not included in any of the cases considered in Paper I either.

If all compartments are not included (as they seldom are) it is important to be aware of the effects of different system boundaries. If only carbon storage in forest (biomass and soil) is considered, carbon storage will normally be maximal if harvest ceases. Sometimes carbon in soil is not included (as in Papers II-III) but soil carbon is normally favoured by reductions in harvest levels (Jandl *et al.*, 2007). If products are included through storage and/or substitution the best management alternative for carbon storage and sequestration might be different from the best option in scenarios in which only forest carbon is included. Determining the optimal alternative for carbon sequestration might be very complex and depend on other assumptions regarding forest management, like harvest levels, economic constraints and the studied object/area. The complexity of the problem clearly highlights the need to use forest management analysis and planning systems. It is also essential to combine different models from disciplines with related dimensions, like house construction and industrial process analysis. In the studies this thesis is based upon sequestration in products was only indirectly considered in Papers II and III through the economic set up of the problem.

Extraction of forest biofuel was considered in Papers I-III but the replacement effect of biofuel was only examined in Paper III, which showed that the contribution from forest biofuel was limited compared to the carbon sequestration in forest biomass. However, the economic restrictions were quite narrow (only today's prices were applied) and the species composition and soil productivity in the studied region was not so favourable for biofuel extraction. The demand for biofuel will most likely increase, which would lead to higher prices. This would make more areas available (from an economic perspective) for biofuel harvest. If the price for biofuel is at the same level as pulpwood, the price for pulpwood might raise and/or the import of pulpwood would increase to keep the industry supplied with raw material. This thesis has only considered biofuel extraction together with other harvest activities as this is the most common method in Sweden today. With increasing biofuel prices, harvests could also be possible in young dense stands (Bergström, 2009) and thereby not compete with the pulpwood market. Intensified biofuel harvest will lower the carbon sequestration in forests (see Paper I) but if the replacement effect is considered the mitigation effect might be positive.

Not only is the demand for biofuels expected to rise. It could also be that demand for wood in the construction sector is increasing, in turn leading to a higher demand for sawlogs. The consequences of an increased demand for sawlogs was analysed with the forest sector model EFI-GTM for Europe in the study by Eriksson *et al.* (2009). The prices for sawlogs increased while the price for pulpwood was unchanged or reduced. This decrease of pulpwood price was explained to be a result of an increase in sawlog chips, due to the increased volume of sawlogs being processed.

## 3.2 Does considering carbon sequestration and climate change demand new forest management regimes and planning approaches?

In general on-site forest carbon sequestration is favored by longer rotations and thinning programs that promote higher stocking levels (Briceno-Elizondo *et al.*, 2006; Kaipainen *et al.* 2004; Liski *et al,* 2001). These general findings are supported by the studies presented in Papers I-III. Results in Paper I indicated that the most favorable management strategy for carbon sequestration was to avoid thinnings. However, this had negative effects on amounts of harvested timber and, for high productivity stands, economic outcome. Even if thinnings was combined with fertilization (which increased sequestration) sequestration was higher without thinning. However, fertilization was only combined with two thinnings in the simulations. Hence, the thinning probably lowered the carbon sequestration more than the fertilization increased it. Since fertilization gave higher sequestration rates for most cases compared to corresponding management without fertilization, a qualified guess is that no thinning combined with fertilization would be even better, solely in terms of carbon sequestration. However, if the economic output is the most important factor, thinning once or twice (together with fertilization or biofuel extraction) are better alternatives for high productivity stands. For low productivity spruce stands is it still best to avoid thinnings, but for low productivity pine stands fertilization combined with two thinnings gave the highest economic yield (soil expectation value). When introducing thinning, the only outcome favored for all stands was mean annual timber harvest (MATH). If all factors are considered, two thinnings combined with fertilization or biofuel harvest might be an attractive middle course.

Differences in economic results for stands of differing productivity were also found in the simulations described in Papers II and III, in which thinnings were excluded first in the low productivity areas when the carbon price increased. Papers II and III also showed that harvesting ceased when the carbon price increased, thereby increasing the standing biomass. However, the standing biomass cannot increase indefinitely, and the results showed that the total carbon storage was increasing at a slower rate at the end of the planning horizon, implying that the carbon flux into the forest was decreasing.

Management actions intended to increase stocking levels also increase the risk for carbon losses by disturbances like wind damage (Galik & Jackson, 2009). These risks were not considered in any of the studies this thesis is based upon. The mortality functions used return higher mortality for high stocking levels, but they have not been developed for unmanaged forests. Further, since serious sudden disturbances are not included in the mortality functions it is possible that carbon storage, especially for old and unmanaged forests, was overestimated. When risks for sudden catastrophic events are incorporated into forest management planning rotation lengths are generally shortened (Valsta, 1992).

To stabilize atmospheric GHG concentration at around 550 ppm $CO_2$-eq by 2030 a carbon price for mitigation in all sectors could rise to 20-80 USD per tonne of $CO_2$-eq (IPCC, 2007b). In the simulations for the county of Västerbotten, reported in Papers II-III, the harvest levels ceased at a carbon price at around 39 USD per tonne of $CO_2$-eq. A total cessation of harvesting might not be realistic, due to the importance of timber production for the regional and national economy, but these findings show that mitigation through sequestration in forests is a relatively cheap alternative. Other advantages of using forests as a carbon sink are that it is a simple and well known technology, reversible (although that is also disadvantageous in some respects, see risks discussed above), and it can have other co-benefits for e.g. biodiversity, eco-tourism and reindeer herding.

The stand management study (Paper IV) – in which the economic value of timber production was the only outcome considered and the only ecological effect of climate change on forests considered was growth of the trees – indicated that management practices would not be strongly affected by climate change. The uncertainty associated with climate change did not justify the application of more sophisticated methods that explicitly encompass the process stochasticity, either. This is in agreement with Valsta

(1992) who concluded, in a similar study, that the overall change in optimum rotation due to growth risk was small. Spring *et al.* (2005), in contrast, found that losses caused by using the wrong plan for a specific climate could be significant. However, their study included incomes from carbon sequestration and water production in addition to monetary income from timber production.

One problem when comparing results from different studies is that differences in system boundaries make the results diverge in ways that can be difficult to interpret (Harmon & Marks, 2002). Many studies have suggested that forests should be left untouched to maximize their use as carbon sinks, while others suggest that intense management is better for carbon sequestration. If the forest is classified as "old-growth" (c.f., Pacific North West, USA) they generally contain high carbon stores in biomass and soil that will be lost after harvest, and the new established forest will not sequester enough carbon to compensate for the losses (Harmon & Marks, 2002). However, for managed forests, if substitution effects of forest products and/or biofuel is also considered, more intense management might be more appropriate to maximize carbon sequestration (Liu & Han, 2009; Hennigar *et al.*, 2008; Eriksson *et al.*, 2007) Assessments of the substitution potential of increased use of wood in the construction of buildings are only recently becoming available; one newly published estimate of the potential for Europe (EU25) indicates that emission reductions in the range of 40 Mt $CO_2$ per year may be possible (Eriksson *et al.*, 2009). It is important to emphasise the need to be careful when setting the boundaries for carbon sequestration studies and that awareness of the boundaries is necessary when results are interpreted.

The choice of interest rate also needs to be considered. The real interest rate was set to 3 % in all main scenarios in this thesis. It is a typical rate in forest economics while it might be considered high in the climate change contex as there might be too risky to postpone mitigation actions and concerns, among others, perceived responsibilities for future generations. For example, Cline (1992) and Stern (2006) set their discount rates to 1.5 % and 0,1 % respectively, while Nordhaus (1994) used 3 % discount rate. As this thesis aims to reflect normal forest management combined with $CO_2$ mitigation 3 % real interest rate was chosen anyway. In general, lower real interest rates leads to longer rotation periods.

It should be noted that all findings this thesis is based upon were obtained from empirical growth models. The major drawback with these models is that effects of climate change are not easily incorporated. A simple correction factor was introduced in Paper IV, but that does not readily allow factors other than temperature to be incorporated. One reason for using empirical models is that they are developed to give responses to classical management problems (traditional forest data as independent variables, 5-year time steps, etc).

In the study for Västerbotten the results were found to depend on the specific region under study. For example, the region was dominated by pine (45 %) and located in northern Sweden where the productivity is relatively low. In a region with more spruce and higher productivity more biofuel could have been extracted, and higher harvest levels would have been possible. Traditional forest management regimes would have been more profitable and would have resulted in higher harvest levels at higher carbon prices compared to the Västerbotten case. In Paper IV it was found that management practices would not be strongly affected by climate change-induced temperature increases (assuming that forest growth is the only ecological variable affected). It was therefore concluded that the need for more sophisticated solution methods was minor. This might not, however, be true if broader aspects of climate change, like increased damage by wind or fire were also considered. These factors also have negative effects on forest growth while increased temperature will generally lead to increased growth. Therefore, to handle these complex problems there is a need to incorporate new adaptive solution methods into forest management planning in the near future.

## 3.3 Concluding remarks and future research

One of the aims of this thesis, and the underlying studies, was to provide guidance for policy-makers when making decisions regarding carbon sequestration issues in relation to the managed forests in Sweden. I hope that some of the findings will be applied in decision-making and serve as a starting point for further research. I am however in all humility, aware that other disciplines are conducting research on how to combine forest, climate change, and energy concerns: the aim of this thesis was limited to the forest management planning viewpoint.

The stand level study (Paper I) showed that most carbon was sequestered in forest biomass and soil when no thinnings were applied. However thinnings were a more attractive alternative from an economic perspective for high productivity stands. In studies of the carbon sequestered in forest biomass in the county of Västerbotten (Papers II and III) it was found that introducing a price for carbon sequestration lowered the harvest levels, and that thinnings were first avoided on low productivity sites when the carbon price increased. This finding is consistent with the results presented in Paper I. It was also concluded that carbon sequestration in forest biomass is relatively cheap. The last study (Paper IV, stand level) addressed the importance of adapting forest management practices to the correct climate (or more strictly, temperature increase) scenario. The results indicate that the importance of finding a management plan to match the correct temperature scenario is minor.

While preparing this thesis new problems have emerged that emphasize the need for more research on the subject. The post Kyoto Protocol process and implications of the EU:s 2020 goal[3] will also increase the need for more research on related issues.

The Heureka system applied in the study described in Paper I provides opportunities to perform forest management studies with consideration of climate change, using recently developed hybrid growth models (empirical models modified by growth calculations using process-based models) (Freeman *et al.* 2009). A set of forest goods and services are incorporated in the system, enabling analyses incorporating timber and biofuel production, biodiversity, recreation, and carbon sequestration in forest biomass and soil, within an optimization framework. Analyses can be performed from stand to national level. A next step in research is thus to include more sophisticated models for examining the effects of product substitution and off-site forest carbon storage (Eriksson *et al.*, 2009). This thesis has only focused on even-aged management but in the future uneven-aged management also needs to be considered. For example could perhaps low intensive uneven-aged management be an interesting alternative for the western low productive areas of Västerbotten (Paper II and III).

The risks posed by increased frequencies of storms, fires or insect outbreaks have not been addressed in this thesis. Since these events are, by nature, stochastic and catastrophic, forest management problems cannot be reliably solved as deterministic problems and we will probably need to apply new solution methods, such as reinforcement learning, a simulation-based dynamic programming method (Sutton & Barto, 1998).

[3] The EU has set goals to reduce GHG emissions by 20 % by 2020 compared to 1990 levels, increase the share of renewable energy sources to 20 % of total energy production and reduce energy consumption by 20 % by increasing energy efficiency.

# References


Alam, A., Kilpeläinen, A. & Kellomäki, S. (2008). Impacts of thinning on growth, timber production and carbon stocks in Finland under changing climate. *Scandinavian Journal of Forest Research* 23, 501-512.

Bergh, J., Freeman, M., Sigurdsson, B., Kellomäki, S., Laitinen, K., Niinisto, S., Peltola, H. & Linder, S. (2003). Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. *Forest Ecology and Management* 183(1-3), 327-340.

Bergh, J., McMurtrie, R.E. & Linder, S. (1998). Climatic factors controlling the productivity of Norway spruce: A model-based analysis. *Forest Ecology and Management* 110(1-3), 127-139.

Bergström, D. (2009). Techniques and Systems for Boom-Corridor Thinning in Young Dense Forests. *Acta Universitatis Agriculturae Sueciae* 2009:87.

Briceno-Elizondo, E. (2006). *Stand level analysis on the effects of management and climate change on the growth and timber yield with implications on carbon stocks in boreal forest ecosystem: a model approach*. Diss. University of Joensuu. Joensuu.

Briceno-Elizondo, E., Garcia-Gonzalo, J., Peltola, H. & Kellomäki, S. (2006). Carbon stocks and timber yield in two boreal forest ecosystems under current and changing climatic conditions subjected to varying management regimes. *Environmental Science & Policy* 9(3), 237-252.

Claesson, S., Sahlén, K. & Lundmark, T. (2001). Functions for biomass estimation of young Pinus sylvestris, Picea abies and Betula spp. from stands in northern Sweden with high stand densities. *Scandinavian Journal of Forest Research* 16(2), 138-146.

Cline, W.R. (1992). *The economics of global warming*. Washington, DC: Institute for International Economics.

de Wit, H.A., Palosuo, T., Hylen, G. & Liski, J. (2006). A carbon budget of forest biomass and soils in southeast Norway calculated using a widely applicable method. *Forest Ecology and Management* 225(1-3), 15-26.

Denman, K.L., Brasseur., G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., U.Lohmann, Ramachandran, S., Dias, P.L.d.S., Wofsy, S.C. & Zhang, X. (2007). *Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment*

*Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)].* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

EEA (2008). *Greenhouse gas emission trends and projections in Europe 2008 : tracking progress towards Kyoto targets*. Copenhagen, European Environment Agency. Report 5.

Ekö, P.M. (1985). *En produktionsmodell för skog i Sverige, baserad på bestånd från riksskogstaxeringens provytor (A growth simulator for Swedish forests, based on data from the national forest survey)*. Umeå, Swedish University of Agricultural Sciences, Department for Silviculture Rapport 16.

Ericsson, E. (2003). Carbon accumulation and fossil fuel substitution during different rotation scenarios. *Scandinavian Journal of Forest Research*. 18, 269-278.

Eriksson, E. & Berg, S. (2007). Implications of environmental quality objectives on the potential of forestry to reduce net CO2 emissions - A case study in central Sweden. *Forestry* 80(2), 99-111.

Eriksson, E., Gillespie, A.R., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R. & Stendahl, J. (2007). Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research* 37(3), 671-681.

Eriksson, L.O. (1983). *Timber class formation by cluster analysis*. Swedish University of Agricultural Sciences, Department of Forest Technology. Report 157.

Eriksson, L.O. (1994). Two methods for solving stand management problems based on a single tree model. *Forest Science* 40(4), 732-758.

Eriksson, L.O., Gustavsson, L., Hänninen, R., Kallio, M., Lyhykäinen, H., Pingoud, K., Pohjola, J., Sathre, R., Solberg, B., Svanaes, J. & Valsta, L. (2009). *Climate implications of increased wood use in the construction sector - towards an integrated modeling framework* Umeå, Swedish University of Agricultural Sciences, Department of Forest Resource Management, Arbetsrapport 257.

Franklin, O. (2004). *Gödslad skog bidrar till minskad växthuseffekt - kvävetillförsel ökar kollagren i skogsmark*. Uppsala, Swedish University of Agricultural Sciences, Fakta Skog 7.

Freeman, M., Wikström, P. & Elfving, B. (2009). Adjustment of an empirical growth and yield model to account for effects of climate change on forest production *(Manuscript)*.

Galik, C.S. & Jackson, R.B. (2009). Risks to forest carbon offset projects in a changing climate. *Forest Ecology and Management* 257(11), 2209-2216.

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E. & Kellomäki, S. (2007). Effects of climate change and management on timber yield in boreal forests, with economic implications: A case study. *Ecological Modelling* 209(2-4), 220-234.

Greig, M. & Bull, G. (2009). *Carbon management in British Columbia's forests: opportunities and challenges*. FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC, Canada, FORREX series 24.

Harmon, M.E. & Marks, B. (2002). Effects of silvicultural practices on carbon stores in Douglas-fir - Western hemlock forests in the Pacific Northwest, U.S.A.: Results from a simulation model. *Canadian Journal of Forest Research* 32(5), 863-877.

Hennigar, C.R., MacLean, D.A. & Amos-Binks, L.J. (2008). A novel approach to optimize management strategies for carbon stored in both forests and wood products. *Forest Ecology and Management* 256(4), 786-797.

Heureka (2009). Available from: http://heureka.slu.se

Hoen, H.F., & Eid, T. (1990). En modell for analyse av behandlingsstrategier for en skog ved bestandssimulering og lineær programmering (A model for analysis of treatment strategies for a forest applying standwise simulations and linear programming). Ås, Norwegian Forest Research Institute. Report 9.

Hoen, H.F. & Solberg, B. (1994). Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. *Forest Science* 40(3), 429-451.

Hyvönen, R., Ågren, G.I., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I.A., Jarvis, P.G., Kellomäki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Strömgren, M., Van Oijen, M. & Wallin, G. (2007). The likely impact of elevated [$CO_2$], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: A literature review. *New Phytologist* 173(3), 463-480.

Ingemarson, F. & Nordin, Y. (2008). Skogens roll i ett framtida globalt klimatavtal. *Kungliga Skogs- och lantbruksakademiens tidskrift*, 147(5).

IPCC (2000). *Land use, land-use change, and forestry: special report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (2007a). *Climate change 2007 : Synthesis report Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)]. IPCC, Geneva, Switzerland.

IPCC (2007b). *Summary for Policymakers*. In: Climate C*hange 2007 : Synthesis report Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)], IPCC, Geneva, Switzerland.

IPCC (2007c). *Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, (eds.), Cambridge University Press, Cambridge, UK, 7-22.

IPCC (2007d). *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K. & Byrne, K.A. (2007). How strongly can forest management influence soil carbon sequestration? *Geoderma* 137(3-4), 253-268.

Johnson, D.W. & Curtis, P.S. (2001). Effects of forest management on soil C and N storage: meta analysis. *Forest Ecology and Management* 140(2-3), 227-238.

Johnson, K.N., Gordon, S., Duncan, S., Lach, D., McComb, B. & Reynolds, K. (2007). *Conserving creatures of the forest: A guide to decision making and decision models for forest biodiversity*. Corvallis, OR Oregon State University, College of Forestry.

Jonsson, M. & Wardle, D.A. (2009). Structural equation modelling reveals plant-community drivers of carbon storage in boreal forest ecosystems. *Biology Letters*. Published online 15 September 2009, doi: 10.1098/rsbl2009.0613.

Kaipainen, T., Liski, J., Pussinen, A. & Karjalainen, T. (2004). Managing carbon sinks by changing rotation length in European forests. *Environmental Science & Policy* 7(3), 205-219.

Karjalainen, T., Kellomäki, S. & Pussinen, A. (1995). Carbon balance in the forest sector in Finland during 1990-2039. *Climatic change* 30(4), 451-478.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G., Erhard, M., Eggers, T., Sonntag, M. & 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.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.J., Eggers, T., Lapvetelainen, T. & Kaipainen, T. (2003). Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget. *Forest Policy and Economics* 5(2), 141-155.

Kellomäki, S. & Leinonen, S. (2005). *Management of European forests under changing climate conditions*. Joensuu: University of Joensuu, Faculty of Forestry. Tiedonantoja 163

Kellomäki, S. & Väisänen, H. (1997). Modelling the dynamics of the forest ecosystem for climate change studies in the boreal conditions. *Ecological Modelling* 97(1-2), 121-140.

Korzukhin, M.D., Ter Mikaelian, M.T. & Wagner, R.G. (1996). Process versus empirical models: wich approach for forest ecosystem management? *Canadian Journal of Forest Research*. 26, 879-887.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., Metsaranta, J. & Apps, M.J. (2009). CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* 220(4), 480-504.

Kurz, W.A., Stinson, G., Rampley, G.J., Dymond, C.C. & Neilson, E.T. (2008). Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences* 105(5), 1551-1555.

Lasch, P., Badeck, F.W., Suckow, F., Lindner, M. & Mohr, P. (2005). Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany). *Forest Ecology and Management* 207(1-2 SPEC. ISS.), 59-74.

Lilliesköld, M. & Nilsson, J. (1997). *Kol i marken: konsekvenser av markanvändning i skogs- och jordbruk*. Stockholm: Naturvårdsverket. Rapport 4782.

Lim, B., Brown, S. & Schlamadinger, B. (1999). Carbon accounting for forest harvesting and wood products: review and evaluation of different approaches. *Environmental Science & Policy* 2(2), 207-216.

Liski, J., Palosuo, T., Peltoniemi, M. & Sievanen, R. (2005). Carbon and decomposition model Yasso for forest soils. *Ecological Modelling* 189(1-2), 168-182.

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R. & Karjalainen, T. (2001). Which rotation length is favourable to carbon sequestration? *Canadian Journal of Forest Research.* 31(11), 2004-2013.

Liu, G. & Han, S. (2009). Long-term forest management and timely transfer of carbon into wood products help reduce atmospheric carbon. *Ecological Modelling* 220(13-14), 1719-1723.

Lundström, A. & Söderberg, U. (1996). Outline of the Hugin system for long-term forecasts of timber yields and possible cut. In: Päivinen, T.*, et al.* (Eds.) *Proceedings of Large-scale forestry scenario models: experiences and requirements*, Joensuu, Finland, 15-22 June, 1995 pp. 63-77.

Lohmander, P. (2001). *On risk and uncertainty in forest management planning systems.* SNS Meeting: Nordic trends in forest inventory, management and planning. Solvalla, Finland.

Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P. & Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature* 455(7210), 213-215.

Lämås, T. & Eriksson, L.O. (2003). Analysis and planning systems for multiresource, sustainable forestry: the Heureka research programme at SLU. *Canadian Journal of Forest Research* 33(3), 500-508.

Masera, O.R., Garza-Caligaris, J.F., Kanninen, M., Karjalainen, T., Liski, J., Nabuurs, G.J., Pussinen, A., de Jong, B.H.J. & Mohren, G.M.J. (2003). Modeling carbon sequestation in afforestration, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modelling.* 164(2-3), 177-199.

Matala, J., Kärkkäinen, L., Härkönen, K., Kellomäki, S. & Nuutinen, T. (2009). Carbon sequestration in the growing stock of trees in Finland under different cutting and climate scenarios. *European Journal of Forest Research* 128(5), 493-504.

McMurtrie, R.E., Rook, D.A. & Kelliher, F.M. (1990). Modelling the yield of Pinus radiata on a site limited by water and nitrogen. *Forest Ecology and Management* 30(1-4), 381-413.

Micales, J.A. & Skog, K.E. (1997). The decomposition of forest products in landfills. *International Biodeterioration & Biodegradation* 39(2-3), 145-158.

Mund, M., Kummetz, E., Hein, M., Bauer, G.A. & Schulze, E.-D. (2002). Growth and carbon stocks of a spruce forest chronosequence in central Europe. *Forest Ecology and Management* 171(3), 275-296.

Nordhaus, W.D. (1994). *Managing the global commons: the economics of climate change.* Cambridge, Mass.: MIT.

Nordpool (2009). Available from: www.nordpool.com

Nuutinen, T., Matala, J., Hirvelä, H., Härkönen, K., Peltola, H., Väisänen, H. & Kellomäki, S. (2006). Regionally optimized forest management under changing climate. *Climatic Change* 79(3-4), 315-333.

Olsson, P., Linder, S., Giesler, R. & Högberg, P. (2005). Fertilization of boreal forest reduces both autotrophic and heterotrophic soil respiration. *Global Change Biology* 11, 1745-1753.

Persson, G., Bärring, L., Kjellström, E., Strandberg, G. & Rummukainen, M. (2007). *Climate indices for vulnerability assessments*. Norrköping: SMHI. SMHI Reports Meteorology and Climatology 111.

Petersson, H. (1999). *Biomassafunktioner för trädfunktioner av tall, gran och björk i Sverige*. Umeå, Swedish University of Agricultural Sciences. Department of Forest Resource Management and Geomatics. Arbetsrapport 59.

Pingoud, K., Savolainen, I. & Seppälä, H. (1996). Greenhouse Impact of the Finnish Forest Sector including Forest Products and Waste Management. *Ambio* 25(5), 318-326.

Pohjola, J. & Valsta, L. (2007). Carbon credits and management of Scots pine and Norway spruce stands in Finland. *Forest Policy and Economics* 9(7), 789-798.

Pohjola, J., Valsta, L. & Mononen, J. (2004). Cost of carbon sequestration in Scots pine stands in Finland. *Scandinavian Forest Economics* 40, 81-90.

Raymer, A.K., Gobakken, T., Solberg, B., Hoen, H.F. & Bergseng, E. (2009). A forest optimisation model including carbon flows: Application to a forest in Norway. *Forest Ecology and Management* 258(5), 579-589.

Schelhaas, M.J., van Esch, P.W., Groen, T.A., de Jong, B.H.J., Kanninen, M., Liski, J., Masera, O., Mohren, G.M.J., Nabuurs, G.J., Palosuo, T., Pedroni, L., Vallejo, A. & Vilén, T. (2004). *CO2FIX V 3.1 - A modelling framework for quantifying carbon sequestration in forest ecosystems*. Wageningen, The Netherlands. ALTERRA. Report 1068.

SLU. (2004). *Skogsdata 2004*. Umeå: Swedish University of Agricultural Sciences. Department of Forest Resource Management and Geomatics.

Seppälä, R., Buck, A. & Katila, P. (Eds.) (2009). *Adaptation of Forests and People to Climate Change. A Global Assessment Report*. Helsinki: IUFRO World Series Volume 22

Skogsstyrelsen (2008). *Skogliga konsekvensanalyser 2008 - SKA-VB 08*. Jönköping, Swedish Forest Agency. Rapport 25.

Smithwick, E.A.H., Harmon, M.E., Remillard, S.M., Acker, S.A. & Franklin, J.F. (2002). Potential upper bounds of carbon stores in forests of the Pacific Northwest. *Ecological Applications* 12(5), 1303-1317.

Spring, D.A., Kennedy, J.O.S. & Mac Nally, R. (2005). Optimal management of a forested catchment providing timber and carbon sequestration benefits: Climate change effects. *Global Environmental Change Part A* 15(3), 281-292.

Stern, N. (2007). *The economics of climate change: the Stern review*. Cambridge: Cambridge University Press.

Sutton, R.S. & Barto, A.G. (1998). *Reinforcement Learning: An introduction*. Cambridge: MIT Press.

Swedish Environmental Protection Agency. (2009). National Inventory Report 2009 Sweden. Stockholm, Swedish Environmental Protection Agency.

UNFCCC (1997). *United nations framework concnetion on climate change. Kyoto protocol to the United Nations Framework Convention on Climate Change*. UNFCCC.

Valsta, L.T. (1992). A Scenario Approach to Stochastic Anticipatory Optimization in Stand Management. *Forest Science* 38, 430-447.

Wang, C., Bond-Lamberty, B. & Gower, S.T. (2003). Carbon distribution of a well- and poorly-drained black spruce fire chronosequence. *Global Change Biology* 9, 1066-1079.

Van Tuyl, S., Law, B.E., Turner, D.P. & Gitelman, A.I. (2005). Variability in net primary production and carbon storage in biomass across Oregon forests - An assessment integrating data from forest inventories, intensive sites, and remote sensing. *Forest Ecology and Management* 209(3), 273-291.

Wikström, P. (2001). Effect of decision variable definition and data aggregation on a search process applied to a single-tree simulator. *Canadian Journal of Forest Research*. 31(6), 1057-1066.

Wikström, P. & Eriksson, L.O. (2000). Solving the stand management problem under biodiversity-related considerations. *Forest Ecology and Management* 126(3), 361-376.

Ågren, G.I. & Bosatta, E. (1998). *Theoretical ecosystem ecology - understanding element cycles*. Cambridge: Cambridge University Press.

Ågren, G.I. & Hyvönen, R. (2003). Changes in carbon stores in Swedish forest soils due to increased biomass harvest and increased temperatures analysed with a semi-empirical model. *Forest Ecology and Management*. 174, 25-37.

Ågren, G.I., Hyvönen, R. & Nilsson, T. (2007). Are Swedish forest soils sinks or sources for $CO_2$ - Model analyses based on forest inventory data. *Biogeochemistry* 82(3), 217-227.

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