# The Potential for Forestry to Reduce Net $CO_2$ Emissions

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# Abstract

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Forestry may have an important role to play in attempts to reduce atmospheric $CO_2$ levels, since countries may choose to account for forest management activities to fulfil their commitments under the Kyoto Protocol. However, the effectiveness of such efforts may depend on the forest management strategies applied. This thesis is based on four separate studies in which the potential for forest management strategies to decrease net $CO_2$ emissions was considered. Long-term field experiments and models were used to: evaluate the impact of different thinning regimes; study broadleaved stands growing on abandoned farmland with different rotation lengths; predict the effects of using different rotation lengths on carbon accumulation and fossil fuel substitution; and perform an integrated analysis of forest management practices and the potential to substitute fossil fuels by wood products. To evaluate the effects of the management regimes considered, carbon stocks in the investigated stands and the potential of the resulting biomass to substitute fossil fuel were estimated.

No significant differences were found in biomass production between the thinning regimes for Norway spruce (*Picea abies* (L.) Karst.) stands, but the standing biomass was significantly larger in unthinned stands, indicating that to maximize the carbon stock in tree biomass thinnings should be avoided. For Scots pine (*Pinus sylvestris* L.), thinned and fertilized stands produced significantly more biomass (2.60-2.72 ton d.w. $ha^{-1}$ $yr^{-1}$) than unthinned and unfertilized stands (2.17-2.34 ton d.w. $ha^{-1}$ $yr^{-1}$) in the northern regions. These findings indicate that fertilization might be a viable measure to increase production of biomass with the potential to replace fossil fuel and energy-intensive material. In addition, for broadleaved trees stands on abandoned farmland, management regimes with a short rotation were found to be better for maximizing the substitution of fossil fuel than regimes with a long rotation. However, the trees have to be grown on good sites; otherwise long rotations could be better options for broadleaved stands. In coniferous stands, a shortened rotation period resulted in lower carbon stocks than a prolonged rotation period, but the amount of residues that could substitute fossil fuel increased with a shorter rotation. However, annual rates of carbon accumulation in biomass might decline in both short- and long-rotation stands in the future. If so, carbon sequestration in biomass would not be the best option. In a long-term perspective, wood products could have high potential to reduce net $CO_2$ emissions, since wood can replace energy-intensive materials like cement, plastics and aluminium. Intensively managed forests (*e.g.* fertilized forests or shortened rotation lengths) could contribute more to reductions in $CO_2$ emissions than current forest management. Using forest products (*i.e.* wood products and biofuel) is probably more important than storing carbon in biomass and soil, but it is necessary to conserve the existing stocks. Intensive forest management and increased use of biomass may, however, conflict with environmental quality objectives.

*Keywords:* biofuel, biomass, broadleaved trees, carbon stock, $CO_2$, fertilization, forest management, Norway spruce, rotation length, Scots pine, substitution of fossil fuel, thinning regimes, wood products.

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# Contents

# Appendix

## Papers I-IV

This thesis is based on the following papers, which will be referred to by their respective Roman numerals:

I. Eriksson, E. 2006. Thinning operations and their impact on biomass production in stands of Norway spruce and Scots pine. *Biomass and Bioenergy 30(10)*, 848-854.

II. Eriksson, E. & Johansson, T. 2006. Effects of rotation period on biomass production and atmospheric $CO_2$ emissions from broadleaved stands growing on abandoned farmland. *Silva Fennica 40(4),* 603-613.

III. Ericsson, E. 2003. Carbon accumulation and fossil fuel substitution during different rotation scenarios. *Scandinavian Journal of Forest Research 18(3)*, 269-278.

IV. Eriksson, E., Gillespie, A., Gustavsson, L., Langvall, O., Olsson, M., Sathre, R. & Stendahl, J. 2006. Integrated carbon analysis of forest management practices and wood substitution. *Canadian Journal of Forest Research* (Accepted).

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## Notes on the authorship of the papers

Eriksson was completely responsible for Papers I and III.

In Paper II, the aim and structure were set by Eriksson. Johansson was responsible for the field data and some writing. Eriksson was responsible for the calculations, analysis and the discussion of the results.

In Paper IV, the aim and structure were jointly set by all of the authors. Langvall modelled the forest growth, Sathre was responsible for the wood products and $CO_2$ emissions analyses, and Stendahl for the soil carbon simulations. Eriksson was responsible for the interactions between the models and for the calculations of litter input and biomass production. All of the authors were collectively responsible for the analysis and the discussion of the results. Eriksson edited the paper.

# Introduction

## Background

Radiation from the sun heats up the Earth, but the Earth's surface reflects some of the radiation to the atmosphere. The natural greenhouse gases (*e.g.* water vapour and carbon dioxide, $CO_2$) absorb some of the reflected radiation and return some of it back to the Earth. Without this greenhouse effect the global mean temperature would be about 35 °C lower than it is today and the conditions for life on Earth would be much poorer. Since 1750, the atmospheric concentration of $CO_2$ has increased by 31% and this increase has been suggested to be the major cause of temperature rises observed during the 20$^{th}$ century (IPCC, 2001). The global average surface temperature has increased by 0.6±0.2 °C since 1861 and most of the warming occurred during the beginning and the end of the 20$^{th}$ century (IPCC, 2001). Other possible explanations for the increased temperature are variations in solar and volcanic activity, but they have not been accepted by the research community since there is no clear evidence that these phenomena contributed to the global warming during the 20$^{th}$ century. Small oscillations have been observed in solar irradiance, but the irradiance has only been measured since 1978, so there are too few data to draw long-term conclusions regarding their possible effects (IPCC, 2001). Volcanic eruptions increase the amount of aerosols in the stratosphere, which could affect the global temperature. However, the general scientific consensus today is that volcanic eruptions result in negative forcing, *i.e.* reduce radiation reaching the earth's surface from the sun and thus cool it rather than warming it (IPCC, 2001).

The greenhouse gases can be divided into three groups: natural greenhouse gases that also can be released by human activities ($CO_2$, $CH_4$ and $N_2O$); ozone-depleting gases (*e.g.* $CFCl_3$ and $CF_2Cl_2$); and fluoride-containing, non-ozone-depleting gases (*e.g.* $CF_4$, C2$F_6$ and $SF_6$) (Bernes, 2003). The climatic impact of specific amounts of these gases differs, so in order to compare their effects, Global Warming Potential ($GWP_{100}$) values can be used. $GWP_{100}$ refers to the global warming potential of a specific mass of a gas, relative to $CO_2$, over 100 years. Carbon dioxide has the least climatic impact of the recognised greenhouse gases on this basis and a $GWP_{100}$ of 1, since it is the reference species, to which the effects of all other gases are related. Methane ($CH_4$) has a $GWP_{100}$ of 23 (*i.e.* 23 times stronger than $CO_2$) and nitrous oxide ($N_2O$) has a $GWP_{100}$ of 296. The $GWP_{100}$ values for the above-mentioned fluoride-containing gases are 6000-22000 (IPCC, 2001). In 2003, $CO_2$ was responsible for 79% of anthropogenic emissions of greenhouse gases from Sweden, while $CH_4$, $N_2O$ and fluoride-containing substances contributed 8%, 12% and 1%, respectively (Anon. 2005a). The total emissions of greenhouse gases in Sweden amounted to 70.6 million tons (t) $CO_2$-equivalents in 2003; 2% lower than the figure for 1990 (Anon. 2005a). Including the uptake in forests in the calculations, the net emissions of greenhouse gases amounted to 49 million t $CO_2$-equivalents. The main contributor of anthropogenic emissions of $CO_2$ is fossil fuel combustion. The anthropogenic emissions of $CH_4$ largely originate from rice agriculture, cattle, and landfills, while chemical industries and agricultural soils are mainly responsible for emissions of $N_2O$ (IPCC, 2001).

About 75% of the anthropogenic emissions of $CO_2$ during the past 20 years are due to the combustion of fossil fuels (IPCC, 2001). The other main contributors to the increased $CO_2$ emissions are land-use changes, especially deforestation in the southern hemisphere. The global forested area was reduced by about 5% during the period 1980-1995, but the deforestation rate in the tropics appears to be decreasing, and in Europe and North America some abandoned farmlands have been afforested (Bernes, 2003). There are natural fluxes of carbon (C) between the Earth's surface and the atmosphere (Fig. 1). However, fossil fuel burning and cement production result in additional fluxes of C to the atmosphere, although these emissions are, to some extent, compensated by uptake of C in the oceans and terrestrial systems. Indeed, the ocean and the land are currently taking up ca. half of the anthropogenic emissions and during the 1990s the carbon taken up by terrestrial systems probably exceeded the carbon released via deforestation (IPCC, 2001). The C stock in vegetation and soil is estimated to be almost three times the stock in the atmosphere, but the major C stock is in the oceans (Fig. 1).

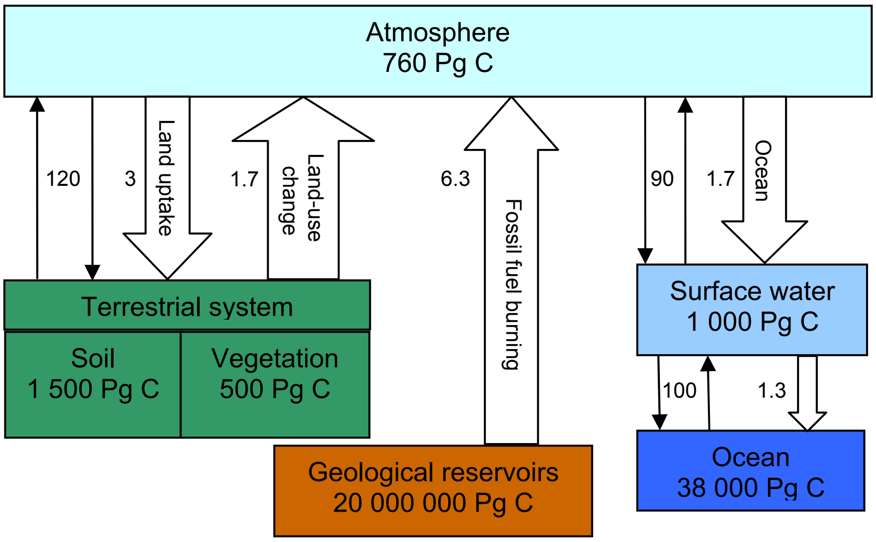


*Figure 1.* The carbon cycle. The thin black arrows represent the natural fluxes of carbon between the different stocks and the wide, unfilled arrows represent additional, anthropogenic fluxes (Pg C year$^{-1}$). (Data adapted from IPCC (2001) and Bernes (2003))

## The role of forestry

Forests and forest management have important roles to play in attempts to reduce net $CO_2$ emissions to the atmosphere (Kurz *et al.* 2002), and the northern hemisphere could be particularly important because of its high potential for carbon sequestration (Liski *et al.* 2000; Myeni *et al.* 2001). Forestry has a part in the

Kyoto Protocol (UNFCCC, 1997) since countries should account for changes in their land-use management (*i.e.* afforestation, deforestation and reforestation) according to Article 3.3, but this is mainly interesting for countries that have large potential to increase afforestation or decrease deforestation, which makes this article less important for the Nordic countries. In Article 3.4 it is stated that countries may choose to account for management strategies that reduces greenhouse gases. This could be of importance for nations with large forest areas. Schlamadinger & Marland (1996) have listed several ways in which forestry activities can affect the amount of $CO_2$ in the atmosphere, namely by: (*i*) increasing carbon sequestration in biomass and soil, (*ii*) increasing the amount of carbon stored in wood products, (*iii*) substituting fossil fuel by biofuel, and (*iv*) substituting energy-intensive materials with wood products. The carbon stocks in biomass and soil have been intensively studied in the past 20 years by (*inter alia*) Cooper (1983), Bengtsson & Wikström (1993), Vesterdal *et al*. (1995), Schlamadinger & Marland (1996), Liski *et al*. 2000, Johnson & Curtis (2001), Liski *et al*. (2001), Myeni *et al*. 2001, Harmon & Marks (2002), Kirschbaum (2003) and Kaipainen *et al*. (2004). The amount of carbon stored in wood products has not been studied so extensively, possibly because the wood product stock is currently assumed to remain constant over time (Maclaren, 2000). Substituting fossil fuel with biofuel is assumed to be an important strategy since it leads to a direct reduction of combustion of fossil fuels, as discussed *inter alia* by Gustavsson *et al*. (1995), Schlamadinger *et al*. (1995), Schlamadinger & Marland (1996), Börjesson *et al*. (1997), and Kirschbaum (2003). Finally, the fourth role for the forest sector is to substitute energy-intensive materials, such as concrete, plastics and aluminium, with wood products. Börjesson & Gustavsson (2000) and Gustavsson *et al*. (2006) reported that using wood products instead of concrete in buildings could result in substantial reductions in $CO_2$ emissions. Forests could release considerable amounts of $CH_4$ and $N_2O$ (von Arnold *et al*. 2005a, b), but in this thesis the focus is on $CO_2$ since much more of it is released than of any other anthropogenic greenhouse gas (Anon. 2005a).

## Forest management strategies

Forest management strategies could be important tools for reducing net emissions of greenhouse gases since countries may choose to apply forest management activities to fulfil their Protocol commitments (UNFCCC, 1997). The rotation length is considered to have substantial effects on carbon stocks in the forest, and thus is an important parameter to optimise (Liski *et al.* 2001; Harmon & Marks, 2002). Increasing the rotation length generally results in increased carbon stock in biomass, but may not increase the carbon stock in the soil (Liski *et al.* 2001; Kaipainen *et al.* 2004). Furthermore, increasing the rotation length may decrease the potential for using logging residues as substitutes for fossil fuel (Paper III). Other management practices that could be important for reducing net $CO_2$ emissions include optimising thinning operations, increasing the forested area, and fertilization. As for meeting any forestry objective, it is also of course important to select appropriate tree species. An unmanaged forest could store more carbon in its biomass than a managed forest (Cooper, 1983; Thornley & Cannell, 2000; Maclaren, 2000; Kirschbaum, 2003), implying that if the purpose is to store as much carbon as possible in the forest there should be no thinning operations. However, not thinning the forest would not be an optimal solution for the forest sector in the Nordic countries since thinnings are economically important for forest owners and the forest industry. Thinnings are essential when managing the forest for timber and pulp production and about a third of the wood consumed by the pulp industries originates from thinning operations (Anon. 2005b; Anon. 2006).

In the Nordic countries, forest growth exceeds the amounts harvested, so increasing the forested area is less important for promoting sustainability than it is for some countries in the southern hemisphere. However, in a climate-related context, increasing the forested area could be interesting even in Sweden, where 348 000 ha of farmland and pasture land was abandoned during the period from 1974 to 1999 (Johansson, 1999a). To meet commitments under both national and international agreements (UNFCCC, 1997, Anon. 2003), it could be valuable to establish forests on this land for carbon sequestration or wood fuel production. Fertilization is another forest management practice that could be usefully implemented. The main rationale for increasing the fertilized area is that it increases the amount of biomass and thereby the carbon stock or the amount of wood fuel that could substitute fossil fuel. Bergh *et al.* (2005) reported that if fertilizers with optimum nutrient contents were applied, yields could increase by 300% in northern Sweden and 100% in southern Sweden. It has also been reported that fertilization not only increases the above ground biomass, but also retards the decomposition of the organic matter in the soil, thereby increasing the amount of carbon stored in it (Olsson *et al.* 2005). Changing the tree species grown could also help to increase forestry's potential to reduce $CO_2$ levels. Klang & Ekö (1999) and Johansson (2003) reported that a mixture of Norway spruce (*Picea abies* (L.) Karst.) and silver and downy birch (*Betula pendula* Roth and *B. pubescen*s Ehrh.) could produce more biomass than a pure stand of spruce. The extra biomass could be used to replace fossil fuel or energy-intensive material. Furthermore, Berg *et al.* (1996) showed that there were higher carbon stocks in the soil of spruce and birch stands than in the soil of corresponding Scots pine (*Pinus sylvestris* L.) stands. In contrast, Brandtberg *et al.* (2000) found no significant differences in soil carbon stock between stands with a mixture of birch and spruce compared with a monoculture of spruce.

The carbon stock in above ground tree biomass in Swedish forests currently amounts to 820 million t C and, on average, the Swedish forests have been a carbon sink (*i.e.* they have accumulated more carbon than they have emitted) since the national forest survey started in the 1920´s (Anon. 2005b). The growing stock in the forests increased by 75% between 1925 and 2000 and, assuming that the increments of the branches and needles have been proportional to those of the stem, it was found that, on average, the above ground biomass in the Swedish forests has increased by 4.7 million t C year$^{-1}$ during the past 75 years (Anon. 2005b). There are however indications that the carbon sequestration in biomass will be lower in the future. Anon. (2000) simulated that 3.7 million t C year$^{-1}$ of carbon will be accumulated between 2000 and 2010, and 1.9 million t C year$^{-1}$ in 2000 to 2100. Karjalainen *et al.* (2002) have also predicted that the rate of carbon accumulation may be lower in the future than it is today. The carbon content of soil is much more difficult to estimate than the carbon in biomass, but it has been reported that soil accumulates more $CO_2$ than it emits (Liski *et al.* 2002). However, according to von Arnold *et al.* (2005a, b), drained forest soils could be considerable emitters of greenhouse gases and Lindroth *et al.* (1998) showed that the forest can act as a carbon source over substantial periods. Lilliesköld & Nilsson (1997) estimated the carbon stock in the Swedish forest soils to be 1 700 million t C. This gives an average of about 80 t C $ha^{-1}$, but the variation is probably large. Low productivity forests have small stocks of carbon (*i.e.* 40 t C $ha^{-1}$), while high productivity forests could store up to 200 t C $ha^{-1}$ (Lilliesköld & Nilsson, 1997). According to estimates based on data from various sites in Finland by Liski & Westman (1995), low and high productivity Finnish forests store ca. 58 $\pm$ 11 t C $ha^{-1}$ and 96 $\pm$ 25 t C $ha^{-1}$, respectively.

## Evaluating the role of forestry in greenhouse gas mitigation

Forestry's potential to reduce atmospheric $CO_2$ levels can be studied in several ways, but there are three main methodologies that can be used to evaluate forestry-related climate issues: full-scale measurements, statistical evaluations of field data, and model simulations. Measuring the total carbon fluxes of the forest in Sweden or the total carbon stock is not currently possible, but measuring the fluxes is important and they have been measured in some areas in Sweden *e.g.* by Lindroth *et al.* (1998). The results from flux measurements can then be scaled up and analysed using statistical tools. Long-term field experiments are important for analysing consequences of different management strategies. In the studies underlying this thesis, both field data and statistical tools were used for this purpose (Papers I and II).

For both forestry decision-makers and practitioners growth models are useful for optimizing forest management strategies and thus maximizing yields. For forest researchers, models are important for understanding different processes and the effects of different management practices on forest stands. There is wide range of models and they can be classified in several ways, but the major distinction is between biologically-based models and management-oriented growth and yield models. Models can also be classified according to the geographical scale they cover, since they may predict outcomes at national, regional, estate, stand or tree levels (see, for instance, Ekö, 1985; Jonsson *et al.* 1993; Lundström & Söderberg, 1996; Söderberg, 1996). Furthermore, models can be deterministic or stochastic (Karlsson, 2005). A deterministic model always predicts the same result as long as the input data are unchanged, while a stochastic model predicts outputs in a range, which means that a stochastic model may be able to explain the variation of a system.

Biologically-based models simulate biological systems using mathematical tools (Maclaren, 2000) and important variables in such models may include temperature, precipitation, and respiration. An advantage of these models is that they can identify parameters that affect growth and describe the impact of increased $CO_2$ levels (Maclaren, 2000). However, biologically-based models are not commonly used in practical forest management since they are considered to contain too many uncertainties and to be too impractical (Maclaren, 2000; Mäkelä *et al.* 2000). In climate change research, biologically-based models have been used *inter alia* by Jansson & Karlberg (2004) and Kirschbaum (2000). A type of biologically-based model used in forest research is the forest gap model, which simulates the establishment, growth, and mortality of individual trees on a specific plot by considering the stochastic effects of both weather and demographic processes (Bugmann *et al.* 1996; Shugart & Smith, 1996). Forest gap models can be used to simulate effects of climate change on forests (Lindner, 2000) and have been used in attempts to determine optimal rotation lengths to promote carbon sequestration (Liski *et al.* 2001) and the forest sector's contribution to reducing atmospheric $CO_2$ levels (Pussinen *et al.* 1997).

Management-oriented growth and yield models (or empirical models) are based on data that are relatively easy to measure (Maclaren, 2000) and they will provide good estimates as long as the forecasts are within the range of the input data (Karlsson, 2005). Empirical models are widely used by forest managers and companies and are easy to understand and implement, but they are not suitable if there are changes in the environment since they are based on historical data. An example of a widely used empirical model in Sweden is HUGIN. This is a deterministic model, with some stochastic components, based on data from national forest inventories and delivers predictions for regional and national levels (Lundström & Söderberg, 1996). Today, HUGIN can also be used to predict the carbon accumulation in the biomass under different forest management strategies. In Finland, the MELA-system has been developed to predict the outcome of different forest management regimes at estate and national levels (Siitonen *et al.* 1996; Redsven *et al.* 2005). Empirical models were used in the studies described in Papers III and IV.

Another type of model is the hybrid model, which contains elements from both biologically-based models and empirical models. Hybrid models combine the flexibility of biologically-based models with the advantages of empirical models (*i.e.* ease of input measurements and implementation for forest practitioners) and are likely to be the most common type of forest models in the future (Landsberg, 2003). Today, most silivicultural models are empirical models, but in research related to climate change several models have been developed in recent years that can be classified to varying degrees as hybrids (see, for instance, Apps *et al.* 1999; Beets *et al.* 1999; Masera *et al.* 2003; Schelhaas *et al.* 2004).

## Estimation of carbon stocks

The amount of carbon in a forest stand can be estimated in several ways. The most accurate technique would be to measure the amounts of carbon that are absorbed by photosynthesis and lost by autotrophic respiration. The difference is called Net Primary Production (NPP). However, it is a very difficult and expensive way to measure carbon fluxes. An easier way is estimate the weight of the trees at different times, since the difference between two measurements always represents NPP. Trees die after a certain time and the carbon they contain is lost due to diverse processes including harvesting, competition, insect or fungal attacks and fire. The difference between NPP and these losses is termed Net Ecosystem Production (NEP). The easiest way to estimate NEP is to use biomass functions, which give the amount of dry weight (d.w.) (*e.g.* Marklund, 1988; Johansson, 1999b). The amount of carbon in wood is 45-55% of the d.w., for most species and fractions (*i.e.* stem, branches, *etc*.; Maclaren, 2000), and the carbon content tends to be around 50% (Thörnqvist, 1985). However, measuring trees only gives the amount of carbon in the woody biomass. Measurements of photosynthesis and respiration give the carbon fluxes in the whole forest ecosystem including trees, soil, field vegetation, *etc*. and could show that a forest stand does not always act as a carbon sink, even if the trees accumulate more carbon than they emit (Lindroth *et al*. 1998). Carbon flux measurements could be important tools for detecting changes in the soil carbon stock under different forest management regimes, but to obtain a complete understanding of the carbon stocks and fluxes in the forest stand, carbon flux measurements would have to be performed throughout a whole rotation period, which would be very expensive. In the studies described in Papers I and III, the above ground biomass was estimated by measuring the stand at different times and by using biomass functions. In Papers II and IV, the average carbon stock was estimated since the studies were performed at a stand level during subsequent rotations. This means that all of the carbon in the above ground biomass that was accumulated in the stand was removed when the stand was harvested and therefore there was no build-up of carbon after subsequent rotations. The average carbon stock was used to detect differences in carbon storage between forest management strategies.

## Substitution of fossil fuel

To compare bioenergy systems and fossil fuel-based systems comprehensively it is necessary to consider factors such as: energy inputs required to produce, process and transport fuels; mass and energy losses along the entire fuel chain; embodied energy in infrastructure; distribution and cogeneration systems; and by-products (Schlamadinger *et al.* 1997). A Life Cycle Assessment (LCA) approach could be useful for this purpose, since such assessments consider the impact of a product during its entire lifetime, including production, usage and disposal (Lindholm, 2006). LCA is a rather new tool for quantifying environmental impacts in forestry, but data on energy use and emissions from forest operations have been reported (Karjalainen & Asikainen, 1996; Berg, 1997; Berg & Karjalainen, 2003; Berg & Lindholm, 2005). However, LCA has limitations, since the effect on flora and fauna, the impact on soil, and the recreational values of the ecosystem are difficult to assess in a LCA (Lindholm, 2006). To increase knowledge of forestry's energy use and the impact on the environment, there is a need for further data on energy use and emissions from forest operations, since data used in earlier studies of the Scandinavian forestry sector have some limitations, particularly for comparing the effects of different forest management strategies. It could also be necessary to develop a LCA-method that can evaluate forestry's impact on biodiversity.

The potential for biofuel to substitute fossil fuel was evaluated in different ways in the four papers underlying this thesis. In Paper I, there was no evaluation of the substitution effect; only the amounts of logging residues were estimated. In Paper II, the wood fuel was assumed to be used to generate electricity and thereby replace electricity generated by coal. Both indirect emissions (*i.e.* emissions generated in transport, production, refining, *etc.*) and direct emissions were considered. In Paper III, the amount of biomass that could replace oil was calculated, but the indirect emissions from biofuel and fossil fuel were not considered. In addition, there was no comparison with different energy carriers (*e.g.* natural gas and coal) and conversion grades (*i.e.* heat, electricity, *etc.*) in Papers I-III. In Paper IV, an integrated carbon analysis was used to evaluate the potential for biomass produced under different management regimes to replace fossil fuel and energy-intensive material.

Wood products have potential to reduce the use of fossil fuel since they can replace energy-intensive materials (Schlamadinger & Marland, 1996; Gustavsson *et al.* 2006). Furthermore, most of the energy that is generated in the forestry sector originates from by-products from saw- and pulp-mills (*e.g.* black liquor, sawdust, and bark). Black liquor is the most important by-product and contributes 36% of the total bioenergy supply (Anon. 2005b). About 45% of the removed amount of biomass (stem wood and branches) from the forest is used for energy in heating plants or in the forest industry (Nilsson, 1999; Anon. 2005b). However, changes in forest management practices (*e.g.* the use of shorter rotation periods or fertilization) to reduce $CO_2$ could affect the end-products since it could result in changes in the way the wood produced is used. Furthermore, some wood products cannot be used for substitution. Sawn wood and biofuel replace other materials and fossil fuel, respectively, but pulp and paper do not replace any other products. It should also be noted that a large amount of energy is used and generated in pulp and paper production.

## Objectives

The objectives of the studies this doctoral thesis is based upon were to estimate the potential for Swedish forests, under various management strategies, to decrease net emissions of $CO_2$. Four studies were conducted to evaluate this issue by: analyzing the effects of different thinning regimes for conifer stands using long-term field experiments (Paper I), evaluating broadleaved trees growing on abandoned farmland under management regimes with different rotation lengths (Paper II), predicting the impact of varying the rotation length on carbon accumulation and fossil fuel substitution (Paper III), and performing an integrated analysis of forest management practices and wood substitution (Paper IV). Carbon stocks and the potential to substitute fossil fuel were estimated for each of the management regimes considered.

# Material and methods

Field data were used to evaluate the impact of various thinning regimes on biomass production for conifers (Paper I) and to identify the optimal rotation length for broadleaved trees growing on abandoned farmland (Paper II). Model simulations were used to analyse the impact of different rotation periods on conifer stands (Paper III) and to conduct an integrated carbon analysis of management regimes and product uses (Paper IV). The spatial extent and timeframe of the studies described in the four papers varied (stand level or landscape level). Changes in the climate and rises in $CO_2$ concentrations may change forest production, biomass allocation, and organic matter decomposition parameters in the future. The current climatic situation was used in these studies as reference conditions, but it should be noted that changes in the climate and rises in $CO_2$ concentrations may change forest production, biomass allocation, and organic matter decomposition parameters in the future. Addressing such changes was beyond the scope of these studies. Furthermore, the effects of changes in climate and $CO_2$ levels on production and decomposition of soil organic matter are not yet fully understood. The baseline parameters established here may facilitate further studies exploring the impact of climatic changes under different forest management regimes. Such studies may be essential, since forest management practices may have to be changed and adapted to new climatic conditions in the future, (for instance temperature increases may increase forest production, and changes in the interactions between forest production, precipitation and soil moisture may change many significant forestry parameters).

## Evaluating field experiments

### *Thinning strategies*

In Paper I, the impact of applying different thinning strategies to conifer stands on their mean annual increment of biomass, standing biomass, and annual production of biofuel that could replace fossil fuel were analysed using data from a long-term field experiment. The study considered experimental plots in a randomized block design, with 21 blocks of Norway spruce and 50 blocks of Scots pine, established between 1966 and 1984 in young stands. The 71 stands are a part of an ongoing large-scale thinning trial, in which measurements are being taken every five to ten years. The blocks of Norway spruce are mainly located in southern and central Sweden, ranging in latitude from 56° to 61° N, while the blocks of Scots pine are spread across Sweden, ranging in latitude from 56° to 67° N (Fig. 2). In each block, six to 10 subplots, with different thinning and fertilization regimes, were established. Each subplot had an area of 0.1 hectares. The data from the Scots pine blocks were divided into four regions: the northern interior (A), the northern coastal area (B), central Sweden (C) and southern Sweden (D) (Fig. 2). The blocks of Norway spruce were situated in regions C and D and the results from these blocks were analysed together. In this study, the effects of five thinning regimes were examined: no thinning, low thinning, thinning from above, low thinning + fertilization with nitrogen, and one heavy thinning. To evaluate the effects of the five thinning regimes, three parameters were calculated: mean annual increment (MAI), standing biomass, and annual production of biofuel that could replace fossil fuel. MAI was defined as the standing biomass after the last thinning and the total harvested biomass (from thinning operations) of the subplot divided by the total age of the stand. The standing biomass was defined as the biomass of the remaining trees of the subplot after the last thinning. The annual production of biofuel was defined as the biomass of the branches and top of the stem. The data were analysed statistically using the software package SAS for Windows (SAS Institute Inc. 1999) and the GLM procedure with Tukey's studentized range test.

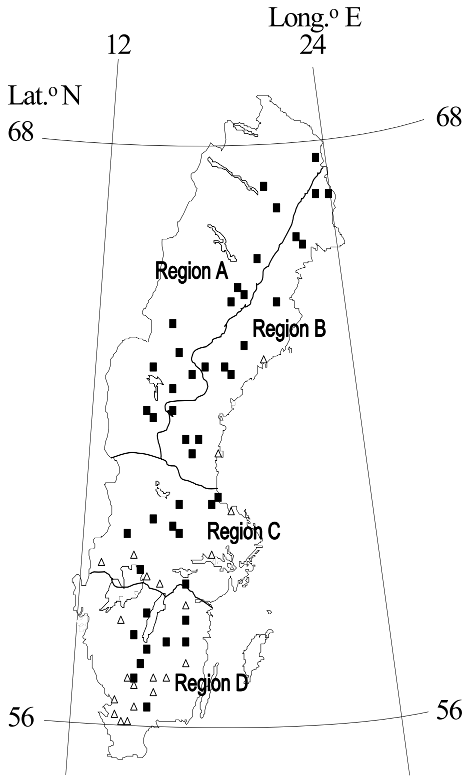


*Figure 2.* Location of the Scots pine (*Pinus sylvestris* L.) (■) and Norway spruce (*Picea abies* (L.) Karst.) blocks (Δ) considered in Paper I. (After Eriksson & Karlsson, 1997)

## *Broadleaved trees on abandoned farmland*

Twenty-eight young stands and 65 mature stands of broadleaved trees growing on abandoned farmland ranging in latitude from 57° to 63° N were examined in the study reported in Paper II. The 28 young stands were between 10 and 20 years of age and included stands of European aspen (*Populus tremula* L.), downy birch, silver birch, common alder (*Alnus glutinosa* (L.) Gaertn.), and grey alder (*Alnus incan*a (L.) Moench). The ages of the 65 mature stands (also of these species) ranged from 26 to 66 years. The above ground biomass (stem and branches) of the stands was calculated using the biomass equations of Johansson (1999b, c, d, 2000, 2002) and Marklund (1988). It was assumed that the young stands were harvested after 15 years, that a new stand was immediately established naturally and that the stands passed through three rotation periods. The mature stands were assumed to be harvested after 45 years, and the harvested biomass from the logging operations in both the short and long rotation periods was assumed to be used for biofuel. It was also assumed that the same amount of biomass was produced in each rotation of the young stands. However, in practice, the yield may not be the same for each rotation during the three rotation periods. Two further scenarios were therefore created, in one of which the biomass yields in the second and third rotations were 25% higher, while in the other they were 25% lower than in the first rotation. The amount of biofuel that could replace fossil fuel was calculated for all species and rotation periods. The average carbon stock during the studied period was calculated to evaluate the difference in the amount of stored carbon between stands managed with the short and long rotation periods.

## Modelling forest management regimes

### *Changes in rotation length*

In Paper III, two models for simulating the effects of changes in rotation lengths were used. The evaluation was conducted on a regional level and the county of Dalarna, central Sweden, was used as a test area. Data from the National Forest Inventory were used in both models. Carbon accumulation and fossil fuel substitution was modelled with HUGIN (Lundström & Söderberg, 1996) and the build-up of soil carbon was simulated with a semi-empirical model (Ågren & Hyvönen, 2003). HUGIN is a deterministic model with some stochastic components that is intended to simulate forest management scenarios at regional or national levels. Harvesting age is not included in the input parameters in HUGIN since it is one of the outputs. Therefore, the lowest allowable harvesting age was manipulated to simulate changes in rotation length. The model predicted results over the next 100 years, in 10-year periods. The input parameters in the soil model were set according to Ågren & Hyvönen (2003) except for the rotation length, which was changed according to the HUGIN simulations. The soil model only simulates the build-up of new soil carbon. The decomposition of the existing soil carbon stocks was not considered, so the soil carbon accumulation data obtained in the study are solely modelled parameters for the accumulation of newly sequestered carbon under the different rotation scenarios during the forthcoming 100 years.

### *Integrated carbon analysis*

Paper IV describes a broad system analysis of carbon fluxes associated with forest management and product use. The development of biomass of the forest stand and the carbon dynamics of the forest soil were considered. The effects of various forest management practices on fossil carbon emissions, significant non-carbon greenhouse gas emissions and biomass logistics were calculated. In addition, the impact of using wood to substitute fossil fuel and energy-intensive materials was assessed. To analyze the effects of several combinations of forest management regimes and product uses on net carbon emissions, three models were combined. A forest growth model was used to estimate biomass production under various forest management strategies, a forest soil model to estimate carbon accumulation in the soil resulting from litter and slash that remained on site, and a product use model to estimate the carbon fluxes associated with the production of sawn wood and biofuel. The forest growth simulations modelled forests managed with three different strategies: ‘traditional’, ‘intensive’, and ‘fertilization’. These strategies differed in management intensity and rotation length. Furthermore, to analyze the effects of removing slash from the forest sites, three slash management practices were considered; no slash removal, slash removal during logging operations, and removal of both slash and stumps. Two product usages were considered in conjunction with these nine forest and slash management strategies: wood-based construction material replacing concrete, and biofuel replacing fossil fuel. Finally, two reference fossil fuels, coal and natural gas, were used to quantify the effects of fossil fuel substitution. Since the forest growth model only simulated a single rotation period and the rotation lengths of the different forest management regimes differed, the evaluation was conducted when the traditional and intensive regimes had each cycled through three rotation periods, and the fertilization regime had passed through four rotations. The biomass production associated with a given forest management regime was assumed to be the same for all rotation periods.

# Results

## Evaluating field experiments

*Thinning strategies*

In the study reported in Paper I, no significant differences were found between the thinning regimes for Norway spruce stands in terms of MAI (Table 4, Paper I). For Scots pine stands, ‘low thinning + fertilization’ yielded significantly larger MAI in region A and region B than the other regimes, and in region D ‘low thinning + fertilization’ yielded significantly larger MAI than any of the other thinning regimes except ‘low thinning’. Furthermore, ‘low thinning + fertilization’ yielded the largest MAI in region C, but the inter-regime differences were not statistically significant. The ‘unthinned’ regime yielded significantly more standing biomass than the others in both the spruce and pine blocks. ‘Thinning from above’ yielded the lowest simulated standing biomass in pine stands in all regions, but the differences in this respect were only significant for regions C and D. There were no significant differences in annual production of biofuel between ‘thinning from above’, ‘low thinning + fertilization’ and ‘one heavy thinning’ for Norway spruce. For Scots pine, the amount of biofuel generated with the ‘low thinning + fertilization’ regime was significantly larger than with ‘low thinning’ in region A, ‘thinning from above’ in regions A and D, and ‘one heavy thinning’ in regions A, B, and D.

*Broadleaved trees on abandoned farmland*

Among the young stands considered in Paper II, the MAI of above ground biomass was highest in the aspen and grey alder stands and lowest in the downy birch and common alder stands. The MAI of the mature stands showed a different pattern from that of the young stands, since it was highest in the common alder and silver birch stands and lowest in the aspen stands. The effects on net $CO_2$ emissions of replacing coal with biofuel produced from stands of each species in both short and long rotation scenarios were estimated. After three rotation periods, the young stands of aspen, grey alder and silver birch substituted 32% to 112% more carbon than the mature stands of these species (Fig. 3, Paper II). If the MAI was 25% lower in the second and third rotations than in the first rotation, 9% to 77% more carbon could be replaced by growing aspen, grey alder and silver birch with 15-year rotations than with the long rotation period. When the MAI was increased by 25% in the second and third rotations, biofuel from trees grown with the short rotations could replace more carbon than the mature stands for all species. The average carbon stock varied from 32 to 41 t C $ha^{-1}$ for the mature stands and 11 to 21 t C $ha^{-1}$ for the young stands (Fig. 4, Paper II). Aspen stored 52% more carbon in the long rotation than in the short rotation scenarios during the studied period. The corresponding figures for the other species were 75%-227%.

## Modelling forest management regimes

### *Changes in rotation length*

In Paper III, the rotation length was changed by 7% (in 2001-2010) to 23% (in 2091-2100) during the simulated period (Fig. 2, paper III). The growing stock increased by 77 $m^3$ $ha^{-1}$ for the prolonged rotation scenario, 47 $m^3$ $ha^{-1}$ for the base scenario and 24 $m^3$ $ha^{-1}$ for the shortened rotation scenario in 2001–2100 (Fig. 3, paper III). When the rotation length was prolonged, the biomass carbon stock was 13% larger than the base scenario in 2100, but the carbon stock for the shortened rotation period was 50% smaller than the base scenario (Fig. 4, Paper III). At the end of the simulated period, the annual accumulation of carbon declined in the prolonged rotation scenario and the difference between the base scenario and the scenario with a prolonged rotation also decreased. For the prolonged rotation period, the amount of residues capable of substituting fossil fuel increased by 12% during the simulated period (Fig. 6, Paper III). In contrast, the annual accumulation of carbon in biomass decreased during the simulated 100 years in the prolonged rotation scenario. For the shortened rotation, the annual amount of residues that could substitute fossil fuel increased by 150%, while the annual accumulation of carbon in biomass decreased by 95% in 2001–2100. On average, the accumulation of new carbon in forest soil in the prolonged and shortened rotation scenarios were 10% larger and smaller, respectively, than in the base scenario (Table 3, Paper III). Removal of all residues resulted in 5% to 9% lower accumulation of new carbon in soil compared with current removal practices.

### *Integrated carbon analysis*

The volume production in a single rotation was largest in the intensive management scenario. However, when compared during a similar time period, *i.e.* three rotations for the traditional and intensive regimes and four rotations for the fertilization regime, the volume production was largest in the fertilization scenario. The mean carbon stock in biomass was largest in the intensive regime scenario during the simulated period. The management regime that resulted in the largest carbon stock in soil at the end of the period was the fertilization regime, followed by the intensive and traditional regimes (Fig. 3).

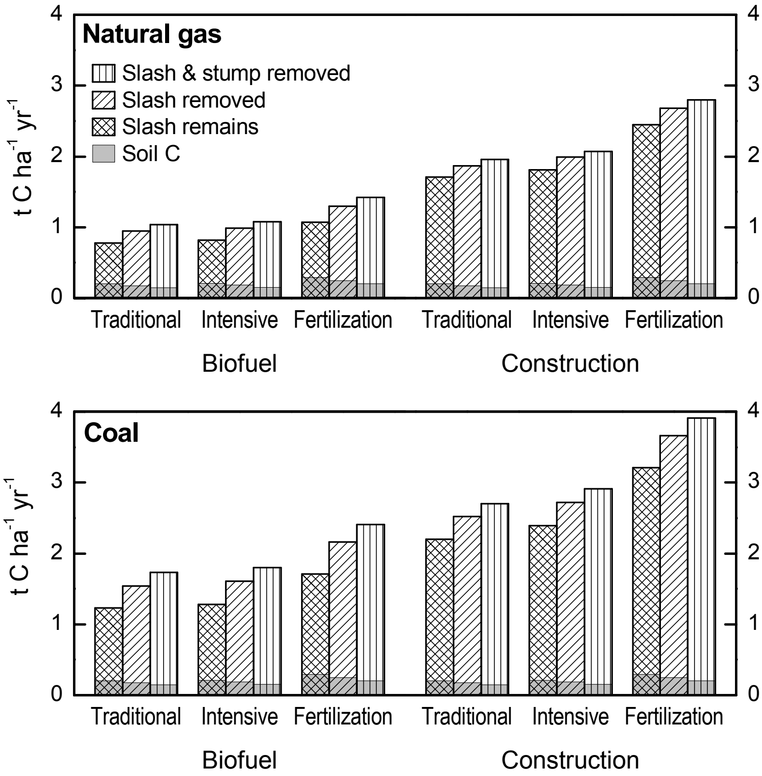


*Figure 3.* Average reduction of atmospheric C due to sequestration into soil C (grey part of bars) and due to product substitution (white part of bars) during the simulated period, as the result of forest management, slash and stump usage, and wood product usage, with natural gas (upper panel) or coal (lower panel) as the reference fossil fuel. (Fig. 2, Paper IV)

The reduction in carbon emissions was greater when biomass was used as construction material rather than directly as biofuel, because the use of energy-intensive concrete was reduced (Fig. 3). The fertilization management regime had a larger impact than other regimes on reducing net carbon emissions, because it resulted in the production of more biomass that could replace other materials and fuels. The reduction in net carbon emissions was higher when the substituted fossil fuel was coal rather than natural gas, since coal emits more carbon dioxide per unit of combustion heat than natural gas (Fig. 3). Removal of slash and stumps after logging operations affected the overall carbon balance by reducing carbon inputs to the soil and by increasing the amount of biofuel used to substitute for fossil fuel (Fig. 3). For the traditional regime, the soil carbon was reduced by 0.05 t C $ha^{-1}$

year$^{-1}$, while the fossil fuel substitution effect was increased by 0.50 t C ha$^{-1}$ year$^{-1}$, when coal was replaced.

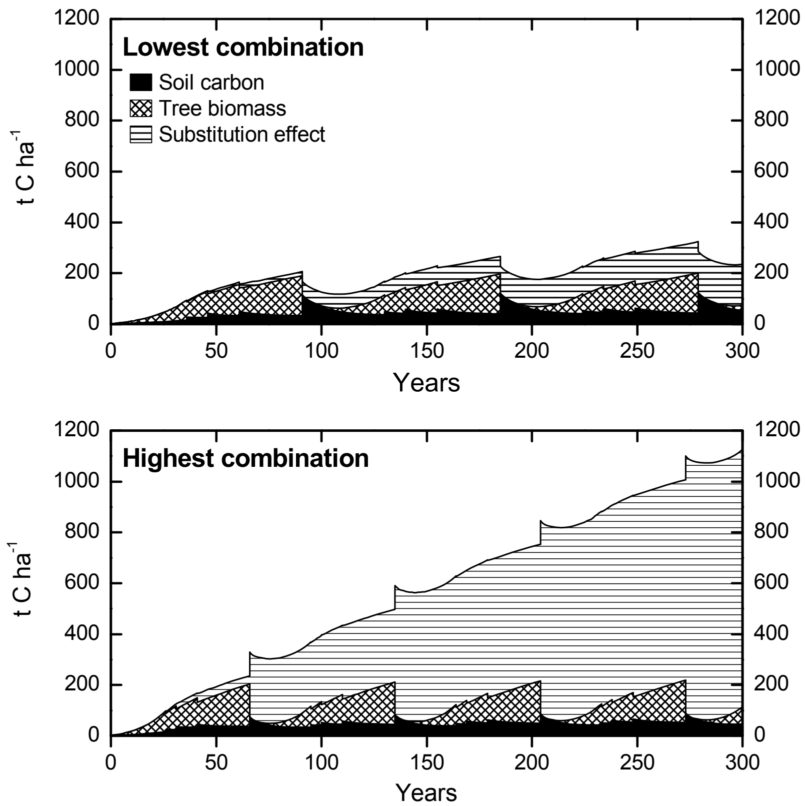


*Figure 4.* Development over time of the soil carbon stock, carbon stock in living tree biomass, and accumulated reductions in carbon emissions due to product substitution for the combinations of parameters giving the lowest and highest reductions in net carbon emissions. (Fig. 3, Paper IV)

The combination of the traditional forest management regime, in which slash and stumps are retained on site, using wood for biofuel, and natural gas as the substituted fossil fuel, gave the lowest reduction in net carbon emissions. The accumulated substitution effect amounted to 162 t C ha$^{-1}$ during the studied period, which was similar to the amount of carbon in the biomass at the time of clear-cutting (Fig. 4). The combination of parameters giving the highest reduction in net carbon emissions was the fertilization regime with removal of slash and stumps, using wood for construction material, and coal as the replaced fossil fuel. The accumulated substitution effect in this scenario amounted to 1 010 t C ha$^{-1}$ (Fig. 4). The larger substitution effect was due to the use of the harvested biomass as construction material instead of biofuel, the higher carbon intensity of coal, the greater volume of roundwood produced by the extra rotation, and the removal of slash and stumps for use as biofuel.

# Discussion

In order to evaluate forestry's potential to reduce net $CO_2$ emissions under different management regimes; four studies were performed. In Paper I, the impact of different thinning regimes was analyzed. In Papers II and III, the effects of applying different rotation periods to conifer and broadleaved stands were measured and simulated. Finally, in Paper IV, an integrated analysis of forestry's potential to decrease net carbon emissions was conducted.

## Biomass production under different thinning strategies

In Paper I, the unthinned regime gave the largest standing biomass for both spruce and pine stands and, therefore, the largest carbon stock. This is consistent with a number of previous reports. For instance, Cooper (1983), Thornley & Cannell (2000), Maclaren (2000), and Kirschbaum (2003), reported that unmanaged forests could store more carbon than managed counterparts. Sievänen *et al.* (2002) showed that the carbon stock in biomass and soil is affected by thinning operations, and the intensity of the thinning is especially important since increasing the thinning intensity of the stem volume reduces the carbon stocks. This suggests that if the ultimate objective is to maximize the carbon stock in forests, thinning operations should cease. Maclaren (2000) argued that there is a conflict between maximizing carbon storage and maximizing biomass production, while Kirschbaum (2003) argued that it is not possible to manage the forest in such a way that both carbon storage and production of biofuel to substitute fossil fuel will be maximised. A strategy with no thinning, which would maximize the carbon stock, would not be ideal from an economic perspective. It would also have an adverse effect on forest owners' profits since revenues from thinning operations are considerable (Anon. 2005b). Furthermore, there would be no wood from thinning operations transported to the pulp industry and the wood supply to the sawmill industry may decrease if forests are not thinned. In contrast, from an ecological perspective, unthinned forests could be desirable since they may have a greater variety of species than thinned counterparts (Jansson & Källming, 2002).

For Norway spruce stands, there were no significant differences in growth between the thinning regimes. Other studies have also found minor differences in volume growth between thinning regimes (Hynynen & Kukkola, 1989; Mielikäinen & Valkonen, 1991; Eriksson & Karlsson, 1997). Fertilization did not have a positive effect on the Norway spruce subplots, possibly because the Norway spruce blocks in this study had a high site index ($H_{100}$ = 33 m) and fertilization with nitrogen in spruce stands with a large site index might have little or no effect (Rosvall, 1980). For Scots pine, the fertilization treatment yielded larger MAI values than the other treatments, but there was no significance in region C. A single heavy thinning yielded the lowest MAI values in pine stands, but the between-treatment differences were not significant. This indicates, however, that removing more than 60% of the basal area at the first thinning could adversely affect MAI. Valinger (1993) concluded that unthinned, unfertilized Scots pine blocks did not significantly differ from thinned, fertilized blocks in terms of MAI, which conflicts with the results for regions A, B and D reported in Paper I. However, Valinger (1993) also found a significant difference between thinned, fertilized blocks and thinned, unfertilized blocks, in accordance with the results in Paper I.

Maclaren (2000) claimed that maximizing forest production would maximize the production of biofuel and Schlamadinger & Marland (1996) suggested that when growth rates are high, the replacement of fossil fuel with biomass could be a positive long-term measure. In Paper I, a high MAI resulted in a large quantity of residues that could be used for biofuel. There were small differences between the active thinning regimes ('low thinning', 'thinning from above', and 'low thinning + fertilization') for spruce stands, indicating that the thinning strategy may not be an important determinant of the amount of energy that residues from thinning operations could yield. Furthermore, Sievänen *et al.* (2002) showed that the thinning method also has a minor impact on carbon stocks. Not thinning the forest would, however, reduce the potential to use harvest residues for energy from forest operations. Today, it would be relatively costly to remove residues from thinnings, implying that there is a need to further develop techniques to harvest residues cost-effectively. In terms of carbon management, there are several negative effects of not thinning forests. Firstly, a strategy that aims to maximize the carbon stock addresses symptoms of the problems caused by the combustion of fossil fuels, rather than tackling the cause of the problems. Furthermore, forest fires, insects or fungi could easily destroy the carbon stock. Finally, maximizing carbon storage would have an adverse impact on the amount of biofuel and wood products that would be available to replace fossil fuel and energy-intensive materials.

## The impact of different rotation lengths

The effects of rotation lengths on various forest parameters have been studied for many years. Faustmann (1849, 1995) constructed a model more than 150 years ago, which is still used in forestry research. Since then, numerous studies have focused on interactions between rotation lengths and interest rates (*e.g.* Ohlin, 1921, 1995; Näslund, 1969) or the optimal age for timber production, but during the past 20 years, there has also been interest in objectives other than optimizing economic value, such as promoting biodiversity and carbon storage (*e.g.* Cooper, 1983; Lämås *et al.* 1996; Backéus *et al.* 2005). Studies seeking to determine optimal rotation lengths for reducing net $CO_2$ emissions have been conducted by (*inter alia*) Liski *et al.* (2001), Bjørnstad & Skonhoft (2002), Harmon & Marks (2002), and Kaipainen *et al.* (2004).

Afforestation on abandoned farmland could make a significant contribution to carbon stocks in the terrestrial system and increase the amount of biofuel that could replace fossil fuel. In the study reported in Paper II, broadleaved trees growing on abandoned farmland were studied to evaluate whether management regimes with short (15-year) or long (45-year) rotations would be preferable for maximizing biomass production and reductions in atmospheric $CO_2$ levels. To maximize the average carbon stock the rotation period should be long, since the carbon stock was larger with long rotations for all species (Fig. 4, Paper II). These results are consistent with reports by Alban & Perala (1992), Maclaren (2000), and Kaipainen *et al.* (2004). On the other hand, if the objective is to maximize the substitution of fossil fuel, and thus reductions in $CO_2$ emissions, a short rotation period should be applied for aspen, grey alder and silver birch stands, since more coal could then be replaced by biofuel than if long rotations were used for these species (Fig. 3, Paper II). Since the MAI values for young stands of downy birch and common alder were low, more coal could be replaced if their management regimes included 45-year rotations rather than 15-year rotations.

The magnitude of MAI is an important factor to consider when deciding which rotation length should be used. When the difference in MAI was low between the young and mature stands addressed in Paper II, the potential for replacing fossil fuel was similar for the two rotation scenarios. The average carbon stock, on the other hand, was larger for the 45-year rotation scenario. Therefore, for broadleaved species, management regimes with short rotations should be applied to stands on rich soils to promote high MAI, and thus high potential to substitute fossil fuel. If the yield of young stands is low (*i.e.* $< 4$ t d.w. $ha^{-1}$), the rotation period should be long, since small amounts of biomass will be produced. Low MAI will result in low average carbon stock in the biomass if the rotation period is short. The carbon stock in the soil was not measured in this study, but harvesting and rotation length could affect the carbon stock in the soil. Paul *et al.* (2002) reported that there is an initial decrease in soil carbon stocks after afforestation, but after about 30 years, the soil carbon stock is often greater than in the previous agricultural soil. However, the rotation length and the amount of biomass removed from the stand could affect the soil carbon stock following afforestation (Paul *et al.* 2002). The choice of tree species to use could also affect soil carbon stocks, but Hagen-Thorn *et al.* (2004) found no significant differences among soil carbon stocks between stands of different species established on former agricultural land.

In Paper III, the impact of different rotation lengths at a regional level was studied. The model used in the paper aimed to maximise the sustainable harvesting level. This resulted in the cutting levels differing among the scenarios, which was one reason for the variations in accumulation of carbon and the amount of available residues among them. Aiming for the highest sustainable cutting level resulted in the highest sustainable level of residues in each scenario. Furthermore, the results were presented at a regional level, providing indications of the way the accumulation in biomass and the amounts of residues would develop in a large number of stands. A prolonged rotation resulted in a larger carbon stock in the biomass at the end of the studied period. This is consistent with findings published by Liski *et al.* (2001) and Kaipainen *et al.* (2004), but their studies were conducted at stand level. The shortened rotation scenario in Paper III only resulted in a small increase in the carbon stock during 2031-2100. The annual accumulation in biomass decreased with time in all scenarios, in accordance with previous predictions (Anon. 2000; Karjalainen *et al.* 2002). Rotations should be shortened to maximize the substitution of fossil fuel since more harvest residues were available in the shortened scenario compared with both the base scenario and the prolonged scenario. Kaipainen *et al.* (2004) also showed that a shorter rotation results in larger amounts of harvest residues. The prolonged rotation in Paper III resulted in a larger accumulation of carbon in soil. However, Liski *et al.* (2001) reported the opposite, finding that when the rotation length is shortened, the soil carbon stock increases. There are several differences between the studies that may explain the conflicting results. In the study described in Paper III only the build-up of new carbon was simulated, which resulted in the respiration of the existing carbon stock not being considered. Furthermore, the study was conducted at a landscape level, using data from the National Forest Inventory. It should be noted that Kaipainen *et al.* (2004) showed that the soil carbon stock increased with longer rotations for stands of spruce species, but the results were conflicting for pine species.

The shorter rotation length resulted in a larger amount of residues due to the increased frequency of final fellings. Increasing the frequency of fellings could affect the soil carbon stock, but according to Johnson & Curtis (2001), forest harvesting has little or no effect on soil carbon stocks. There were relatively small changes in the accumulation of new soil carbon when the needles were left on-site compared with when they were removed, as also previously reported (*e.g.* by Bengtsson & Wikström, 1993; Ågren & Hyvönen, 2003). Leaving the needles on-site has a negligible effect on the soil carbon stock because the removed needles only represent a small proportion of the total amount of residues produced during the course of a rotation (Ågren & Hyvönen, 2003). However, to minimize nutrient losses and reduction in biomass accumulation, the needles should ideally be left on-site (Egnell *et al.* 1998).

## Management regimes and product uses

Three separate models of forest growth, soil carbon accumulation, and wood product usage were combined in Paper IV to evaluate the different carbon stocks and the interactions between the stocks under various forest management regimes and product uses. The fertilized regime produced more biomass than the traditional and intensive regimes during the simulated period, suggesting that the forest stands should be fertilized and managed with a short rotation length to maximize the amount of biomass. Fertilization resulted in a larger standing volume at the time of harvest compared with the other management regimes, but a large standing biomass persisted longer in the intensive regime (from 60-90 years of age in each rotation), which resulted in a larger mean carbon stock. This suggests that the fertilization regime may not be the best option to maximize the carbon stock in standing biomass. Fertilization also gave the largest soil carbon stock at the end of the studied period. This was due to larger biomass production, which resulted in larger litter inputs to the soil. There are reports indicating that fertilization not only results in larger biomass production, but also retards the decomposition of organic matter in soil and thereby increases the soil carbon stock (Olsson *et al.* 2005).

Using forest products as construction materials resulted in larger reductions in $CO_2$ emissions than when biomass was only used as fuel. This is because wood products replaced other energy-intensive building materials as well as fossil fuel when the material was burned at the end of its life cycle. The alternative of not managing the forest and using the forest products becomes less attractive as the time horizon increases (Schlamadinger *et al.* 1997), since the carbon sink in the forest biomass and soil is either limited or increases at lower rates (Fig. 4). This indicates that an intensively managed forest has the largest potential to reduce net $CO_2$ emissions if the biomass is used to replace fossil fuel and energy-intensive materials. However, it should be noted that removal of harvest residues could decrease the carbon stock in soil. Palosuo *et al.* (2001) estimated that 80-90% of the emissions of greenhouse gases could be avoided if logging residues substituted fossil fuel, but the reduction in the soil carbon stock reduces the avoided emissions by about 10%, which is consistent with the results reported in Paper IV (Fig. 3).

It should be noted that some of the product uses and management regimes considered in Paper IV were extreme. The study was based on data comparing two multi-storey apartment buildings, one constructed with a wood frame and the other with a concrete frame. However, multi-family apartment buildings are usually made with concrete frames in Sweden. This suggests that in the short-term perspective, it is not very likely that a large amount of multi-storey apartments will be built with wood frames. However, it also reveals that there is large potential to reduce $CO_2$ emissions in the Swedish housing sector. The fertilization regime gave the largest reduction of $CO_2$ emissions, since larger amounts of biomass were produced. In practice, however, fertilization is rare since less than 0.1% of the forested area in Sweden is fertilized each year (Anon. 2005b). Furthermore, fertilizer is often applied only once or twice per rotation, when it is applied at all. The fertilization regime considered in Paper IV was intensive, with 12 applications of fertilizer during each rotation. In a landscape perspective, the impact of fertilization would probably be weaker than that indicated in the paper since forest land may have to be excluded from timber and pulp wood production to compensate for the intensively managed stands. Finally, large-scale fertilization of a forest stand might affect wood properties, which could result in that the reduction in $CO_2$ emissions due to intensive fertilization might not be this large.

## Revenues from stored carbon

If there were revenues for storing carbon in biomass, the land owner could choose to manage the forest for carbon sequestration. Backéus *et al.* (2005) studied the likely impact of introducing payments for storing carbon on forest harvestings, while van Kooten *et al.* (1995) and Bjørnstad & Skonhoft (2002) assessed the likely effects on the rotation length. The effects of introducing payments for storing carbon for Papers I-III are considered below.

### *Rotation length*

A prolonged rotation period, as described in Paper III, resulted in the net present value (NPV) for wood yield decreasing by 255 € $ha^{-1}$ compared with the base scenario (Table 1), using the revenues and costs for forest operations presented by Anon. (2005b) and Brunberg (2005). The biomass carbon stock for the prolonged rotation was 3 t C $ha^{-1}$ larger than in the base scenario after 100 years, while the biomass carbon stock for the shortened rotation was 11 t C $ha^{-1}$ lower than in the base scenario. Assuming payments for storing carbon of 16 € t $CO_2^{-1}$ (the trading price for $CO_2$ emissions in the EU in June 2006 (EEX, 2006)), the NPV for storing carbon in biomass was 65 € $ha^{-1}$ higher for the prolonged rotation scenario than for the base scenario (Table 1). This suggests that extending the rotation length for conifers on forest land would decrease the revenues from wood yield. Introducing carbon storage payments in forestry could counteract this decrease, but they would have to be higher than 16 € t $CO_2^{-1}$.

*Table 1.* Differences in net present values for wood yield and carbon storage for different rotation lengths compared with the base scenario in Paper III.

| Management regime | Difference in net present value (€ $ha^{-1}$) | |
|---|---|---|
| | Wood yield | Carbon storage |
| Prolonged rotation period | -255 | 65 |
| Shortened rotation period | 298 | -238 |

Assigning a monetary value to carbon storage affects both carbon sequestration and harvesting levels. Thus, increasing payments for storing carbon in forests are likely to increase rotation lengths. According to Backéus *et al.* (2005), no harvestings will be conducted when carbon storage payments of 29 € t $CO_2^{-1}$ are applied. It should be noted that Backéus *et al.* (2005) used a forest product approach and included transportation costs for roundwood to industrial sites and the cost of $CO_2$ emissions from products. In the studies underlying this thesis, the NPV was calculated from a forest owner perspective and the revenues from storing carbon were based on differences in carbon stocks. Several other studies have found that the rotation length would increase following implementation of carbon storage payments. Van Kooten *et al.* (1995) reported that for the most likely values of carbon prices, timber prices, and lifetime of wood products would increase the rotation length by about 20% and Bjørnstad & Skonhoft (2002) demonstrated that accounting for carbon storage increases the economically optimal rotation length, while accounting for the forest as a source of bioenergy decreases the rotation length.

In Paper II, aspen stands were found to store 11 t $ha^{-1}$ more carbon in 45-year rotations than in 15-year rotations, resulting in the NPV for storing carbon being 410 € $ha^{-1}$ higher for the 45-year rotations using a carbon storage price of 16 € t $CO_2^{-1}$ (EEX, 2006). If the forest owner received 6.4 € t $d.w.^{-1}$ for using the aspen biomass as biofuel, the revenues from biofuel were 560 € $ha^{-1}$ higher for the 15-year rotations compared with the 45-year rotations. This indicates that the shorter rotations were a better option than the longer rotations with the assumed prices for carbon storage and biofuel, probably because the land owner's revenues for storing carbon were relatively low. The carbon storage price in this study was based on the trading price of $CO_2$ emissions in the EU and the price has decreased since January 2006, possibly because the governments within the trading system have been fairly generous when distributing emission allowances. An increased difference in carbon stocks between the rotation periods and a higher price for storing carbon would increase the financial advantages of the 45-year rotation period. On the other hand, revenues from biofuel are still fairly low for the forest owner and could be expected to increase with increases in demand for biomass from the forest. This would require even higher payments for carbon storage.

*Thinning regimes*

The following results were obtained when a similar approach was applied to the spruce stands considered in Paper I. After four thinning operations, the carbon stock for the unthinned regime was on average 38 t C $ha^{-1}$ higher than for the 'low thinning' regime. Using a carbon price of 16 € t $CO_2^{-1}$ (EEX, 2006) resulted in the NPV for carbon storage being 1 300 € $ha^{-1}$ higher for the unthinned regime compared with the 'low thinning' regime. However, the revenues from the thinning operations should be included in the comparison. The NPV for wood yield was 1 750 € $ha^{-1}$ larger for the 'low thinning' regime than for the unthinned regime. This suggests that after four thinning operations for spruce, the thinned regime would have a higher total NPV than the unthinned regime. Adding the revenues from a possible fifth thinning and the revenues from the final fellings for both regimes would make the difference even larger. However, if the payment for storing carbon was twice as high (*i.e.* 32 € t $CO_2^{-1}$), the unthinned regime could be a more profitable alternative. It should be noted that not thinning the forest would prevent residues from thinning operations being used for replacing fossil fuel. Furthermore, pulp wood from thinning operations is an important raw material for the pulp industry.

## How should the forest be managed?

The forest has many important roles to play since it: produces biomass that can be used for timber, pulp and biofuel; is an important habitat for many species; is used by many people for recreational purposes; and provides employment. These roles sometimes conflict, and the forest should therefore be managed in a sustainable way to fulfil as many objectives as possible. The forest can also contribute to reductions in atmospheric $CO_2$ levels, which are considered to affect the climate. Implementation of forest management strategies to reduce $CO_2$ emissions would have an impact on the other roles of forestry, since maximizing carbon storage in the forest may favour biodiversity and some social activities (*e.g.* recreation), but would have a negative influence on timber and pulp wood production. In contrast, maximizing the substitution effect could favour timber production, but may have a negative impact on biodiversity.

There is a conflict between maximizing carbon storage and substitution of fossil fuel since storing carbon requires large standing biomass while replacement of fossil fuel requires high growth rates. In a long-term perspective substitution of fossil fuel might be the best option since the biomass could replace large amounts of fossil fuel each year. Furthermore, the carbon stock in biomass is vulnerable since it could be destroyed. However, storing carbon in biomass is important to some extent since global deforestation is considered to have been responsible for a quarter of the anthropogenic emissions of $CO_2$ in the past 20 years (IPCC, 2001). In the studies underlying this thesis, it was found that a shorter rotation period is favourable if the objective is to maximize replacement of fossil fuel (Paper III). However, Liski *et al.* (2001) reported that long rotations seem to be preferable, even if the revenues for forest owners decline, since they result in the largest reductions in net emissions of fossil $CO_2$ and use of primary energy. In Paper IV, more intensive management (*e.g.* fertilization and shorter rotations) was found to be preferable since it resulted in large substitution of fossil fuel. These findings indicate that the best option for reducing atmospheric $CO_2$ levels depends on the main objectives (*e.g.* maximising carbon stocks or substituting fossil fuel) and the parameters that are measured (carbon stocks, carbon sequestration, substitution effect, revenues, emissions of $CO_2$, *etc.*). If the objective is to promote large carbon stocks, the forest should not be thinned (Paper I) and the rotations should be long (Papers II and III), but if the objective is to maximize the substitution potential, the forests should be managed more intensively than they are today. The analysis in Paper III showed that shorter rotations should generate more residues that could substitute fossil fuel, since there are more final fellings in a given period, while in the analyses in Papers I and IV fertilization resulted in larger biomass production and thus greater potential to replace fossil fuel.

According to the results presented in Paper IV, wood products have greater potential to reduce atmospheric $CO_2$ levels than biofuel, since the material that wood can replace requires a large amount of fossil energy to produce. Furthermore, replacement of energy-intensive material seems to have higher potential to reduce $CO_2$ emissions than sequestration of carbon in biomass and soil. These findings indicate that active forest management has the largest potential to reduce $CO_2$ emissions and that managing the forest for carbon sequestration has the lowest potential, especially when the forests have reached steady-state and only act as a carbon store. Then, the carbon stock is vulnerable since fire, insects, fungi, *etc.* could release the stored carbon. Intensive management practices, like shorter rotations (Papers III and IV) and fertilization (Papers I and IV) resulted in higher production rates of biomass that could replace other materials and fossil fuels. Furthermore, from a landowner's perspective coniferous forests should be managed with shorter rotations to maximize the NPV. The prolonged rotation scenario gave the lowest NPV using the present price for carbon emissions. This suggests that implementing current EU trading prices for $CO_2$ for storing carbon will not result in extended rotation lengths or unmanaged forests, but if the price for carbon storage was increased, the prolonged rotation could be a better option for the forest owner.

However, intensive forest management may not be fully compatible with the official Swedish environmental objective of developing 'sustainable forestry', including aims to increase amounts of protected land, old-growth forest, broadleaved trees, and dead trees (Anon. 2004). Thus, there could be a conflict between economic objectives (timber and pulp production) and ecological objectives. There could also be conflict between the two environmental objectives;

developing ‘sustainable forestry’ and ‘reduced climate impact’ (including aims to reduce the climatic effect of human activities). The main aim in the latter is to decrease emissions of $CO_2$ from fossil fuel, without accounting for the carbon stocks in the forests (Anon. 2003). The climatic impact could be reduced by using more biomass to replace fossil fuel and energy-intensive materials, but such a management strategy may not be compatible with the sustainable forestry objectives. Increasing the amount of broadleaved trees may be compatible with reducing the climatic impact since it has been reported that mixed stands could produce considerable amounts of biomass (Mielikäinen, 1985; Klang & Ekö, 1999). However, increasing the amount of protected land could have a major impact on the potential to use wood to reduce the climatic impact since large amounts of biomass could not then be used to replace fossil fuel and energy-intensive material. To maximize forestry’s potential to reduce emissions of $CO_2$, more intensive management (*e.g.* fertilization) could be required, but increased fertilization could result in a need to protect larger amounts of land areas from timber and pulp wood production to compensate for the intensive management. This could lead to major spatial variations in the nature of the forests and the forestry objectives being pursued; forests in some areas being intensively managed while forests in other areas are protected from timber and pulp wood production. Such an outcome would be far removed from that promoted in current Swedish environmental policy, which stipulates that environmental considerations shall be applied to all forested land. Finally, there could also be conflicts between timber and pulp wood production and the climate objectives if large amounts of biomass (*e.g.* stem wood from thinning operations) are used to replace fossil fuel instead of using it for wood products.

## Future research

In the studies this thesis is based upon the impact of the forest management strategies considered on soil organic carbon contents was only addressed in Papers III-IV, and even then the development of the soil carbon was only simulated. There were no studies of this parameter based on field data. Furthermore, removal of logging residues or stumps affects the soil carbon stocks and intensified harvesting of biomass, which might be necessary to increase the replacement of fossil fuel, could have an adverse impact on soil carbon stocks. Therefore, to fully understand forestry’s potential to reduce $CO_2$ emissions, the effect of different management practices on soil stocks has to be further studied.

There is also a need to evaluate the effects of other management practices. The studies underlying this thesis focused on thinning regimes, fertilization, rotation length, and the removal of logging residues. Further variables and practices that could warrant attention include tree species (both individual tree species and mixtures of species), ditching, and scarification. Furthermore, pre-commercial thinning could also be an important factor. Biomass from pre-commercial thinning could be used for energy, but removing the material could affect the soil carbon stock and is very costly. It would also be interesting (indeed, essential for a comprehensive audit) to investigate the potential use of stumps and coarse roots to reduce $CO_2$ emissions. There was some research on potential uses of stumps in the

1970's and 1980's in Sweden, but the interest subsequently waned. However, increases in energy prices and the greenhouse gas debate have revived interest in using stumps for biofuel. In Finland, stumps have been developed as a new type of fuel during the past five years. However, the removed amount of stumps was not even 10% of the total amount of forest chips in 2004, but the future potential is large (Leinonen *et al.* 2005). The management regimes in this thesis were studied under the current climate and $CO_2$ concentrations. Future studies should also consider the impact of climatic changes.

In Paper IV, management strategies were evaluated using a broad system analysis, which included tree biomass, forest soils, and product uses. To fully understand the potential for different strategies to reduce carbon emissions it is necessary to perform a holistic, system-wide analysis. Such analyses require a lot of data collection and explicit system boundaries since analyses of carbon fluxes and stocks are complex, but further studies using a holistic perspective would be highly valuable. As discussed previously, intensifying forest management could increase the potential to reduce $CO_2$ emissions, but such a strategy could conflict with environmental quality objectives (Anon. 2004) and it is important to study forestry's potential to mitigate the adverse effects of greenhouse gases without compromising environmental considerations. Finally, harvesting wood for energy use could affect supplies for the timber and pulp industries. This potential conflict should be evaluated. Further economic analyses are also needed to fully assess the consequences of different management strategies.

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