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Preface

This report is the result of a common effort of several research institutes and university departments: Department of Forest Resource Management, SLU (Ljusk Ola Eriksson), Department of Engineering and Sustainable Development, Mid Sweden University (Leif Gustavsson, Roger Sathre), METLA (Riitta Hänninen, Maarit Kallio, Johanna Pohjola), Department of Forest Economics, University of Helsinki (Henna Lyhykäinen, Lauri Valsta), VTT Technical Research Centre of Finland (Kim Pingoud), Department of Ecology and Natural Resource, UMB (Birger Solberg), and Norsk Treteknisk Institutt (Jarle Svanaes). The work is characterized by a high degree of integration, meaning that everyone has to some extent been involved in most parts. Yet, the following chapters have to a higher degree been prepared by specialists according to the following:

- Ch. 4: Leif Gustavsson, Riitta Hänninen, Kim Pingoud, Roger Sathre, Jarle Svanaes
- Ch. 5: Maarit Kallio, Birger Solberg
- Ch. 6: Ljusk Ola Eriksson
- Ch. 7: Henna Lyhykäinen, Johanna Pohjola, Lauri Valsta

For other parts, Johanna Pohjola had a special responsibility for preparing Ch. 1, 2 and 3. Ljusk Ola Eriksson acted as editor. The research was financed by SNS, Samnordisk Skogforskning, and the involved organizations.

Contents

Summary

There is a growing interest in efficient ways to use biomass for the substitution of fossil fuels and non-biomass materials. Wood-based building material can affect the energy and carbon balances through at least four mechanisms: the relatively low fossil energy needed to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions; the increased availability of biofuels from biomass byproducts that can be used to replace fossil fuels; and the physical storage of carbon in wood building materials. Increased use of wood-based building materials will likely affect relative prices on timber markets. That translates into changed forest management, which in turn affects forest growth, biofuel availability and mitigation through carbon storage in the forest.

A more comprehensive analysis of the climate effects of increased wood in the construction sector would be made possible by integrating a range of models. These include models of wood substitution, sector product markets, and forest management models on regional and stand levels. Several partial studies have been conducted in this field. Still, a modeling framework that extends all the way from the construction sector over international markets down to the individual forest stand has not been employed.

The purpose of this study is twofold. One is the analysis of climatic implications of increased wood use in building construction. For this purpose, a new integrated modeling framework is developed (see Figure 1). This framework is then used for the analysis of four different wood construction scenarios. The other objective of the current pilot project is to demonstrate the viability of the proposed modeling approach and the improvements needed. Thus, it constitutes a preparation for more comprehensive future studies.

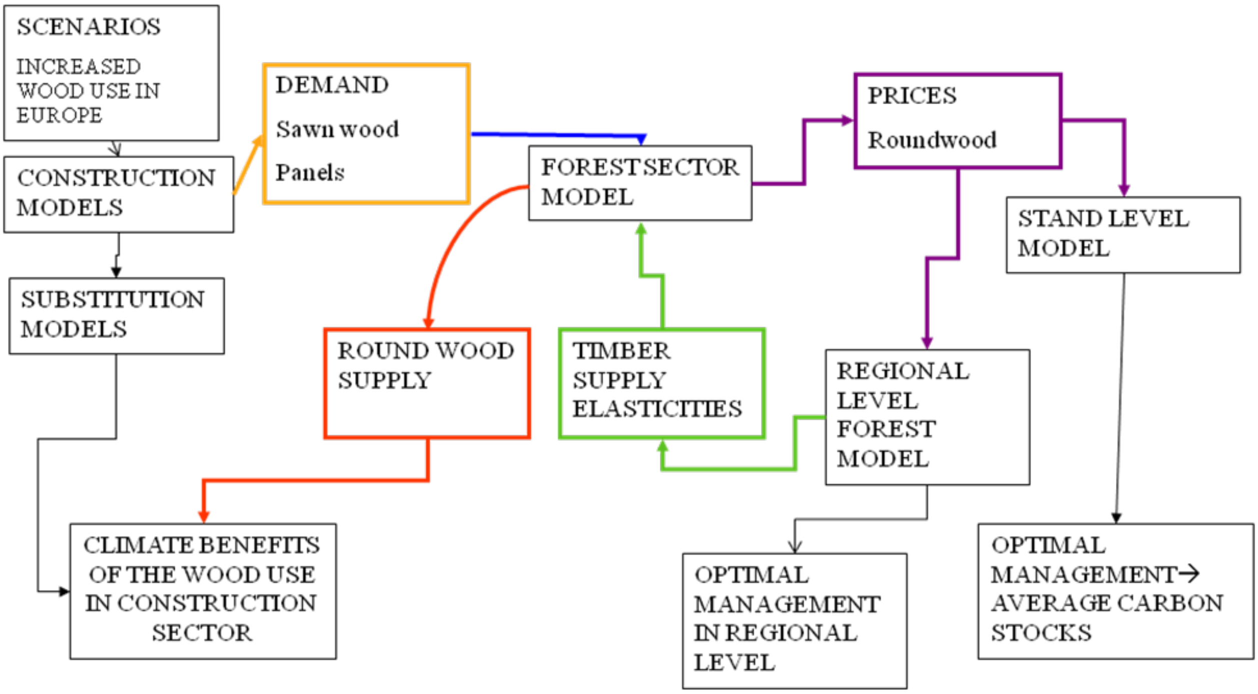

Figure 1. The information flow between models.

The four wood construction scenarios depict wood consumption up to the year 2030 for the European construction sector. They are characterized as follows:

- Base: "Business-as-usual" corresponding to a growth rate of total European softwood sawn wood consumption estimated at 1.48% annually up to 2030. (The results of the other scenarios are measured against the Base scenario.)
- Sweden: Wood is used instead of conventional concrete construction for building apartment blocks in Europe, gradually increasing to 1 million flats per year by 2030. The construction data are from a case study of a building constructed in Växjö, Sweden.
- Finland: The same as case Sweden, but using construction data from a case study of a building in Helsinki, Finland.
- 1m3cap: Consumption of sawn wood in all European countries will reach 1.0 m^3 per capita by 2030 (from the current average of 0.2 m^3 per capita), corresponding to a European growth rate of 7% per year. This is a rather extreme and probably unrealistic scenario.

Table 1 summarizes the effects at year 2030, i.e. the last year of the projection period. The emission reduction figures are based on computations for all materials composing the buildings. The emission balance takes account of (i) fossil fuel combustion for material processing and logistics, (ii) reduction of emissions due to replacing fossil fuel with biomass residues from harvest, processing and demolition, (iii) avoided emissions from cement process reactions, and (iv) carbon stock change in wood materials. The marginal energy is assumed to be coal. It should be noted that the impact on carbon stocks in the forests is not included in the emission balance; this effect is assessed by the forest models (see below).

Table 1. Emission reduction and roundwood demand compared to scenario *Base* by 2030

Scenario	Emissions reduction (Mt C/year)	Roundwood demand (Mm^3/yr)
Sweden	4.2	9.7
Finland	9.7	23.8
1m3cap	200.0	600.0

The roundwood demand in each year of the projection period was distributed among supplying countries by the EFI-GTM model. The EFI-GTM is a partial equilibrium model for the forest sector, i.e. it encompasses forestry, wood using industries, markets for round wood and forest industry products, and solves the market clearing problem by consumers' and producers' surplus maximization. The global market consists here of 55 regions, where almost all the European countries are represented by their own regions. The model contains markets for 34 forest sector commodities (25 forest industry products, five types of roundwood and chips, and four types of waste paper). For each region, supply functions for production factors are defined, as well as a set of fixed-input technologies with specific capacities for producing intermediate and final products. The forest supply is represented by supply elasticities for timber and pulpwood. The Swedish roundwood supply is described with an elasticity of 0.5 for both timber and pulpwood, based on runs with the Swedish regional forest model in this study.

The model predicts that competition over the wood fibre increases in the future, and the prices of both pulpwood and saw logs rose in the *Base* case. Also, the Russian timber export tariff increases the prices in Scandinavia. In the *Base* case, the prices for softwood saw logs are projected to be 30% higher, and pulpwood prices 54% higher, in 2030 than in 2004. Note, however, that these increases can be considered a high estimate, since, for technical reasons, we chose to accept a higher rate of forest industry capacity accumulation than what we would have chosen in some other analyses.

Table 2 shows the changes in Swedish harvest volumes and price changes in the scenarios *Finland*, *Sweden* and *1m3cap*, compared to the *Base* case, in year 2030. The scenario *Sweden* had the lowest market impacts, with the softwood saw log price being about 3% up from the *Base* case level in 2030. In scenario *1m3cap*, the saw log price more than doubled from the *Base* case due to the drastically increased softwood lumber demand. The growth in softwood lumber production made saw log chips supply abundant and led to a decline in the pulpwood harvests and price. In scenario *1m3cap*, softwood pulpwood price came down by close to 20% compared to the *Base*. Due to the substitution effect in panel production, the hardwood pulpwood price also fell.

Table 2. Changes in Swedish round wood harvests and prices in relation to the *Base* scenario in year 2030

	Harvest						Prices		
	Mill. m3 under bark			%			%		
	Finland	*Sweden*	*1m3cap*	*Finland*	*Sweden*	*1m3cap*	*Finland*	*Sweden*	*1m3cap*
Softwood saw logs	0.9	0.5	14.2	2	1	35	5.2	2.7	110
Hardwood saw logs	0	0	0	0	0	1	0.2	0.1	0.6
Softwood pulpwood	-0.1	0	-4.8	0	0	-16	0.3	0.3	-19
Hardwood pulpwood	0	0.1	-0.2	0	0	-4	0.2	0.2	-9

Either harvest volumes or timber prices for Sweden could then be transferred from the EFI-GTM to the Swedish forest regional model. In this analysis prices were put in the forest regional model and the ensuing result studied. For the forest regional model for Sweden, the SMAC model was used. The model is an area matrix model where harvests are derived by assuming that forest owners maximize their net present value over an infinite horizon with current prices (i.e. they assume constant prices; solution procedure is value iteration on the Markov model). Since the SMAC model operates with 5-year growth periods, prices from EFI-GTM were averaged over 5-year periods.

Comparisons between EFI-GTM and SMAC of harvest volumes were only conducted for *Base* and *1m3cap* since price figures for scenarios *Sweden* and *Finland* are almost identical with the *Base* scenario. The saw log volumes of the two models are fairly similar for each of the scenarios over the first 10 years. However, for scenario *1m3cap* during the rest of the period, where the EFI-GTM projects a substantial increase, the SMAC model presents a reduced harvest of saw logs despite a rather dramatic increase in saw log price. The reason for this reduction is essentially that it is profitable, with relatively more profitability in final felling compared with thinning, to postpone final harvests and increase both the relative and absolute yield of timber in the future. In the long run, after some 60 years, saw log supply became larger for *1m3cap* than *Base* in the SMAC model projection.

More detailed analyses of the management implications of the EFI-GTM price series were performed with a stand model, the Stand Management Assistant (SMA). SMA is an individual-tree, distance-independent growth and mortality model that finds optimal steady state stand management programs (planting density, timing and form of thinning and time of final harvest) by solving a non-linear, non-differentiable optimization problem with the Hooke and Jeeves method.

The differences between scenarios *Base* and *1m3cap* were studied for a range of stand types. In most cases the model predicted for *1m3cap*: prolongation of the rotation period, increased number of thinnings, increased planting density, increased average standing volume, increased saw log production, reduction of pulpwood production, and increased average carbon stock. The effects were more pronounced on more fertile sites than in poorer sites, and more for spruce than for pine stands. The qualitative results from the SMAC and SMA models are more or less in agreement. Differences in the results can be attributed to the fact that stand establishment cannot change in the SMAC model, contrary to the SMA model, something which the SMA model shows has considerable influence on the design of the optimal management program.

On the practical side the results indicate the following:

- An increase of wood framed buildings would reduce net carbon emissions in the construction sector. The total net effect was not quantified because the changes could not be traced down to the forest.
- The changes in the price relations between sawnwood and pulpwood of the EFI-GTM lead in the forest regional model to a change in the management programs towards prolonged rotations, leading to a medium term reduction of sawnwood supply.
- The long term steady state analyses indicate small differences in carbon stock due to the price increases predicted by the scenarios. Sawnwood output increases, but is in most cases balanced by a similar reduction of pulpwood output. Rotations are prolonged and for several stand types the number of thinning is increased.

The modeling system in this report represents an ambitious effort to combine models from different disciplines into one coherent system. It is no surprise that several gaps, overlaps and missing links have been detected. The following more general experiences were gained:

- Linking the wood construction scenarios with the EFI-GTM, however demanding, works without major problems. The resulting demand for sawnwood can be distributed among countries by the EFI-GTM model in consistency with the construction scenarios.
- The most problematic part of the system appears to be the linkage between the EFI-GTM and the forest regional model. In particular, the reaction of supply stemming from different price relations between sawnwood and pulpwood needs to harmonized. The SMAC model gives lower harvest volumes in Sweden in the first 2-3 decades compared to the EFI-GTM results because, seen from the forestry side, it is more profitable to postpone harvest given the assumed increase in saw log prices. To avoid this difference between EFI-GTM and the SMAC results one could run SMAC with both prices and volumes of saw logs and pulpwood fixed until 2030 according to the EFI-GTM results, so that only the forest management (silviculture and harvesting operations) are decided endogenously. It would also be advantageous to have the same temporal resolution in both models.
- None of the models – the sector, regional or stand model – explicitly include biofuels. Given the growing importance of the biofuel market it would be desirable to adjust the models such that one could study the effects of changing demand and supply relations on economic indicators and forest management activities.
- The detailed stand level model and the regional forest model could be better integrated with each other.
- The overall consistency relies on a number of common parameters that are used in the different models, such as carbon emission factors and discount rates. They need keen attention to ensure consistency.

1. Introduction

1.1 Background

Climate change mitigation is a major issue that can be addressed with different means within the forestry sector, and with consideration of the wood lifecycle as a whole. The amount of carbon stored in the forest (carbon stock) can be increased or decreased, depending on forest management practices. Wood energy and wood products can replace fossil fuels and energy intensive materials such as steel and concrete. Carbon is temporarily sequestered in wood products during their life span. Substitution management is affected by several factors (Gustavsson et al. 2006a), some of which are covered below. There exist trade-offs between different mitigation measures, and substitution appears to give high carbon benefits in the long run (Eriksson et al. 2007a).

The potential supply of wood raw material for substitution in Europe is large. Wood harvested in Europe in the mid 1990s was about 60% of the net increment of European forests, leaving an unused increment of about 300 Mm^3y^{-1} over bark (UNECE/FAO 2000). In Finland and Sweden, the figures are 20.2 Mm^3y^{-1} (73%) and 28.1 Mm^3y^{-1} (71%), respectively. Furthermore, continuation of the current harvesting levels would change the age class structure towards older classes, and the increment would decline in the long run (Nabuurs et al. 2002). If harvests were increased, the age class structure would change towards younger age classes and growth would increase. This would further increase the substitution potential. Intensification of forest management on at least part of the forest area through, e.g. fertilisation, choice of tree species, or optimisation of thinning operations, would further increase the increment and the substitution potential, within ecological constraints (Börjesson et al. 1997).

However, the substitution potential is not directly proportional to the increment. The benefit derived from fuel and material substitution is also related to wood quality and the kind of products and services that can be obtained from the harvested wood. For example, sawn wood typically requires less processing energy than some other wood products such as panels (Pingoud and Lehtilä 2002). From a climate change mitigation perspective, it would be beneficial to choose the less energy-intensive wood products to fulfil a given service demand, although demand for the various products has so far been largely independent of climate implications. In principle, greater emission reduction can be obtained if the lifecycle of a wood product is extended by cascading, in which both material *and* fuel substitution is considered (Dornburg 2004).

Although biomass production can be increased substantially, it is nonetheless a limited resource. Hence, if biomass is to be used in place of fossil fuels and materials, it should be done in the applications where it most effectively serves society’s objectives. The choice of biomass uses and the parameters chosen for comparing them vary according to the objectives of the analysis. For example, greenhouse gas benefits of biomass use can be optimised with respect to any of several limiting factors, including: per ton of biomass feedstock, per hectare of land, per unit of monetary resources spent for carbon emission reduction, or per unit of bioenergy output that can be absorbed by a specific market or sector (Schlamadinger et al. 2005). Regardless of the factor to be optimised, it has become widely accepted to include the full chain of biomass use within the analytical system boundaries, from primary plant growth to final fuel consumption (Schlamadinger et al. 1997).

Political and global drivers, like the Kyoto Protocol, are increasing the use of wood. In order to reduce the amount of fossil fuels in the economy, policy instruments like emission trading and carbon taxes are adopted, changing the relative prices in favour of wood (Sathre and Gustavsson

2007). Also, regulations and information on environmental impacts promote the use of wood. In case of energy substitution, the implemented and planned policy instruments improve the competitiveness of forest biomass notably. As the price of carbon is internalized into the price of fossil energy, renewable fuels like forest biomass are becoming more competitive. In addition, the EU and some other regions have set targets on the use of renewable energy. The use of renewables is promoted by implementing e.g. green certificates and feed-in tariffs. The importance of forest biomass as an energy source is thus increasing. The demand for forest biomass is further increased due to the problems related to agricultural biomass, namely possibly negative carbon balances and impacts on global food prices. In case of material substitution, wood is in principle given a competitive advantage by setting carbon payments for competing materials like concrete or steel.

Relative prices are not, however, the only aspect affecting consumer demand for e.g. heating systems or construction materials. Consumer demand is dependent on socio-economic factors, beliefs, culture and tradition, and the level of comfort offered by wood-based technologies and products (Gustavsson et al. 2006a). These factors are especially important in the construction sector.

There has been growing interest in efficient ways to use biomass for the substitution of fossil fuels and non-biomass materials, and many studies have compared the substitution efficiency of various technologies. It is increasingly recognized that material uses for biomass-based products can bring energy and GHG balance benefits, especially if the material production system is integrated with the energy supply system (Börjesson and Gustavsson 2000, Gustavsson et al. 2006b, Perez-Garcia et al. 2005, Pingoud et al. 2006). Wood-based building material can affect the energy and carbon balances through at least four mechanisms: the relatively low fossil energy needed to manufacture wood products compared with alternative materials; the avoidance of industrial process carbon emissions; the increased availability of biofuels from biomass byproducts that can be used to replace fossil fuels; and the physical storage of carbon in wood building materials.

1.2 Objectives

The purpose of this study is twofold. One is to analyse the climatic implications of increased wood use in housing construction. For this purpose, a new preliminary approach of an integrated modelling framework is developed. Research and modelling on integration between wood substitution strategies and forest management is nearly lacking despite the importance of and need for such research (Gustavsson et al. 2006a). A comprehensive analysis of the issue requires the integration of forest management models at stand and regional level and with wood substitution. Implementation issues, including consequences for future international agreements in the area, are an important element, although not covered in this study. The scope ranges from natural resources to services required by end users and thus requires a multidisciplinary analytical framework. The second objective of the current pilot project is to establish such a framework in order to prepare for more comprehensive studies. This entails the following activities:

1. Combining suitable existing models of wood substitution in building construction, models for forest product markets and forest management models on forest and stand levels.
2. Investigating the consistency of the linkages between models, and identifying missing models and linkages.
3. Conducting preliminary regional level application of the framework with scenarios of material and energy substitution, to demonstrate (i) the viability of the proposed approach, (ii) the possible improvements needed, and (iii) the greenhouse gas mitigation potentials of the forestry related system as a whole, including carbon sequestration into ecosystems and wood products and avoided emissions due to the wood products chain.

1.3 Scenario analysis

We analyze the impacts of three scenarios on wood use and how they affect material substitution in housing construction and the total carbon balance of forests and wood-using chain.The material substitution in the construction sector affects the demand for and prices of various timber species, as determined by a forest sector model. This has impacts on the forest management over time, which is analysed with the regional forest model and the stand model. The demands for timber species are implemented on a regional scale to quantify the accumulated effect on carbon storage and harvested timber over time. The overall impacts are estimated for Sweden, for which the available regional model was applicable.

The scenarios are a means to illustrate the greenhouse gas mitigation potentials of combined material and energy substitution and demonstrate the trade-offs between carbon sequestration into forest biomass and avoidance of fossil carbon emissions due to increased wood use. By identifying the most important interactions, the scenarios assist in developing the integrated modelling framework in the next stage. Two of the scenarios (see Chapter 4) are formed by extrapolating the results of existing micro level studies on material substitution in construction to a macro level.

2. Previous research on integrated modeling

A growing body of knowledge supports that using wood-based material typically results in lower energy use and CO_2 emissions compared to other materials such as concrete, brick or steel (Koch 1992; Buchanan and Honey 1994; Buchanan and Levine 1999; Börjesson and Gustavsson 2000; Lippke et al. 2004; Gustavsson and Sathre 2006; Petersen and Solberg 2005). Gustavsson et al. (2006b) developed a method to compare the net CO_2 emissions from the construction of concrete- and wood-framed buildings. The method, applied to two buildings in Sweden and Finland, includes carbon accounting from emissions due to fossil fuel use in the production of building materials; the replacement of fossil fuels by biomass residues from logging, wood processing, construction and demolition; carbon stock changes in forests and buildings; and cement process reactions. They found that the most important contributor to the lower CO_2 balance was the recovery of wood residues, including logging, processing, construction and demolition wastes, for use as biofuel to replace fossil fuels. Pingoud and Perälä (2000) estimated the maximum wood substitution potential in new building construction in Finland. The results indicated that nearly twice as much wood material could have been used in Finland in 1990 compared to the amount that was actually used. Most substitution studies, however, lack an active integration between wood demand from the industry and timber supply from the forest.

Managing forest stands to achieve increased carbon sequestration in forests results in silvicultural guidelines that differs from the current practices. Zhou (1999) and Pohjola et al. (2007) suggest that increased carbon sequestration in forests is achieved by increasing growing densities and rotation length. These results neglect the use of wood as a substitute for energy intensive materials and fossil energy. Taking substitution into account will typically change the optimum timber assortment composition and the rate at which carbon is passed through the forest ecosystem. Stand level analyses using a simulation-optimization model such as the SMA software (Valsta and Linkosalo 1995) allow for optimum combination of the multiple objectives in silviculture.

Incorporating carbon storage into forest planning at the regional scale clearly affects forest management by e.g. changing clear felling priorities (Hoen and Solberg 1994). When carbon storage in forest biomass is given a monetary value, harvest levels will decline, an effect that is more pronounced in areas with lower production (Backéus et al. 2005). Petersen et al. (2004, and 2005) used the GAYA/JC model to connect forest planning with climate change mitigation impacts based on forest and forest products use. The model permits an analysis of the impacts of including energy and material substitution effects in carbon benefits. Studies at the forest or regional level are performed using an integrated analysis and planning system similar to the Heureka-system (Lämås and Eriksson 2003).

A preliminary case study integrating forest management, carbon sinks and substitution was performed by Pingoud et al. (2006), who analyzed the impacts of various forest management strategies on both carbon stocks and substitution. The supplies of sawnwood, pulpwood and energy wood were given as input into a framework similar to that used by Gustavsson et al. (2006b), to estimate the impacts on emissions and carbon stocks of replacing concrete-frame buildings with wood-frame buildings. The results showed that the quality of the wood produced (saw logs, pulpwood, energy wood) had a substantial impact on the substitution potentials. Some substitution factors were found to be greater than one, implying that relative emission reduction was larger than the carbon content of the wood itself. Consequently, maximizing the biomass production does not necessarily lead to the maximal substitution benefits. These results suggest that there could be win-

win solutions in the long run: both higher substitution benefits and higher carbon storages might be obtained by the same forest management strategy in some cases.

Eriksson et al. (2007a) conducted a broad system analysis of carbon stocks and flows in trees, soil, wood products, and substitutable materials and fuels, finding that overall carbon emissions were lowest when forests were managed intensively to produce construction materials. The mean forest carbon stock was slightly higher under intensive management than under traditional management, but had a relatively minor effect on the overall carbon balance. The substitution effect of using wood instead of non-wood materials had the greatest single impact on the overall carbon balance. Removing harvest residues for use as biofuel led to avoided fossil emissions that were 7-10 times greater than the reduced soil carbon stock. Similarly, the CORRIM consortium (e.g. Perez-Garcia et al., 2005) analysed management alternatives for individual forest stands and taking into account the whole lifecycle from forest growth to wood products used in buildings. They found that management strategies with shorter rotation lengths, higher biomass yields, but also lower forest carbon stock gave the best overall greenhouse gas benefits.

Taverna et al. (2007) examine the impacts of different forest management and wood use strategies on CO_2 sinks and emissions. The analysis is performed by linking a forest model, a wood flux model of the timber industry, and a model of carbon stocks and substitution effects. The analysis covers sequestration and substitution in detail; both energy and material substitution and waste wood are included. The analysis is made for Switzerland, but the impacts of products used abroad are also estimated. Both short and long term impacts are analyzed. The models are simulation models; economic decision making is not involved in the analysis. The main conclusion of the study is that the growing stock of forests should first increase to the level that may be accounted for in the Kyoto Protocol, and after that one could start to use extra wood for long-lived wood products and for energy.

3. System boundaries and linkages between sub-models

The model system used in this study enables us to analyse a wide range of impacts of increased wood use, including impacts on timber and wood product markets and effects on carbon balance in both forests and wood products. Several existing models representing different parts of the forestry sector are linked in order to cover the full life-cycle of wood. The models to be integrated include (a) a model for wood substitution in building construction, (b) a global forest sector model, (c) a forest regional model, and (d) a forest stand model.

a) In the model for wood substitution in building construction, the model inputs are the amounts of building materials needed to build a wood-framed building and a reference house built mainly with non-wood materials. The outputs are: (1) the carbon emissions from producing the building materials, (2) the avoided fossil carbon emissions from using processing residues and demolition wood for bioenergy, and (3) the amount of tree biomass needed to produce building materials. These outputs are given for both the wood building and the reference building.

b) The global forest sector model links forest resources, wood supply, the forest industry production and the market demand for forest products and wood-based bioenergy in various models. Simulating the competitive markets, the model solves for supply, demand, trade and prices for forest sector products in different regions and time steps.

c) In the forest regional model, simulations for forest growth are made for sample plots from e.g. National Forest Inventory. Guidelines for forest management are received from the stand level model. Under these guidelines, the behaviour of forest owners is simulated by maximizing the net present value of the forests. The results of the simulations serve two purposes: (1) to yield price elasticities to the global forest sector model, and (2) to evaluate the price scenarios produced by the global trade model in terms of, for instance, harvest level and carbon sequestration.

d) In the stand level model, the forest owner maximizes the discounted net income from timber production and possible carbon sequestration over time subject to economic and ecological parameters. The model provides the optimal rotation age and the timing and intensities of thinnings, with given targets or economic incentives for carbon sequestration, or with changes in timber prices.

The models are linked by using results from one model as inputs for other models. The forest sector model provides timber prices and forest industry production levels that are used as inputs to other models in order to estimate the climate impacts of the scenarios examined. Unlike earlier studies, we account for the price impacts through markets. Including market level analysis with price responses is important as the prices of timber and end products are likely to be linked by feedback loops that impact on the amount of substitution and sequestration. However, in this pilot study it has not been possible to impose feedback from other models back to the market model. The impacts of different market conditions are evaluated with the stand level model and the forest regional model, while substitution impacts are estimated with the micro-level model for wood substitution.

Figure 3.1 represents the models and their linkages. Three scenarios for increased use of wood in the construction sector form a basis for the analysis. The analysis is thus demand-driven. The estimated demand for sawnwood and panels shifts in Europe in the *Base* case and the three scenarios are used as inputs in the global forest sector model, EFI-GTM, which provides the market equilibrium prices and volumes for both timber and end product markets in the *Base* case and alternative scenarios. The timber supply elasticity for Sweden is calculated with the forest regional model. Prices and demands of timber are used in other models when calculating climate implications.

Impacts on carbon balances include both impacts from the use of fossil fuels (substitution) and the amount of carbon in forests and wood products (carbon sequestration). The substitution impact and the impact on carbon stock in buildings are estimated by using data on consumption of wood products from the EFI-GTM model. In scenario *1m3cap*, simple substitution factors are utilized, while for scenarios *Sweden* and *Finland* the substitution impacts are estimated with substitution models based on case studies of building construction.

Impacts on the carbon balance in forests are estimated both with a regional and a stand level model. Both models use prices of timber from EFI-GTM. The forest regional model provides detailed information on the development of timber stock and carbon balance over time, and profitability of forestry. The stand level model SMA is used to obtain implications of new timber prices in forest management, long-term timber supply and average carbon storage in forests. As the regional model solves the new equilibrium path, the input prices differ for every period according to EFI-GTM results. On the other hand, in the stand level model a new price level is selected to represent the long term price impact.

Stand and regional level models of forestry should ideally be linked through guidelines for final cutting age and thinnings that are obtained from the stand level model. These guidelines should reflect different balances of carbon mitigation goals against economic gain. The simulations with the regional model would then utilise the guidelines to provide a regional scale to quantify the accumulated effect on carbon storage, timber supply and biofuel supply over time. Economic gains from carbon mitigation derived from the stand level model and from substitution could then be compared when making a regional forest management plan. In this pilot study it has not been possible to elaborate on the transferral of information from the stand model to the regional model because both models had to be operated in parallel due to time limitations.

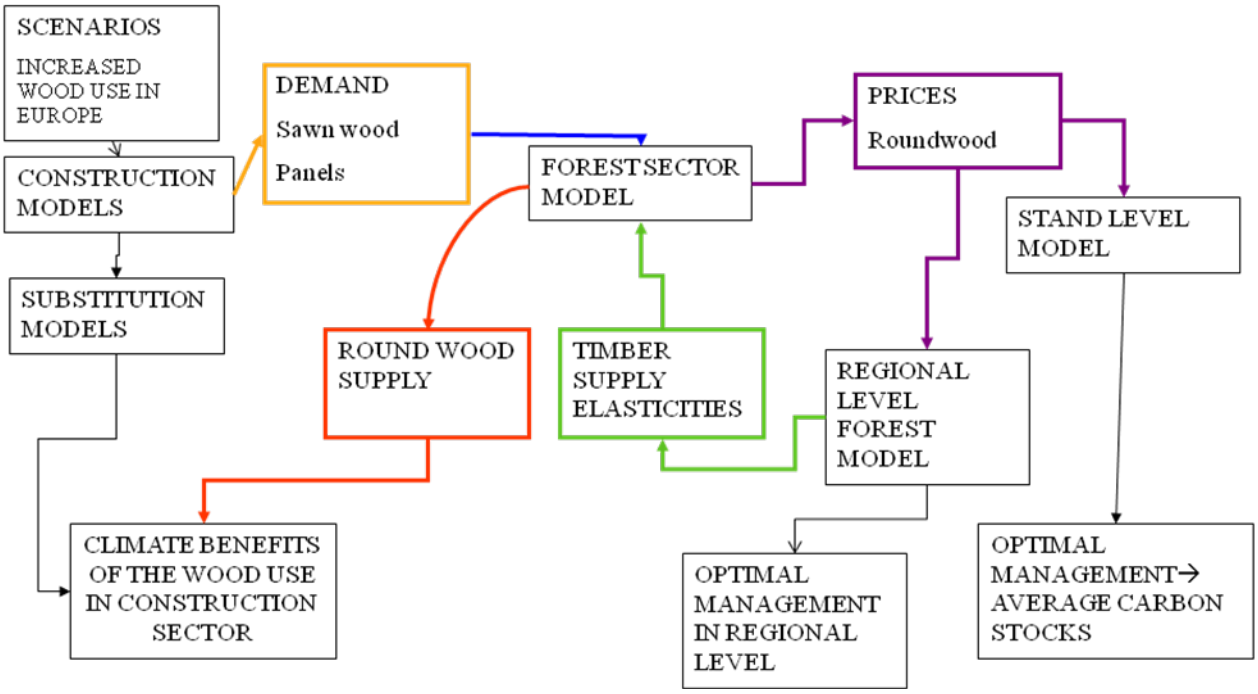

Figure 3.1 The information flow between models.

Since all models in the system were not solved simultaneously, the overall consistency cannot be guaranteed, as will be evident below. The models in the system are partly overlapping. For example, timber supply is solved in the market model, in the forest regional model, as well as in the stand model. All these models are based on economic optimization. The stand level model is an intertemporal model that provides results on a long term steady state. The forest regional model is forward looking such that forest owners take the prices in future periods into account when making their current decisions. The forest product market model (forest sector model) assumes the maximization of profits or welfare myopically, with no foresight to the future periods. The market model is the only model in which prices are determined inside the model; in the other models they are given as exogenous parameters. In addition, the biological descriptions e.g. on forest growth differ, as do data and values of the parameters. Due to these differences, the volumes obtained as outcome of the models will be different. Different models shed light on different aspects and time scales, and the impacts of different assumptions. The results are compared and discussed in Chapter 8.

The analysis focuses on harvests and carbon balance impacts for Sweden. However, the changes in timber supply and prices in Sweden are based on the increased demand scenarios of wood in EU and on the implied new equilibrium within wood product and timber markets on the European level obtained from the EFI-GTM model. The regional forest model and the substitution model were originally developed for Sweden. A stand level model for Sweden was not available, thus growth model and stand data represent southern Finland, and correspond closely with Swedish conditions. Also, timber prices for Sweden are used in the stand level analysis.

The increase in demand for sawnwood also impacts on the supply and prices of pulpwood. When evaluating the carbon sequestration in the forest, this impact is taken into account by giving the new prices for both saw log and pulpwood. On the other hand, the substitution analysis covers only the impacts of increased amount of saw logs. Extending the system boundaries to include biofuel and paper production would be desirable but is outside the scope of this study.

4. Wood construction scenarios

4.1 Potential for wood building material substitution in Europe

The level of wood use in building construction varies significantly between European countries. Table 4.1 shows that the share of wood for constructing one and two family houses is rather low in Europe, except in the Nordic countries. Wood is commonly used in Nordic countries for single-family houses, but is less common in multi-storey apartment buildings. In contrast, wood is commonly used in North America for construction of both single-family as well as multi-family houses.

Table 4.1 Share of wood construction in one and two family house construction in selected countries or regions.

Country	Share of wood construction
USA[1]	90-94%
Canada[1]	76-85%
Nordic countries[1]	80-85%
Scotland[2]	60%
UK[3]	20%
Germany[1]	10%
The Netherlands[4]	6-7%
France[2]	4%

References: [1] HAF (2000); [2] Reid et al. (2004); [3] Toratti (2001); [4] Kuilen (2001)

In recent years, however, wood has shown signs of increased market penetration in many European countries. For example, in Germany the amount of timber used for construction of one and two family houses increased somewhat from 8% in 1993 to 11% in 2000 (see Figure 4.1). There are large differences between regions within the country and between different types of buildings. The share of timber-framed one and two family houses is significantly higher in the eastern part of Germany (15%). Only 2% of all multi-family houses in Germany are built of wood. (Statistisches Bundesamt 2002).

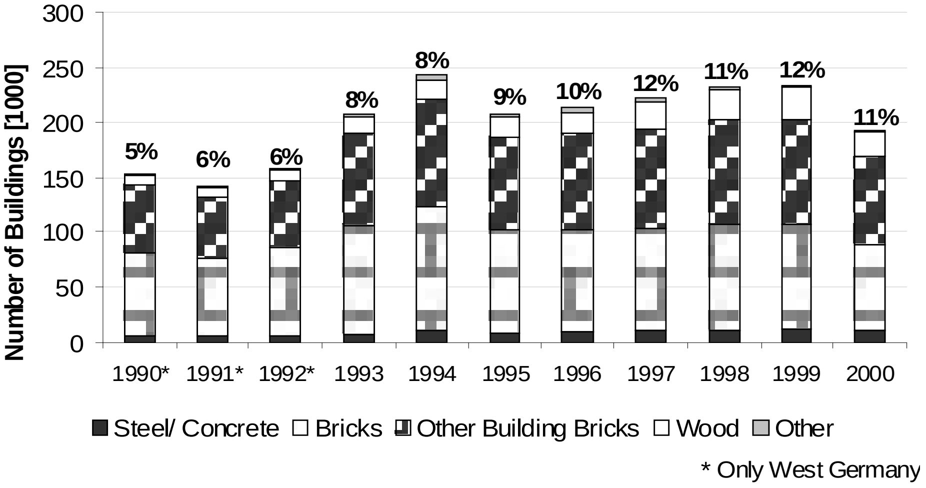

Figure 4.1 Market share of different materials used in construction of small residential houses in Germany, 1990-2000 (Statistisches Bundesamt 2002). The percentage figures refer to the share of wood material.

Various obstacles exist to the increased use of wood-based construction material. In Sweden, for example, the use of wood frames in multi-storey buildings was prohibited by the Swedish law for over 100 years, during which time a path dependency favouring concrete construction developed (Bengtson 2003). Mahapatra and Gustavsson (2008) describe several criteria for the eventual emergence of wood-frame multi-story building construction in Sweden, including investments in knowledge creation, incentives for entry of new firms, and the formation of actor networks. The use of economic instruments to internalise the external costs of construction materials increases the economic competitiveness of wood construction materials in relation to other, non-wood materials (Sathre and Gustavsson 2007, 2009). This would encourage the adoption of the new technologies. Taxation of fossil fuel use and/or carbon emission may act as an economic incentive to overcome organizational inertia, encouraging firms to adopt innovations that result in both lower environmental impact and increased economic benefits (Porter and van der Linde 1995). Still, the taxation of fossil fuel use and/or carbon emissions would have a minor influence on total construction cost, under current Swedish taxation regimes (Sathre and Gustavsson 2009).

The inter-European and intercontinental trade in wood-based products and fuels is increasing, and there is a large potential for exporting wood products, or prefabricated wooden buildings, from forest-rich countries in northern Europe to other regions that predominately use brick or concrete construction. This would expand the energy and greenhouse gas benefits of wood construction further, decreasing total energy use and climate change impact. By exporting wood or wood-based products to be used in applications that result in high CO_2 emission or energy use reductions per unit of biomass, the total impact of the available supply of biomass could by increased. Substituting wood construction material in place of e.g. concrete has a high CO_2 emission reduction per unit of biomass, and constructing buildings in Nordic countries with wood instead of concrete would effect an emission reduction in those countries. However, the total number of new buildings built per year in Nordic countries is small in relation to the total quantities of biomass potentially available. If the export potential were ignored, the additional biomass would then be used for other uses with lower efficiency of emission reduction or left in the forest. However, if additional biomass is exported, either in the form of prefabricated houses or as lumber to be processed in the importing countries into prefabricated houses, and used instead of non-wood houses in other countries, the higher emission reduction per unit of biomass could be gained by a larger share of the biomass, thus resulting in a greater overall emission reduction globally. The production of energy efficient wood buildings can be done in other EU countries, if suitable factories are established outside of the Nordic countries.

4.2 Wood construction scenarios

In this analysis, we create three scenarios for increased wood consumption through the year 2030, by using two different approaches. These scenarios for increased wood use are all compared with a projected baseline (*Base*) of wood use through 2030. In the first approach, *1m3cap*, the scenario is based on the aggregate consumption of final wood products. The substitution impact of increased wood use on emissions is estimated by using a rough emission displacement factor calculated for sawnwood, based on a study by Pingoud and Perälä (2000). The second approach, used to derive two scenarios (*Sweden* and *Finland*), is based on data adopted from case studies of two multi-story wood apartment buildings, one built in Sweden and the other in Finland (Gustavsson et al. 2006b). Here the emission impacts of wood use are summed up from the detailed micro-level data of the case study.

In the first approach, future demands for the final forest industry products are assumed to be affected by the product price and consumer income in each European country assuming certain price and income elasticities (Chapter 5.2). Because softwood sawnwood is, however, an important product in the European construction, it was modelled separately. In the *Base* case describing "business-as usual" the reference sawnwood consumption, i.e. projected consumption from 2008 to 2030 assuming no price changes, is based on the past per capita consumption and population forecasts (Table 2 in Hänninen 2008). The *Base* case is created using statistical smoothing methods for the available country-specific time series. Because data were missing for several countries, expert assumptions are also combined in the forecasting process. In the *Base* case, the growth rate of total European softwood sawnwood consumption quantity was estimated to be 1.48% annually up to 2030.

For all scenarios the roundwood consumption was estimated for the entire EU and specifically for *Sweden*, for which an integrated analysis was performed comprising the carbon balances of both forests and wood-product chains. The relative emission reductions of each scenario compared to the *Base* are also presented both for the entire EU and for the wood that originates in Swedish forests.

4.2.1 Scenario 1m3cap

In scenario *1m3cap*, it was assumed that the annual per capita consumption of sawnwood in all European countries gradually reaches 1.0 m^3 per capita in 2030, except for those countries that already now have reached it (Hänninen 2008), starting from the present average European level of 0.2 m^3 per capita. Here the annual consumption growth in Europe is about 7% up to 2030. It must be noted that this is an extreme scenario, which was created only to have an idea of the scale of effects for such a consumption level.

The historical data for the softwood sawnwood were obtained from FAOSTAT for calculating the country-specific apparent consumption (production+imports-exports) in cubic meters. Population data are from the World Bank database, and population forecasts from the US Census Bureau, International database (www.census.gov/ipc/www/).

Table 4.2 shows apparent consumption (production+imports-exports) of sawn softwood in several European countries in 2006. There is a large range in wood consumption, with an average for EU-25 countries of 0.196 m^3 per inhabitant per year. In this scenario, it was assumed that softwood consumption rises linearly in Europe from a per-capita annual consumption of 0.2 m^3 in 2007 to a level of 1.0 m^3 in 2027.

Table 4.2 Apparent consumption of sawn softwood in European countries in 2006.

Country	1,000 m3	m3 per 1,000 inhabitants
Europe	102,025	169.3
Albania	55	17.5
Austria	5,212	640.3
Belgium	2,178	209.1
Bosnia and Herzegovina	61	14.1
Bulgaria	144	18.5
Croatia	393	88.5
Cyprus	102	137.6
Czech Republic	3,242	317.8
Denmark	2,111	390.8
Estonia	1,717	1,268.5
Finland	4,948	946.6
France	10,241	165.9
Germany	20,187	244.7
Greece	862	78.0
Hungary	823	81.5
Iceland	91	309.3
Ireland	1,569	386.9
Israel	334	49.1
Italy	7,296	125.7
Latvia	1,641	709.4
Lithuania	916	266.5
Luxembourg	123	271.9
Malta	10	25.8
Netherlands	2,384	146.5
Norway	2,872	625.6
Poland	2,803	73.4
Portugal	675	64.3
Romania	1,027	47.4
Serbia	510	50.2
Slovakia	724	134.6
Slovenia	109	54.6
Spain	5,335	130.0
Sweden	4,848	539.0
Switzerland	1,698	229.0
The fYR of Macedonia	277	139.1
Turkey	4,772	66.0
United Kingdom	9,735	163.4
EU25	89,791	196.3

The carbon balance implications of the increased wood use in Scenario *1m3cap* is based on substitution factors developed by Pingoud and Perälä (2000), in which 1 kg of wood-based building materials substitutes for 3.6 kg of masonry products (concrete, bricks, tiles) and 0.12 kg of metals. These numbers are based on a study where the potentials of increased wood use in new Finnish construction in the 1990s were estimated: how much wood could have been used compared with the realized construction, and how much less concrete and metals would have been needed in proportion to the increase in wood use. In the scenario it has been assumed that the increased use of sawnwood would in general have similar impact on emissions in other sectors such as renovation or furniture manufacture.

The relative emission reductions with respect to *Base* resulting from increased wood use are composed of the following factors:

- Carbon sequestered in the permanent wooden structures (none of these long-lived products are assumed to be demolished before 2030)
- Production of sawnwood causes less fossil C emissions than production of its substitutes
- Foliage and branches from harvesting; bark, chips and sawdust from sawmills; and construction waste are used as bioenergy to replace fossil fuels.

The same specific emissions and energy demand parameters for production of construction materials are used in calculations as in Gustavsson et al. (2006b). 10% of the used sawnwood was assumed to be construction waste. Further, 100% of wood waste from sawmills, 90% of construction waste and 70% of foliage and branches was assumed to be used as bioenergy. The results are also dependent on which marginal fuel is used in electricity generation and energy production in general. The results were calculated both for coal and natural gas condensing power. Coal is the marginal fuel at present, but natural gas cannot be excluded as future marginal production option. The emission reductions are higher when coal is the marginal fuel, due to its higher emission factor – i.e. the relative benefits from biofuels is higher when coal is replaced. The relative emission reductions with respect to *Base* at EU level are illustrated in Fig. 4.2. The total numbers are also summarized in Table 4.6, together with those of scenarios *Sweden* and *Finland*. Note that we assume here that the wood residues from sawmilling are only used in energy production and not, for instance, as raw material for pulp. If these residues were used in the pulp industry less fossil fuel could directly be replaced, reducing the estimated emission benefits.

The huge growth of European sawnwood demand in this scenario could not be realized without imports from outside the EU region. It would have significant impacts on global timber prices and could also lead to unsustainable harvest levels. The impact of scenario *1m3cap* on forest carbon balance on a global level is not considered in this study.

The growing sawnwood demand in Europe also has an impact on roundwood production in Sweden. Since in this study we consider the carbon balance impacts in Swedish forests due to scenario *1m3cap*, we present here the relative emission reductions allocated to the increased use of Swedish saw logs, shown in Figure 4.3. These emissions reductions, together with the carbon balance of Swedish forests in scenario *1m3cap* with respect to *Base*, determine the total carbon benefits/drawbacks of scenario *1m3cap* in Sweden. The estimated demand for Swedish sawnwood – used as input in the wood use scenario *1m3cap* for Sweden – was calculated using the EFI-GTM model. Details of this are presented in Chapter 5.

Scenario *1m3cap* is an extreme scenario of sawnwood demand, with its annual growth rate of more than 7%. Furthermore, the assumed substitution impacts in terms of displaced fossil carbon emissions and carbon sequestration in wood products are also most likely overestimates, because they characterize new construction. In reality a substantial share of the increased use of sawnwood in scenario *1m3cap* may go to other uses than new construction, e.g. to end-products with very short lifetime, or to renovation where demolished wood is replaced by new wood.

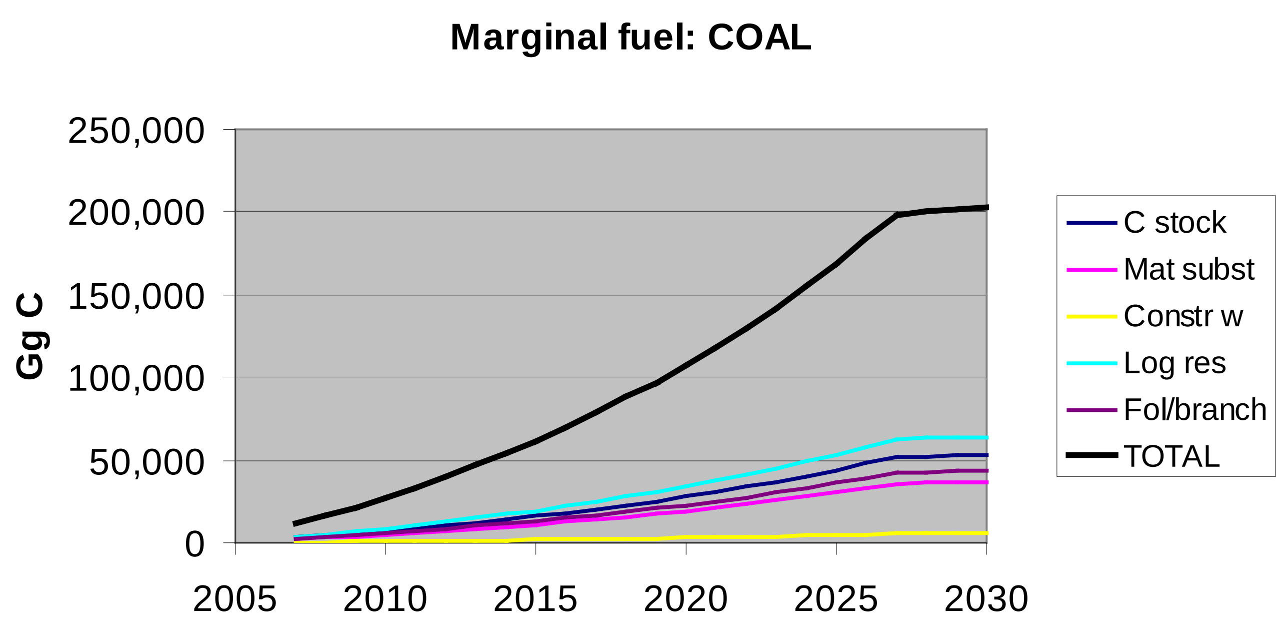

Figure 4.2 Scenario *1m3cap*: Estimated relative emission reductions due to increased use of sawnwood within EU with respect to the baseline (*Base*). Only the wood-use chain is included, not the carbon balance in forests.

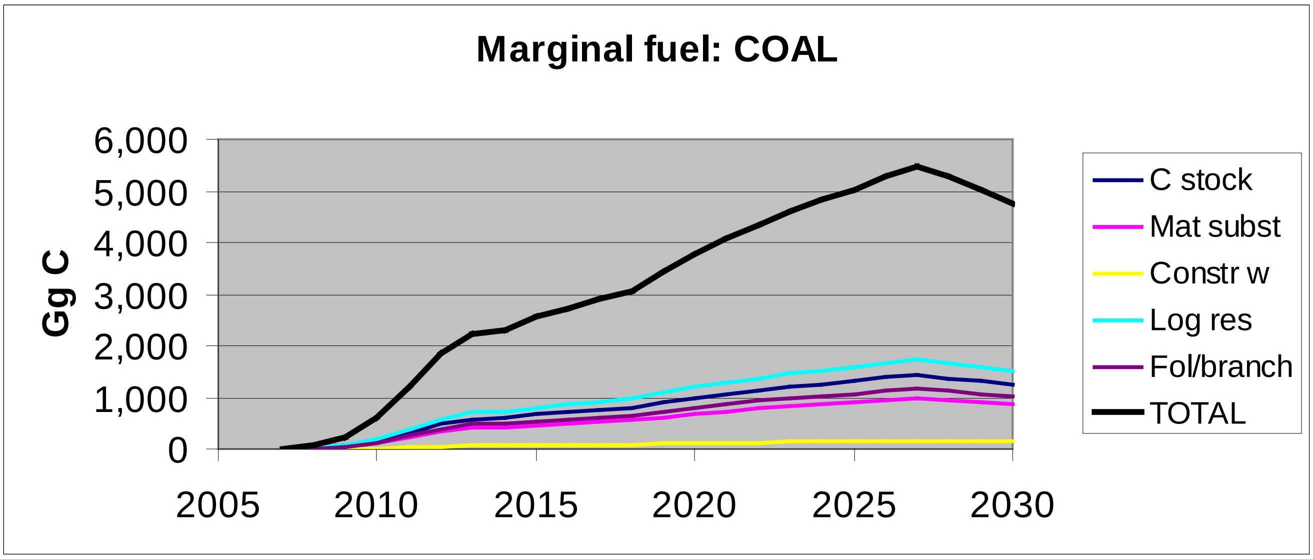

Figure 4.3 Scenario *1m3cap* SWE: Estimated relative emission reductions due to increased use of sawnwood within EU with respect to the baseline (*Base*) allocated to wood that was harvested from Swedish forests. Only the wood-use chain is included, not the carbon balance in forests.

4.2.2 Scenarios Sweden and Finland

In scenario *Sweden* and scenario *Finland* we assume that an increasing number of wood-framed multi-story buildings will be built, replacing conventional concrete apartment blocks in new construction. We assume that the annual number of new flats in wooden houses will gradually increase to 1 million by 2030. The difference between the two scenarios is the type of wood construction, and the type of reference concrete construction replaced. In the scenarios, the results of micro-level case studies of individual multi-story houses are scaled up to macro-level.

Table 4.3 shows that significantly more than one million flats were built each year in Europe during 2003, 2004 and 2005, so the construction of one million wood-based flats appears not limited by the overall demand for flats. Because the diffusion of construction innovations will take time (Mahapatra and Gustavsson 2008), we show a scenario for the use of wood in multi-family housing increasing linearly over a 23-year period, from 2008 until 2030. Thus in 2008, 50,000 new flats will be constructed of wood materials instead of concrete. In 2009 100,000 wood-based flats will be constructed, and so on until 2030 when one million wood-based flats will be made. After 2030 we assume this number of flats will continue to be made each year.

Table 4.3 Number of apartment flats completed (thousands) in various European countries (Euroconstruct Conference, 2006).

Country	2003	2004	2005
Austria	25	24.3	23.5
Belgium	18.5	23	24.5
Czech Republic	13.2	15.8	15.8
Denmark	10	12	11.5
Finland	17.7	17.2	18.8
France	109	120	145
Germany	70.9	70.6	61.7
Hungary	15.4	21	20.5
Ireland	14.8	16.1	19.2
Italy	164.2	187.2	210.8
Netherlands	16.4	16.3	19.8
Norway	9.6	11.2	14.5
Poland	44.7	43.2	50.8
Portugal	45.9	42.4	39.4
Slovakia	6.4	4	6.2
Spain	410	456	483
Sweden	11.8	13.7	17.6
Switzerland	20.6	24	25.6
United Kingdom	48	51.3	52.3
TOTAL	1072.1	1169.3	1260.5
SUBTOTALS			
Nordic	49.1	54.1	62.4
Central Europe	402.9	429.6	464.9
Southern Europe	620.1	685.6	733.2

Scenario *Sweden* uses data from a case study of the Wälludden building constructed in Växjö, Sweden (Gustavsson et al. 2006b). This is a 4-story building containing 16 apartments and a total usable floor area of 1190 m^2. It is one of the first multi-story buildings constructed in Sweden after the building code was changed in 1994 to allow wooden-framed buildings higher than two floors (Bengtson 2003). The foundation consists of concrete slabs. Two-thirds of the facade is plastered with stucco, while the facades of the stairwells and the window surrounds consist of wood panelling. The outer walls consist of three layers, including plaster-compatible mineral wool panels, 120 mm thick timber studs with mineral wool between the studs, and a wiring and plumbing installation layer consisting of 70 mm thick timber studs and mineral wool. The floor frame is made of light timber joists, consisting of several layers to provide a total thickness of 420 mm. All rooms except the bathrooms have parquet floors.

Scenario *Finland* uses data from a case study of a 4-story apartment block built in 1997 in the ecological building area of Viikki in Helsinki, Finland (Gustavsson et al. 2006b). The building considered in this study contains 21 apartments with a total usable floor area of 1175 m^2. It has prefabricated load-bearing wooden wall framing, with facade materials of mostly sawn wood products with 150 mm mineral wool insulation. The internal wall cladding is mainly plasterboard. The foundation is constructed of hollow core slabs, base beams and pile footings, all in concrete. Flights of stairs include potstone slabs and glue-laminated boards. The intermediate floor framing is made of plywood and sawn wood balks with mineral wool insulation, covered by parquet except in bathrooms. The total floor thickness is 400 mm. Roof structures are sawn wood, plywood and steel sheet with 222 mm mineral wool insulation.

Wood material usage for Scenarios *Sweden* and *Finland* is compared to reference buildings in which reinforced concrete is used as the frame material. Calculations are based on an analysis of the case-study apartment buildings constructed using wood structural framing, compared to a functionally equivalent building constructed with a reinforced concrete frame (Gustavsson et al. 2006b). The comparison is made on a building level, and all materials composing the two buildings are included in the calculations. The amount of construction materials in the finished buildings with wood- and concrete-frames is shown in Table 4.4.

Table 4.4 Comparison of material quantities (tonnes of air-dry material) contained in the case-study buildings in Scenarios *Sweden* and *Finland*.

Material	Scenario *Sweden* (Wälludden)		Scenario *Finland* (Viikki)	
	Wood frame	Concrete frame	Wood frame	Concrete frame
Lumber	59	33	103	23
Particleboard	18	17	27	9
Plywood	21	20	15	0
Concrete	223	1,352	190	2,014
Blocks	4	4	0	0
Mortar	24	23	0.1	0.1
Plasterboard	89	25	139	22
Steel	16	25	19	16
Copper/Zinc	0.6	0.6	0	0
Insulation	21	25	23	9
Macadam	315	315	15	0
Glass	4	4	0	0
Paper	2	2	0.1	0
Plastic	2	2	2	2
Putty/Fillers	4	4	11	14
Paint	1	1	8	0.4
Ceramic tiles	1	1	0	0
Porcelain	0.6	0.6	0	0
Appliances	3	3	0	0

The reduction in net CO_2 emission over the building lifecycle, per unit of additional wood needed to make the wood-frame building, was calculated (Gustavsson et al. 2006b). The CO_2 reduction takes into account emissions from fossil fuel combustion for material processing and logistics, the reduction of emissions due to replacing fossil fuel with biomass residues, the avoided emissions due to cement process reactions, and the carbon stock change in wood materials. Primary energy used for production of materials is shown in Table 4.5. As we consider all biomass flows associated with the building construction to be part of the system, the biomass residues from the harvest, processing and demolition that are available for use outside of the production process are assumed to be used as biofuel to replace fossil fuel. In this analysis the reference fossil fuel is coal, meaning that the biofuel replaces coal fuel, and electricity used for material production comes from coal-fired condensing plants.

Table 4.5 Primary energy use (GJ) for production of materials for wood and concrete versions of wood- and concrete-framed versions of multi-story apartment buildings in Scenarios *Sweden* and *Finland,* broken down by end-use energy carrier.

	Final-use	Distribution/ Conversion	Fuel Cycle	Total
Scenario *Sweden* (Wälludden)				
Wood-frame				**2330**
Electricity	311	482	79	873
Fossil Fuel	1251	0	69	1320
Biofuel	137	0	0	137
Concrete-frame				**2972**
Electricity	408	632	104	1144
Fossil Fuel	1661	0	91	1752
Biofuel	76	0	0	76
Scenario *Finland* (Viikki)				
Wood-frame				**2907**
Electricity	383	594	98	1075
Fossil Fuel	1512	0	83	1595
Biofuel	237	0	0	237
Concrete-frame				**3205**
Electricity	372	577	95	1043
Fossil Fuel	2000	0	110	2110
Biofuel	52	0	0	52

The calculated emission reduction of these results is subject to some uncertainty. The primary energy used for building material production is not constant, but varies with time, place, and process technology. Further uncertainties exist regarding the decomposition dynamics of biomass left in forests. The proportion of biomass residues recovered from forests, processing facilities, construction sites, and demolition sites, as well as the fossil fuel that is replaced by recovered biomass residues, affects the resulting carbon balance. In addition, the differences between scenarios *Sweden* and *Finland* show the significance of different engineering and architectural designs of the wood-based buildings and the reference buildings they substitute in place of. Many of these uncertainties were analysed by Gustavsson and Sathre (2006), and although the quantitative extent of the carbon benefit of wood construction was shown to vary, the conclusion that wood construction results in lower net carbon emission than concrete construction was found to be robust.

4.3 Results of the scenarios

Summarized results of the scenario analysis are presented in Table 4.6. The numbers describe the difference in roundwood demand and emission reduction with respect to the baseline (*Base*). In scenario *1m3cap*, increasing the use of sawnwood within the EU from about 0.2 to 1 m3/cap/yr would create an additional roundwood demand of about 600 Mm^3 annually. The reduction in emissions is estimated at 200 Mt C per year, which is more than 700 Mt CO_2 /yr. The impact on carbon stocks in the forests is not included here. This scenario is extreme, and it is unlikely that this much sawnwood will be used with such a high fossil carbon displacement factor. The roundwood demand for this scenario would partly be satisfied by imported roundwood. As a by-scenario we consider the part of the sawnwood demand that would be fulfilled from Swedish harvest (Scenario *1m3cap* SWE), the associated emission reductions of which are estimated to be of the order of 5 Mt C/yr by 2030, or about 20 Mt CO_2/yr.

The scenarios *Sweden* and *Finland* are based on a realistic estimate of the new construction level in Europe. However, it is not presumable that the market share of wooden houses would be close to 100%, especially for multi-story houses. For the construction of one million wood-framed flats instead of concrete-framed flats, 9.7 million m^3 (under bark) additional roundwood will be needed when using the Swedish design (scenario *Sweden*) where the houses are wood-framed with stucco surface. In scenario *Finland*, using the Finnish house alternative with a wood frame and wooden surface panels, 24 million m^3 additional roundwood would be needed. This is only a small part of about 300 Mm^3y^{-1} (measured over bark) unused net growth increment of European forests (UNECE/FAO 2000). By 2030 when one million additional flats of the Swedish design are made with wood frames, the carbon emission during the year of construction will be 4.3 million tC less than it would have been if concrete frames had been used. Of this carbon emission reduction, 23.9% is from reduced fossil fuels used for material production, 26.8% is from reduced cement process reaction emission, 31.8% is from increased substitution of fossil fuels by biomass residues, and 17.5% is from increased carbon storage in building materials. Over the complete lifecycle of the buildings produced each year, the carbon emission reduction will be 4.2 million tC. Of this, 24.4% is from fossil fuels for material production, 25.3% is from cement process reactions, and 50.3% is from fossil fuel substitution. Over the complete life cycle of the buildings there is no permanent emission benefit due to carbon storage in building materials, but by 2030 this carbon stock will still remain in the building materials. Using the Finnish design, the estimated emission reductions are 9.7 million tC compared to the concrete alternative. The specific emission reductions are 0.44 and 0.41 Gg C per 1000 m^3 roundwood, for scenarios *Sweden* and *Finland*, respectively.

Table 4.6 Results of the four construction scenarios from the years 2007 to 2030, showing the additional roundwood demand, and the resulting C emission reduction.

Year	Roundwood demand in addition to *Base* (1000 m^3 u.b./year)				Relative C emission reduction (Gg C)			
	Scen *1m3cap*	Sce *1m3cap* SWE	Scen *Sweden*	Scen *Finland*	Scen *1m3cap*	Sce *1m3cap* SWE	Scen *Sweden*	Scen *Finland*
2007	34898	0	0	0	11792	0	0	0
2008	48493	244	422	1036	16386	83	187	424
2009	63750	665	844	2071	21541	225	374	847
2010	81109	1780	1265	3107	27407	601	560	1271
2011	99290	3560	1687	4143	33550	1203	747	1694
2012	119458	5429	2109	5178	40365	1834	934	2118
2013	139936	6578	2531	6214	47284	2223	1121	2541
2014	160762	6795	2953	7250	54321	2296	1307	2965
2015	182069	7549	3374	8286	61521	2551	1494	3388
2016	206186	8018	3796	9321	69670	2709	1681	3812
2017	232316	8545	4218	10357	78499	2887	1868	4235
2018	260115	9051	4640	11393	87892	3058	2054	4659
2019	287039	10183	5062	12428	96990	3441	2241	5082
2020	316521	11166	5483	13464	106952	3773	2428	5506
2021	349473	12017	5905	14500	118086	4060	2615	5930
2022	383499	12858	6327	15535	129583	4345	2801	6353
2023	419359	13657	6749	16571	141700	4615	2988	6777
2024	459108	14320	7170	17607	155132	4839	3175	7200
2025	500437	14877	7592	18643	169096	5027	3362	7624
2026	542875	15628	8014	19678	183436	5281	3548	8047
2027	587873	16185	8436	20714	198641	5469	3735	8471
2028	594603	15600	8858	21750	200915	5271	3922	8894
2029	597544	14827	9279	22785	201909	5010	4109	9318
2030	598595	14119	9701	23821	202264	4771	4295	9741

The results of these scenarios show a large range of increased roundwood demand, and resulting C emission reduction. Scenario *1m3cap*, which assumes an increased sawnwood demand in Europe from 0.2 to 1.0 m3/cap/year, has a roundwood demand increase in 2030 that is 62 and 25 times greater, respectively, than scenarios *Sweden* and *Finland*. Of this increased roundwood demand in scenario *1m3cap*, only a relatively small part would be met by forest harvests in Sweden. As discussed above, scenario *1m3cap* is extreme. From scenarios *Sweden* and *Finland*, we can conclude that even a massive new construction program of 1 million flats in wooden multi-story houses annually would not create especially high demand for roundwood. Total annual demand for roundwood in 2030 would increase by 9.7 and 23.8 Mm^3 in scenarios *Sweden* and *Finland*, respectively. There would be a slight increase in Swedish roundwood demand after 2013, growing to a level of 0.5 Mm^3 /yr in scenario *Sweden*, and to a level of 1 Mm^3 in scenario *Finland* (not shown in Table 4.6). The differences between scenarios *Sweden* and *Finland* highlight the importance that the building design (of both the wood building and the reference building it substitutes for) has on wood demand and C emission reduction.

5. Forest sector

5.1 Forest sector models

Considering the offshoot of national and international models, the Global Trade Model (GTM) developed at the International Institute for Applied Systems Analysis (IIASA) (Kallio et al. 1987) is among the most influential economic models of the forest sector. With the forest sector, we refer to forestry activities, industries using wood, and the markets for wood and forest industry products. In Europe, applications in active use include the global EFI-GTM (Kallio et al. 2004), the NTM II for Norway (e.g., Bolkesjø and Solberg 2003) and the SF-GTM for Finland (Ronnila 1995). The background of these partial equilibrium models is in the economic theory that assumes profit maximizing producers and utility maximizing consumers making decisions upon consumption, production and trade of commodities. The forest sector models typically assume perfectly competitive markets, but a range of non-competitive market assumptions may also be embedded in them, e.g. as in Ronnila (1995).

An important characteristic of the above models is the assumption that the decision makers have imperfect foresight on what happens in the future. Thereby the long run market equilibrium problem is broken up into a sequence of short run static problems. Following Samuelson (1952), the market equilibria are solved by maximizing the sum of consumers' and producers' surpluses. The EFI-GTM, SF-GTM and NTM models are rich in detail in their description of the forest industry, and their applications on the questions concerning the development of the forest sector in the medium-term are ample (e.g., Solberg et al. 2003, Bolkesjø and Solberg 2006, Hänninen and Kallio 2007). The static formulation (assumption of myopic decision makers) makes it less attractive to consider forest management endogenously, which sets some limitations to their usability in the analysis of long-term responses of the forest sector to climate change policies.

The Forest and Agricultural Sector Optimization Model, FASOM (e.g. Adams et al. 1996) simulates land use management under environmental, political, and technical change. Considering the research question of the present study, one of its main differences compared to the GTM models is that it assumes that the decision makers (e.g., the forest industry and the owners of forest and land) have perfect foresight on what happens in the markets in the future. Hence, the model is cast into a dynamic setting where the market equilibrium is solved simultaneously for all time periods. Both the long term forest management decisions and timber prices are solved for endogenously. Technically, like its static counterparts, the FASOM uses constrained welfare maximization adapted from Samuelson (1952) to solve for the market equilibria. The EUFASOM (Schneider et al. 2008) is the European application of the FASOM model with country-level spatial resolution.

In our analysis, the main focus region is Sweden, for which no detailed forest sector model currently exists. However, due to the fact that international trade plays an important part in the analysis, using a large scale global model with Sweden as one region is a good option. Because the forest industry module in the EUFASOM currently consists of preliminary, crudely aggregated data, and is still in the in testing stage, we chose to use the EFI-GTM model. With the time horizon considered, 20–30 years ahead, it suits well to capitalize on the detailed engineering knowledge of the forest industry production technologies, production capacities and their location, and the prospects for near-term technological innovations presented in the EFI-GTM. Currently the main handicap with the EFI-GTM is that its data base reflects the year 1999. The complete and consistent update for the model is under way in the project EFORWOOD, but those data were not available by the time of this analysis. Nevertheless, we updated the data as much as possible and reasonable considering the pilot nature of this project.

5.2 The EFI-GTM and the main assumptions employed in this study

The version of the EFI-GTM used here divides the globe to 55 regions. Almost all the European countries are represented by their own regions. We model the markets for 34 forest sector commodities (25 forest industry products, five types of roundwood and chips, and four types of waste paper; biofuel is not among the products considered). For each region, supply functions for production factors are defined, as well as a set of fixed-input technologies with specific capacities for producing intermediate and final products. For each European country and product, three or more alternative production technologies are specified. Kallio et al. (2004) provide a more detailed presentation of the model and the listing of its main data sources.

While the EFI-GTM is calculated for each period independently, the model has dynamic features related to the development of timber supply, forest industry capacity and the final product demand over time.

5.2.1 Product demand (Consumers)

Demand for the final forest industry products is assumed to be affected by the price and available income in the countries. The demand increases if the prices decrease or if the income of the consumers (proxied by the GDP) increases. The relationship between product prices, income and the demand is modelled through price and income elasticities. The elasticities were parametrized considering the previous studies for the different products and countries (for instance, Chas-Amil & Buongiorno 2000, Kangas & Baudin 2003, Li et al. 2004, Li & Luo 2006, Hetemäki 2005), and the expert estimates based on the market trends. The markets for the forest industry products are rather mature in industrialized countries, with income elasticities typically below one, and sometimes closer to zero, e.g. for newsprint demand in the US. In the developing countries, the forest industry demand is growing more closely with the GDP. For plywood and particle board, the additional demand in the scenarios *Finland* and *Sweden* were added on the top of the reference demand first updated using the income elasticities and GDP growth.

The price elasticities were assumed to be between –0.7 and – 0.1, depending on the product and the region. The demand functions were benchmarked to the price-quantity observations in the base year 1999. When both demand and price data were available, the demand functions were updated to the latest available data. Examples of the data sources used include European Federation of Corrugated Board Manufacturers (2007), FAOSTAT database (http://faostat.fao.org), CEPI (2007) and RISI (2007).

Because softwood sawnwood is of special importance to the European construction sector and to this study, its consumption in Europe is modelled in a more elaborated manner. In our baseline case, the reference consumption levels of softwood sawnwood in Europe (projected future demand quantities given that the prices do not change) are based on the analysis accounting for the present per capita consumption and assumed population development as discussed in Chapter 4. In the scenarios *Finland* and *Sweden*, the assumed additional demand due to increased consumption of wood in the construction sector is added to the *Base* case demand. In the scenario *1m3cap* the reference demand quantities are projected based on the assumption that the per capita consumption in all EU/EFTA countries will reach 1 m^3 by 2027. Nevertheless, the eventual sawnwood demand is not modelled as fixed, but is responsive to the prices according to the assumed price elasticities. Thus, both the prices and the consumption levels are endogenous. Price elasticities for sawnwood supply ranged from –0.1 (e.g., Canada) to –0.54 (France), based on the studies of e.g., Myneni et al. (1994), Baek and Yin (2006), Fuentes et al. (2006), and Kangas and Baudin (2003).

GDP growth rates for Europe during 2007–2025 are based on figures provided by Centre d'Observation Economique of Chambre de Commerce et d'Industrie de Paris based on the Nemesis model projections made in the EU project MATISSE (see e.g. Jäger et al. 2008). For other regions and for the years before 2007, the GDP estimates were based on the International Monetary Fund (2007) database and projections. For these regions, the latest available figure (for 2008) was assumed up to year 2010. Thereafter we assumed some decline in the GDP growth in the very rapidly growing economies. During 2010–2025, the assumed GDP growth rates in some main non-European economies were 2% in North America, Japan and South Africa, 2.5% in Oceania, 3% in South America, 4% in Russia, India and Indonesia, and 5% in China.

Demand for recycled paper, pulp and wood fibre is derived endogenously based on the use of these factors in the production processes.

5.2.2 The forest industry

In the EFI-GTM, the forest industry maximizes its profit as a price taker, and thus it is assumed to supply to the market whenever the market prices are not below the production costs. The production in each country is limited by the available production capacity, but the industry may invest in new capacity whenever the investments are profitable. Initial and potential investments, production capacities and input coefficients for various industrial processes are provided as input to the model. The data on technologies and initial capacities are based on the year 1999. The main source for the technology data was Jaakko Pöyry Consulting. When possible, the data on the production capacities after 1999 was updated based on sources such as RISI (2006), Confederation of European Paper Industries (2007), CEPIPRINT (2007) and FAO.

The capacity investments in the EFI-GTM model can be allowed to take place entirely freely whenever new production capacities with best known new technologies would result in profit in the markets. However, because the forest industry operates in the world with the investors typically having already large amount of existing capacity, the profitability of which the new capacity would adversely affect, we have in previous studies set some exogenous limits to the maximum annual capacity increases in the continents. Because in the scenario *1m3cap* we explore the impacts of exaggeratingly high demand increase for softwood sawnwood, which can strongly affect not only the wood markets but also indirectly the markets for other forest industry products, we kept such limits very slack in all the scenarios in order to make them comparable. The product specific production capacities in the different continents (North America, South America, Europe, Oceania, Asia, Africa) or globally were not allowed to increase by more than 20% annually. In the case of no previous capacity for a particular product existing in a continent, only a global capacity constraint was applied.

Regarding individual countries, we applied additional guidelines for some of the products when specifying options for new investments, which will be discussed below. With the exception of some paper grades such as tissue, the state-of-the-art paper machines tend to be rather large, typically more than 300 000 tonnes/year. The new capacity is most likely to be built in the regions close to the market demand. When this is not the case, the investing region must at least have good access to raw material. Optimally both conditions would apply. With the exemption of tissue and sack paper, we required that the region can add new paper or paperboard machines only if *one* of the following conditions is satisfied: the region is a significant consumer of the paper grade considered (consumption more than 400 000 t/a), the country has significant forest resources (over 400 mill.

m^3), or the country has significant amount of previous chemical pulp capacity (at least 1 million t/a). Regarding chemical pulp, the modern mills are typically approaching the size of one million tonnes per year or even more. For chemical pulp investments, we required that the investing region has to have an *excess* supply of wood fibre measured by the annual growth of forests - in addition to what is used with the existing capacity - to be able to host a new one million tonne pulp mill.

The investments in solid wood products (sawnwood and plywood) were only allowed in countries which have underutilized forest resources to host new mills. Underutilization was evaluated by looking at the difference in the annual growth of timber stock and the amount of roundwood used by the existing production capacity in the region in the previous period. Although the distance to the markets cannot be neglected when investing in the sawnwood production either, the availability of raw material is a more essential factor in locating the mills (see Aguilar 2008). The high transportation costs of roundwood are the main reason for this.

5.2.3 Timber supply (Forest owners)

Timber supply is assumed be affected by the price and volume of growing timber stock. The higher the market price or the timber stock, the higher the timber supply is assumed to be. In the EFI-GTM, this relationship is modelled via the elasticity parameters of wood supply with respect to the growing stock and timber price. The timber supply functions are defined to four grades: non-coniferous and coniferous pulpwood and saw logs. Growing stock changes from period to period are accounted for as the net of forest growth (growth rates given as input data) and harvests. For the countries in the EU/EFTA region, the growing stock data were separated into coniferous and broadleaved forests. For the rest of the regions, all the four roundwood categories were considered to share one stock. For each region, maximum annual harvest was limited to remain less than double of the forest growth. This limit was not binding in the *Base* case.

Elasticity of wood supply with respect to the growing stock was assumed to be 0.7 in all countries. Hence, it was assumed that the changes in the timber stock are not fully reflected in wood supply. A main reason why we consider this assumption to be justified is the fact that part of the growth always takes place in the younger age classes, which are not ready to be harvested given the optimal forest management strategies.

The timber supply elasticities with respect to the wood price were based on econometric studies (e.g., Bolkesjø and Solberg 2003, Hänninen et al. 2006), expert estimates and model simulations. For Russia and non-European countries, unitary elasticity was applied. For countries in Europe, the elasticity 0.5 was applied for all timber grades. The elasticities for Sweden were examined with simulations by Matrix model (see Section 6.2). The results supported the assumption of price elasticity of pulpwood supply on the order of 0.5 under the most plausible real rates of interest. For saw logs, elasticities slightly lower than that were suggested. Nevertheless, because the elasticity 0.5 gave a better fit for the model output against the actual observations in 2000–2004 for Sweden, we chose to use that value for the saw log supply also.

Data on the growing stock in forests available for wood supply and the growth rates of the stocks were based on the database of the European Forest Institute (EFI) and on the UN-ECE/FAO Forest Resources Assessment (UN-ECE 2000).

5.2.4 Other assumptions

The development of foreign exchange market is among the key drivers to the forest sector. The exchange rates strongly affect the competitiveness of the regions against each other, but they are extremely difficult to forecast. At the time being, the Euro currency (€) is at a historically strong level against many currencies important to the forest sector, and we had to make the choice whether to assume the current situation to prevail in the future. We ended up assuming that the value of the Euro against other currencies gradually returns to its average level of the years 2000–2006, reaching the average in 2015 and maintaining that level to 2025. Hence during 2015–2025, one Euro was assumed to be worth 1.1 US dollars, 1.5 Canadian dollars, 9.1 Swedish crowns, 0.66 UK pounds and 125 Japanese yen, to name but a few currencies.

Russia has been planning to gradually increase tariffs on its roundwood exports to 50 €/m^3, which would, in practice, stop timber exports from Russia to other countries. We assumed the tariffs to be raised to 10 €/m^3 (the tariff level in 2007) and kept at that level with no further increases.

The real energy prices were assumed to be double of what they were in the year 1999 during the period 2006–2025.

5.3 The results from the simulations with the EFI-GTM

We used the EFI-GTM to project demand for and supply of forest industry products, timber prices and timber harvests. The main focus of the project is the wood products industry and roundwood markets in Sweden. Nevertheless, in order to better understand the results and the overall impacts of the studied assumptions, we start by reporting the key results at the European level. For Europe we use the acronym EU/EFTA, by which we refer to countries in EU27, Norway and Switzerland.

5.3.1 Results for EU/EFTA region

Base case

Table 5.1 shows the development of consumption and production of roundwood and forest industry products in EU/EFTA. In the *Base* case, consumption of timber increases on the average by 0.7% p.a. during 2008–2030. Consumption of softwood sawnwood, other wood products, chemical pulp and paper increase at the average rates of 1.0%, 0.9%, 0.5% and 1.3%, respectively. The increase in consumption is slower than the assumed GDP growth, which is in accordance with the GDP elasticities of demand used. Production of softwood sawnwood, paper and paperboard increase less than consumption, which leads to a decrease in the EU/EFTA self-sufficiency in these product groups.

Scenario 1m3cap

As expected, the most significant changes to the *Base* case occur in scenario *1m3cap*, where the softwood sawnwood consumption was assumed to raise to 475 million m^3 in 2027, given no price changes. The actual consumption met by the globally increasing sawnwood supply increased only to 417 million m^3 in 2027. The reason for the gap was the rise in wood costs in the sawnwood production, which made it impossible for the industry to expand more, despite the sawnwood price increase caused by the strong demand. The main part of the capacity added to satisfy the demand increase in Europe was installed outside EU/EFTA region. The softwood sawnwood production in EU/EFTA increased to 213 million m^3 in 2030, up 111 million m^3 from the *Base* case.

The increase in softwood lumber production in EU/EFTA is partly relying on timber imports, which is also indicated by the fact that the timber consumption grows more than harvests. The rise in lumber production makes the supply of sawmill chips ample and thus makes pulpwood prices fall, benefiting the producers of panels and pulp. In particular, production of panels increases considerably. The increase in chemical pulp production reflects further on the rise in paper production.

Scenarios Finland and Sweden

As Table 5.1 indicates, the impacts of the assumed increase in wood consumption of the construction sector are rather moderate in scenarios *Finland* and *Sweden*. For instance, there is no change in the pulp and paper supply in EU/EFTA. In both scenarios, EU/EFTA forest industry product demand increases more than production, which means that the large part of the growth in wood products consumption in the construction sector is satisfied by imports. In scenario *Finland*, timber imports also increase considerably.

Table 5.1 Projections for production and consumption of roundwood and forest industry products in EU/EFTA region

Scenarios	Growth of consumption, p.a., Average 2008–2030	Growth of production, p.a., Average 2008–2030	Consumption 2030 (mill. m^3, mill. tn)	Production 2030 (mill. m^3, mill. tn)	Change in consumption to *Base* in 2030 (mill. m^3, mill. tn)	Change in production to *Base*, 2030 (mill. m^3, mill. tn)
Roundwood						
Base	0.7 %	1.2 %	421	407		
1m3cap	2.2 %	1.6 %	607	448	186	41
Finland	0.8 %	1.2 %	429	410	8	3
Sweden	0.8 %	1.2 %	423	409	2	2
Softwood sawnwood						
Base	1.0 %	0.1 %	123	102		
1m3cap	5.7 %	3.1 %	417	213	294	111
Finland	1.3 %	0.3 %	133	107	10	5
Sweden	1.1 %	0.2 %	127	103	4	1
Other mechanical forest industry products						
Base	0.9 %	1.2 %	101	87		
1m3cap	1.1 %	2.4 %	106	113	5	26
Finland	1.1 %	1.3 %	104	89	3	2
Sweden	0.9 %	1.2 %	102	87	1	0
Chemical pulp						
Base	0.5 %	1.0 %	28	31		
1m3cap	0.6 %	1.2 %	29	32	1	1
Finland	0.5 %	1.0 %	28	31	0	0
Sweden	0.5 %	1.0 %	28	31	0	0
Paper and paperboard						
Base	1.3 %	1.0 %	128	117		
1m3cap	1.3 %	1.1 %	128	121	0	4
Finland	1.3 %	1.0 %	128	117	0	0
Sweden	1.3 %	1.0 %	128	117	0	0

5.3.2 Results for Sweden

Base case and scenarios Finland and Sweden

Table 5.2 shows the development of consumption and production of the forest sector products in Sweden at an aggregate level. It can be seen that there are differences mainly between the scenario *1m3cap* compared to the other scenarios. In the *Base* case and also in scenarios *Finland* and *Sweden*, both the harvests and use of roundwood are about 78–79 million m^3 in 2030. Softwood sawnwood production and consumption increase at a pace slower than EU/EFTA average, while the production of other wood products increases by about 5% p.a., due to growing demand in the export markets. In the *Base* case, the Swedish production of softwood sawnwood was about 19 million m^3 in 2030, about one million m^3 up from the current level. This presents a very modest growth annually, but it is of the same magnitude as the increase in production in EU/EFTA region. Chemical pulp production increases about 0.4% annually, and paper production about 1% annually.

Scenario 1m3cap
In the scenario *1m3cap*, the Swedish softwood sawnwood supply increases at the rate of close to 2% annually during the 2008–2030, ending up at some 26 million m^3 in 2030. The growth in supply is below the European average, but so is the growth in demand. In 2030, the difference in softwood lumber production between the scenarios *Base* and *1m3cap* is about 7 million m^3, which leads to an increase in saw log harvest of about 14 million m^3. Because the increase in sawmill chips supply causes a decline in demand for the substitute product, pulpwood, the total harvests increase only some 9 million m^3. See Table 5.4 for the development by roundwood category.

The rise in softwood saw log prices caused by the drastic increase in saw log demand hurts the plywood producers that are forced to go out of business in the scenario *1m3cap*. As indicated by Table 5.3, the changes in panels (MDF and particle board) are rather moderate on an absolute volume basis. On a percentage basis the figures show a drastic change. The panel producers are favoured by the decline in chips prices. Still, the particle board production declines due to a large rise in production elsewhere in the world due to improved fibre availability. However, the changes are small in absolute terms and are sensitive to the assumed investment costs.

Roundwood prices
Competition over wood fibre increases in the future, and the prices of both pulpwood and saw logs rise in the *Base* case. Also, the Russian timber export tariff increases the prices in Scandinavia. In the *Base* case the prices for softwood saw logs are projected to be 30% higher, and pulpwood prices 54% higher, in 2030 than in year 2004. Note, however, that these increases can be considered a high estimate, since for technical reasons we chose to accept a higher rate of forest industry capacity accumulation than what we would have chosen in some other analyses.

Table 5.5 compares the price changes in scenarios *Finland*, *Sweden* and *1m3cap*, with respect to the *Base* case in 2030. The Swedish case has the lowest market impacts, with softwood saw log price being about 3% up from the *Base* case level in 2030. In *1m3cap*, the saw log price more than doubles from the *Base* case due to the drastically increasing softwood lumber demand.

The growth in softwood lumber production makes saw log chips supply abundant and leads to decline in the pulpwood harvests and price. In scenario *1m3cap*, the softwood pulpwood price comes down by close to 20% compared to *Base*. Due to the substitution effect in panel production, the hardwood pulpwood price also falls.

Table 5.2 Projections for production and consumption of roundwood and forest industry products in Sweden (wood in m^3 and products in tons)

Scenario	Growth of consumption, p.a., Average 2008–2030	Growth of production, p.a., Average 2008–2030	Consumption 2030 (mill. m^3, mill. tn)	Production 2030 (mill. m^3, mill. tn)	Change in consumption to *Base* in 2030 (mill. m^3, mill. tn)	Change in production to *Base*, 2030 (mill. m^3, mill. tn)
Roundwood						
Base	0.6%	0.8%	77.6	77.7		
1m3cap	1.3%	1.3%	90.1	86.8	12.5	9.1
Finland	0.7%	0.9%	79.0	78.6	1.4	0.9
Sweden	0.7%	0.9%	78.6	78.2	1	0.5
Softwood sawnwood						
Base	0.3%	0.2%	6.7	18.7		
1m3cap	1.3%	1.7%	8.8	26.1	2.1	7.4
Finland	0.4%	0.4%	6.8	19.4	0.1	0.7
Sweden	0.3%	0.3%	6.7	19.2	0	0.5
Other wood products						
Base	1.1%	5.0%	2.3	3.6		
1m3cap	1.1%	5.2%	2.3	3.7	0	0.1
Finland	1.1%	5.4%	2.3	3.9	0	0.3
Sweden	1.1%	5.3%	2.3	3.8	0	0.2
Chemical pulp						
Base	1.1%	0.4%	4.4	8.5		
1m3cap	1.1%	0.9%	4.4	9.5	0	1
Finland	1.1%	0.4%	4.4	8.5	0	0
Sweden	1.1%	0.4%	4.4	8.5	0	0
Paper and paperboard						
Base	0.7%	1.1%	2.5	11.9		
1m3cap	0.8%	1.0%	2.5	11.7	0	-0.2
Finland	0.7%	1.1%	2.5	11.9	0	0
Sweden	0.7%	1.1%	2.5	11.9	0	0

Table 5.3. Changes in Swedish production of wood products in the alternative scenarios with respect to the base line in 2030.

	Change to *Base* case in 2030, mill. m^3			Change to *Base* case in 2030, %		
	Finland	*Sweden*	*1m3cap*	*Finland*	*Sweden*	*1m3cap*
Softwood sawnwood	0.7	0.5	7.4	4%	3%	39%
Hardwood sawnwood	0.0	0.0	0.0	17%	-3%	5%
Plywood	0.0	0.0	-0.1	0%	-3%	-100%
Particle board	-0.1	0.0	-0.7	-5%	2%	-44%
MDF	0.4	0.2	1.1	29%	16%	72%

Table 5.4. Changes in Swedish roundwood harvests in the alternative scenarios with respect to the *Base* case in 2030.

	Change to *Base* case in 2030, mill. m^3 sub bark			Change to *Base* case in 2030, %		
	Finland	*Sweden*	*1m3cap*	*Finland*	*Sweden*	*1m3cap*
Softwood saw logs	0.9	0.5	14.2	2%	1%	35%
Hardwood saw logs	0	0	0	0%	0%	1%
Softwood pulpwood	-0.1	0	-4.8	0%	0%	-16%
Hardwood pulpwood	0	0.1	-0.2	0%	0%	-4%

Table 5.5. Changes in Swedish roundwood prices in the alternative scenarios with respect to the *Base* case in 2030 (%).

	Finland	*Sweden*	*1m3cap*
Softwood saw logs	5.2	2.7	110
Hardwood saw logs	0.2	0.1	0.6
Softwood pulpwood	0.3	0.3	-19
Hardwood pulpwood	0.2	0.2	-9

6. Regional analysis

The focus of this chapter is to link the EFI-GTM sector model with a regional forest management model. The ideal outcome of this analysis would be to understand what forest management activities result as a consequence of the market situation implicated by the EFI-GTM. This would also make it possible to trace in detail the forestry and forest carbon effects of increased use of construction wood. However, as will be seen (section 6.3), the dynamics of the forest, including the assumed reaction of forest owners, is such that it does not allow an analysis along those lines. There is a lack of consistency between what is specified by the EFI-GTM and what emanates from the forest system.

The first section will elaborate on available models and systems for the kind of integrated analysis that is the object of this report. Section 6.2 gives the specifics of the model, SMAC, which is employed here. Section 6.3 relates the results of the analyses of the EFI-GTM scenarios with the SMAC model.

6.1 Models for regional analysis

The discussion in this section is about the choice of a forest projection model, or forest analysis system. The task is to find a suitable model that can be integrated in a sector model system that can analyze consequences of increased wood use on a European scale. What considerations could or should be made?

There exist a considerable number of systems for the analysis of long term forest management. The list below (see Table 6.1) contains 22 European systems without being comprehensive. It would then seem that there are good opportunities to find instruments for the kind of analysis that is conducted in this study. There are, however, obvious limitations to the models or systems that could be used. This will be investigated following a typology based on two dimensions, one pertaining to the method by which management actions are determined in the projection, and the other on the entity by which the forest is described.

Table 6.1. A selection of European systems for forest management analysis with emphasis on large scale applications.

Name	**Type**	**Comment**	**Link**
MELA (FI)	OU	Well established system. Can use different input data and is intended for use on forest holdings as well as at regional and national level.	http://www.metla.fi/metinfo/mela/index-en.htm
SIMO (FI)	OU	Is rather a platform on which to build planning systems. Should in principle have the same range of application as other major systems like MELA, Monsu and Heureka.	http://www.mm.helsinki.fi/mmvar/SIMO/
Monsu (FI)	OU	Includes a different optimization methods and support for multiple criteria decision making.	www.monsu.net
SMA (FI)	S	Same growth functions as MELA. Optimizes stand management.	
Heureka (SE)	OU	A new system being developed with applications for forest holdings as well as for regional and national levels. The former is optimizing while the latter is simulating.	http://heureka.slu.se
Hugin (SE)	SU	A system with roots in the early 80's. Built on NFI data and simulating based on policy; to be replaced by Heureka.	
FMPP (SE)	OU	The current system for larger enterprises; to be replaced by Heureka.	
SMAC (SE)	OM	A research tool. An area matrix model built on NFI data.	
GAYA/JLP (NO)	OU	A system with in principle the same structure as for instance MELA. Originates from a generic stand simulator developed in Sweden.	
PEB/AC (DK)	OU	A system built on EXCEL including the EXCEL LP solver.	
Silva (DE)	SU	Simulates the development of single stands or landscapes based on expert advice.	
Sibyla (SK)	SU	Essentially a Slovak version of Silva.	
CONES (AT)	SU	Specialized on harvesting and natural regeneration of forest stands in steep terrain with cable yarding system; spatial aspects based on ArcGIS.	
DSD (AT)	S	Stand based specialized on the evaluation of silvicultural treatment for Scots pine and Norway spruce; includes multiple criteria support.	
Monte (ES)	OU	(See Monsu)	www.forecotech.com
SADfLOR (PT)	OU	System with considerable flexibility as regards system components; optimizing with LP and simulated annealing.	
CAPSIS (FR)	S	Platform for analyzing stand models; special emphasis on characterizing tree properties (e.g. taper).	http://coligny.free.fr/
ETCAP (TR)	SU	For regional level planning.	
DRYMOS (GR)	S	Single tree model for the study the reaction of forest stands of broad-leaved oak to forest management operations	http://cordis.europa.eu/greece/news_rd70.htm
EFIMOD (RU)	SU	A system linking 3 parts: a tree, a soil (ROMUL) and statistical climate generator (SCLISS) model.; process based with emphasis on forest management vs. climate change.	http://eco.wiz.uni-kassel.de/model_db/mdb/efimod.html
FORRUS (RU)	SU	Links individual-tree modeling of the multispecies uneven-aged forest stand dynamics (FORRUS-B), structure of phytomass of growing stand (FORRUS-P), and the forest area dynamics (hundreds and thousands ha; FORRUS-S).	http://www.ipef.br/publicacoes/scientia/nr73/cap08.pdf
EFISCEN (EFI)	SM	Applications hitherto on regional and national level; basis in the SMAC model.	http://www.efi.int/portal/virtual_library/databases/efiscen/

Forest management actions can be set by: (1) specifying objectives for the output from or state of the forest, and then (2) making the model determine what actions maximize the objectives. Actions are confined to a proper domain; for instance, final felling is allowed only above a certain age.

Actions can instead be determined by linking them to the state of the stand or the forest before the model run. An example is to specify that final felling should be done above a certain age. The results in terms of objectives are shown when the model is run. The former approach is here termed optimization and the latter simulation.

Concerning forest representation, the distinction that will be drawn here is between those models that operate with a set of unique areal units and those that describe the forest through a predefined set of forest states. The former will here be termed unit area based and the latter matrix area based. The reason for drawing on this distinction is the following: Unit area based models almost universally project the future development of each unit individually. The system uses more or less complex biophysical models to perform this projection. In contrast, the area matrix models only can and needs to shuffle areas between the preset states. In most cases this means that at run time the projection model is simple, using linear relations. The important difference here is that while unit area models retain the integrity of each unit during projection, matrix area models essentially deal with the distribution of one common resource, the forest area. Thus, the different forms offer different possibilities of arranging the analysis.

The forest representations may also be interpreted as a distinction between growth models: between area production models and area matrix models (Munro 1974). The different forms are not necessarily associated with more or less data although unit models tend to be more data intensive; there could be just a few area units with a few data items that represent the forest as against a huge number of matrix elements. Large scale here means anything from a private forest holding of a few hundred hectares to a whole nation or continent. What is of importance is the number of units used. A private forest holding may require some tens of units while a reasonable description of Sweden can be captured by some tens of thousands of NFI plots.

Thus, there are four categories – OU for optimizing and unit area based, SU for simulating and unit area based, OM for optimizing and matrix area based, and SM for simulating and matrix area based. The systems listed in Table 6.1 cover most of, if not all, the systems that fall into the categories defined here that are found in Europe. Most of them could probably be classified as Decision Support Systems (DSS), i.e. they have some degree of flexibility such that they can be adapted to different planning problems for different users. The SMAC model is an exception as it only exists as a research tool, although commercial DSS applications have been built with components from the model. An analysis of similar systems in North America was conducted by Johnson et al. (2007). Some models intended only for stand wise analyses are also included in Table 6.1. In the table they are denoted by S; they will not be commented further.

One can note that unit area models dominate over matrix models. This is not surprising, considering two circumstances. First, research on growth and yield models have very much focused on the development of stand models. The stand model is the basic element of a unit area system; the kernel of a unit area model is the administration of data that feeds into the stand models for projection and summarizes the results over the units. Second, unit area models have great potential in coping with all the details that shape the development of and output from a unit of forest land. Besides, forest data is traditionally formatted on a unit by unit basis.

Optimizing systems dominate in the Nordic countries, according to Table 6.1. This does not capture the entire truth as, for instance, the simulating systems used by private forest owners in Sweden and Norway are not in the list. Central Europe, on the other hand, is dominated by simulating systems, whereas Southern Europe, at least the Iberian Peninsula, is represented by optimizing systems. If this distribution should be attributed to some rational causes, it may be correlated with the prevalence of large scale forest owners. Former SEV countries and Soviet republics are less well represented than other European countries.

What models or systems would be suitable for the current project? The following requirements apply: It should (i) be large scale, encompassing a whole country, (ii) react to price and/or volume information from the EFI-GTM, and (iii) be able to yield information on the carbon flow or content of the forest system. It is then a matter of outlook whether the analysis should answer to the question "What would be the likely or possible effects of changed market conditions according to the EFI-GTM?" or to the question "What are the consequences of delivering forest products according to the EFI-GTM scenario?" The question on likely effects assumes that prices are known, or presumed to be known, by the forest owners, whereas an investigation of consequences is based on a requirement of volume deliveries.

One implication of the requirements is that one needs an optimizing system. It is not feasible to try to fix all the management rules such that the consolidated result of a projection on the national level agrees with the EFI-GTM scenario. (We limit ourselves to OU and OM from now on.) Are then all optimizing systems viable? In principal they are. Given that data are arranged and adequate computer capacity is allocated, one should be able to answer both of the above questions. The way to do it varies, however.

An almost universal procedure for conducting an optimization of long range problems with an OU system is, first, to compute a set of projections over the planning horizon under an (almost) exhaustive set of different treatment schedules. Then, with the projections corresponding to the variables in the optimization problem, the data are fed into a solver and a solution retrieved. By far the most common optimization problem is LP problems, but MIP (Heureka) and simulated annealing and other heuristics (Monsu, SADfLOR) can also be found. The size of the optimization problem would be huge. For Sweden, with about 20,000 units (NFI plots) to describe the forest, one would expect to have something like 2 to 20 million variables in the problem. This is not prohibitive but needs to be taken account of.

The procedure is quite different for OM systems. Here, the matrix growth model is built into the optimization problem and the problem is solved in one step. This means that all relevant data, including the growth model, are fed directly into the solver. For OM systems the size is dependent on the number of classes, or elements, in the matrix and the number of periods. (Of course, since matrix models are growth models like other growth models, they could also be administered like an OU system.)

The difference in procedure could be an advantage for OM models. Since optimization relies on just one step, it could be easier to set up an OM than an OU model in an iterative analysis in search of, for instance, market clearing prices. This kind of application has been demonstrated with the SMAC model (Sallnäs and Eriksson 1989).

Depending on whether it is likely effects or consequences that are at focus, the size and complexity of the problem will vary both for OU and OM systems. For the analysis of likely effects, where the prices are input from EFI-GTM, we have an unconstrained problem (except for the forest endowment). For OU we only need to pick the best program for each unit given the price vector over time. For MU we could solve the problem as a sequence of one-period problems (this is also the formula followed in this study). The output would be, among other items, a set of volumes over the planning horizon, though without guarantee of consistency with the EFI-GTM scenario. For an analysis of consequences, where specific volumes should be delivered over the planning horizon according to the EFI-GTM scenario, we have a constrained problem. In both OU and OM models we need to use LP or some other method to solve for the required volumes. The output would be, among other items, a set of shadow prices over the planning horizon, though without guarantee of consistency with the EFI-GTM scenario. Whether OU or OM should be preferred in this respect cannot be generally stated but has to do with what is practical in the individual case.

The availability of carbon data varies among systems. This can be analyzed along two dimensions, one pertaining to the carbon stock and the change of the carbon stock in the forest system, and the other to the ability to differentiate among assortments with different uses. The stock issue can be divided into soil, tree layer and field layer. The tree layer should normally not be a problem, given that conversion figures exist. The more detailed the description of the tree layer, the more elaborate calculations can be made; systems with single tree models, like Heureka, MELA, and Monsu, would do better than aggregated models like SMAC. A soil model is integrated with Heureka; how it is with other systems has not been investigated. (The most advanced systems in this respect appear to be the process-based models EFIMOD and FORRUS; they are on the other hand simulating systems and do not qualify for this reason.) We do not have good information on the treatment of layer and natural mortality and associated decomposition processes. The assortment issue has essentially to do with to what extent and with what realism the amount of fuel wood can be assessed. This is a problem of the same nature as the estimation of carbon stock in the tree layer, and can be approached in very much the same manner.

Finally, practical aspects are decisive when choosing a forest system. One aspect to consider is the institutional backing of the forest model. Some OU models are “institutionalized” and do not hinge on individuals; others are not. Another question is whether data are available for the system. This should not be a problem for OU systems that are based on NFI data such as MELA and Heureka. Yet another is consideration of the geographical extent of the analysis. Most or all the systems have been developed based on some growth and yield models and associated data. The range of flexibility in this respect may be limited. Systems like SIMO, Heureka and SADfLOR are built with a modular structure and should in principle be transferable. Other systems may be more “hard coded” and thus less flexible.

The model used in this report is the OM model SMAC. The choice was based in part on practical consideration. The computer code was available to one of the authors, as were forest data in the form of NFI plots for Sweden, and the model has, as mentioned above, been used in similar exercises before. Finally, since Heureka has not yet left the test bench, there was not much of a choice, at least not if the analysis should be made for Sweden.

6.2 Matrix model and data

The SMAC model is built on the dynamics of the forest model developed by Sallnäs (1990). It is an area matrix model which distributes the forest on some 10,000 states. The model operates with 5-year periods. One consequence of this is that in the analysis the yearly EFI-GTM data has to be aggregated to 5-year periods (see section 6.3).

The problem that is solved with the model is the following: Given the endowment of forest resources and economic and other conditions, what forest management activities will be pursued by the forest owners? The most important assumptions concerning the behaviour of the forest owners are here that they (i) seek to maximize monetary profits, and (ii) expect the current price level (and other economic conditions) to persist throughout time. The first assumption is only approximately true; the other should be consistent with efficient timber markets. The general outline of the analysis is presented below; a more detailed description of the procedures is found in (Eriksson et al. 2007b).

Assumption (ii) allows us to approach the problem as a series of one period problems. This means that the optimal management of the forest owners for period *t* is derived, and the state of the forest is updated and projected into period *t*+1 with the growth model. Then the procedure is repeated until the end of the planning horizon. The optimal management under given conditions (prices, etc.) is derived by solving an infinite horizon problem with value iteration. The discount rate was assessed by using the method presented by Berck and Bible (1984), i.e. the discount rate that gives model results coinciding with observed behaviour is used. Here, the model was run with the current state of the forest and with original prices (see section 6.3). A discount rate of 2.5% generates a harvest level of the first two five-year periods that quite closely coincides with the current harvest level in Sweden. Prices are given by the EFI-GTM model. It should be observed that assumption (ii) implies that forest owners do not have perfect foresight, i.e. they do not know the result of the EFI-GTM. They base their calculations exclusively on the price prevailing in the period that is currently analyzed. Forest owners can only vary the times of thinning and final harvests; stand establishment is fixed to a preset program (based on NFI data) and thinning is not implemented in the model.

To ensure greatest possible consistency between the EFI-GTM and the SMAC model, the models were calibrated with elasticities. Thus, the SMAC model was run with price levels ranging between 0.5 to 2 times the original price at the current state of the forest and the ensuing supply curve was delivered to the EFI-GTM.

A data set consisting of 21,301 sample plots of the National Forest Inventory (NFI) from 1996, 1997 and 1998 was classified according to the definitions of the SMAC model (Sallnäs 1990). The forest area taken into account here was 20.4 million hectares, corresponding to the area of productive forest in Sweden, 22.4 million hectares, from which is deducted 2 million hectares for reserves and nature-oriented modified management following the SKA99 study (Skogsstyrelsen 2000).

Timber and pulpwood prices were taken from the EFI-GTM model. For timber, the EFI-GTM price was set at the price for timber with a top diameter of 20 cm. The relative distribution at different top diameters was based on the price list in (Eriksson et al. 2007b). Prices and costs for silviculture and harvesting were also taken from Eriksson et al. (2007b) (see Table 6.2). Even though the base year of those prices were 1997, the prices were used since an analysis of nominal prices for the years 1998 to 2006 showed practically no change (Skogsstyrelsen 2007).

Tabel 6.2. Harvesting and silvicultural costs

	Region			
	Reg1	Reg2	Reg3	Reg4
Forwarder including operator (SEK/h)	357	357	357	357
Harvester in final felling including operator (SEK/h)	818	818	818	818
Harvester in thinning including operator (SEK/h)	612	641	678	720
Cleaning and precommercial thinning (SEK/h)	203	203	162	162
Scarification including operator (SEK/h)	934	934	1116	1116
Planting excluding plants (SEK/h)	170	170	170	170
Plants (SEK/1000)	2200	2200	2200	2200

6.3 Results

Scenarios are here analyzed based on prices on round wood computed by the EFI-GTM and reported in section 5.3. The prices for timber with a top diameter of 20 cm was 446 SEK per m^3 top for softwood saw logs and 212 and 286 SEK per solid m^3 under bark for softwood and hardwood pulpwood, respectively. These prices will here be termed original prices. As the time step in the

SMAC model is 5 years, the prices for each 5-year period of saw logs and pulpwood, respectively, was multiplied by a factor computed by taking the average of the EFI-GTM price series for the period divided by the original price. The factors are given in Table 6.3 for the five 5-year periods from 2006 to 2030 for the *Base* and *1m3cap* scenarios. In the following, scenarios *Finland* and *Sweden* will not be studies since the price figures for these two scenarios are almost identical with the *Base* scenario. Yet another scenario is introduced, Zero, where the original prices are retained throughout. It is only run by the SMAC model and does not emanate from the EFI-GTM.

Table 6.3. Saw log and pulpwood relative change factors for 5-year periods from 2006 to 2030

		5-year period				
	Scenario	2006-10	2011-15	2016-20	2021-25	2026-30
Sawn wood	*Base*	100%	101%	106%	109%	136%
	1m3cap	103%	136%	168%	209%	290%
	Zero	100%	100%	100%	100%	100%
Pulpwood	*Base*	100%	118%	130%	149%	164%
	1m3cap	98%	96%	100%	109%	127%
	Zero	100%	100%	100%	100%	100%

Volumes are presented by 10-year periods although the time step of the model is 5 years. This is because the initial two 5-year periods reveal an adjustment pattern which makes comparisons difficult. The first 10-year period is also the basis for the elasticity assessment (see section 6.2). The use of 10-year periods for presentation makes it slightly difficult to compare the results from SMAC and EFI-GTM. Here is the convention that the first three 10-year periods of the SMAC model is aligned with years 2008, 2018 and 2028, respectively, of the EFI-GTM.

The analysis will begin by looking at the shorter term, i.e. the 25 years covered by the EFI-GTM. After that, the consequences on a time scale of 200 years will be observed. In the 200-year projections the price level of the last 5-year period is assumed to continue.

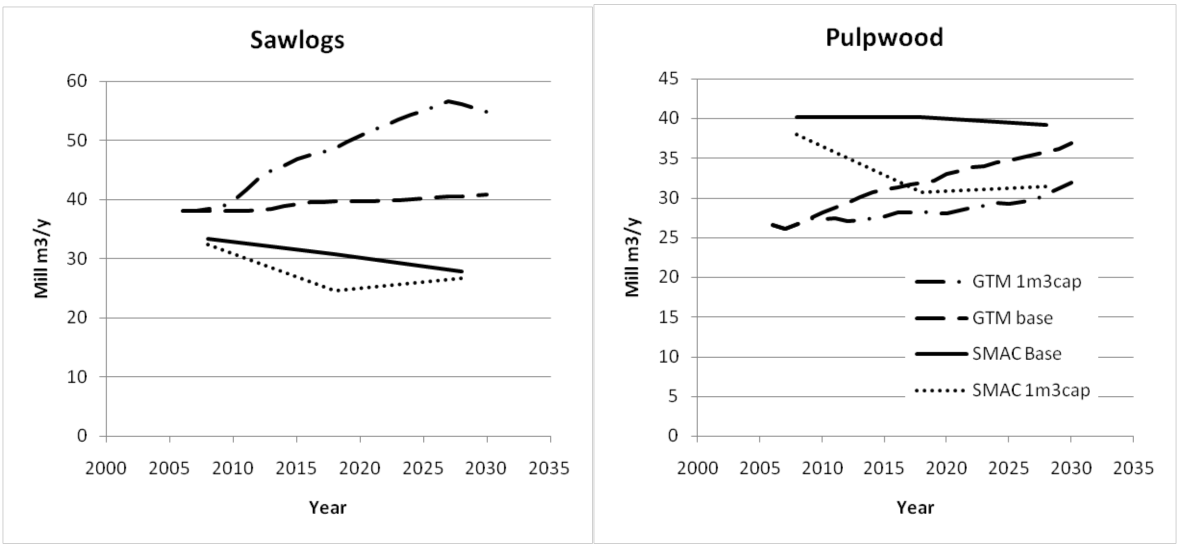

Fig. 6.1. Saw log and pulpwood volumes from EFI-GTM and SMAC under different price scenarios over the first 3 10-year periods (data points for each year for EFI-GTM and for years 2008, 2018 and 2028 for SMAC).

Figure 6.1 shows the harvest of saw logs and pulpwood projected by the SMAC model under the price scenarios. For comparison, the volumes of the EFI-GTM are included. Two observations can be made. First, the saw log volumes given by the SMAC volumes are slightly smaller than the EFI-

GTM volumes in the first 10-year period. What is more conspicuous is that in the following periods saw log volumes in SMAC are reduced, whereas they increase in EFI-GTM. Furthermore, timber volumes according to SMAC are smaller in the *1m3cap* scenario than in the *Base* scenario despite a higher price increase in the former.

The SMAC pulpwood volumes are higher in the beginning compared with EFI-GTM. The trend of the SMAC pulpwood volumes then closely follows that of the timber volumes. That pulpwood volume in the SMAC projection exceeds that of EFI-GTM, partly due to the inclusion in the former of about 6 million m^3 that is used as fuel wood.

These results of the SMAC model are not only contradictory but also seem somewhat counterintuitive. Why is the *Base* scenario producing more timber than *1m3cap* during the initial 25 to 30 years in the SMAC model? The reason is essentially that the total harvest volume is greater (Figure 6.2). This compensates for the fact that relatively less of the solid volume in scenario *Base* is timber; 43% and 42% in 10-year period 2 and 3, respectively, for scenario *Base* as compared to 44% and 46% for scenario*1m3cap*.

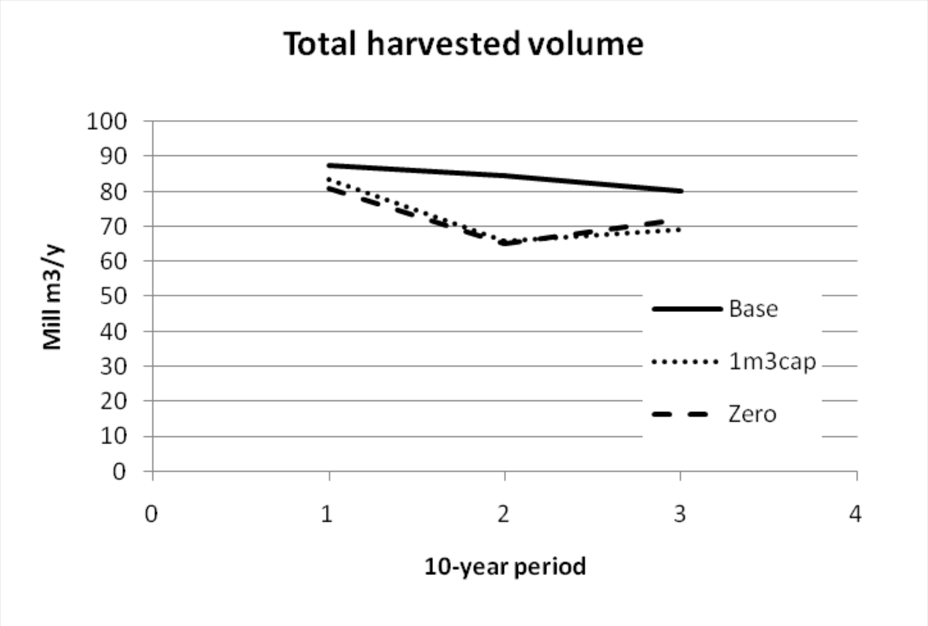

Fig 6.2. Total harvest volume per year over the first three 10-year periods for different scenarios with the SMAC model.

That harvests are greater in scenario *Base* can be explained by the increase of the pulpwood price by 18% in the second 5-year period of the first 10-year period of scenario *Base* as compared to a price reduction by 4% in scenario *1m3cap* (cf. Table 6.3). Why is not the increase of the saw log price by 36% in the second 5-year period in scenario *1m3cap* stimulating harvests to the same extent? Since relatively more saw logs are on average extracted in final felling compared with thinning one would expect that relatively more comes from final felling with an increased saw log price. This is also what happens in a comparison with *Base* and Zero (Figure 6.3). However, in the second 10-year period thinning as a fraction of total harvests is instead increased compared with period 1 in scenario *1m3cap*. The reason is obviously that it is profitable, with relatively better profitability in final felling compared with thinning, to postpone final harvests (resulting in a reduced total harvest, Table 6.2, and an increase of thinning, Table 6.3) and increase both the relative and absolute yield of timber in the future. Thus, the seemingly counterintuitive results of the *1m3cap* scenario are, at least partly, explained by prolongation of the rotation period that creates a temporary reduction of timber volumes.

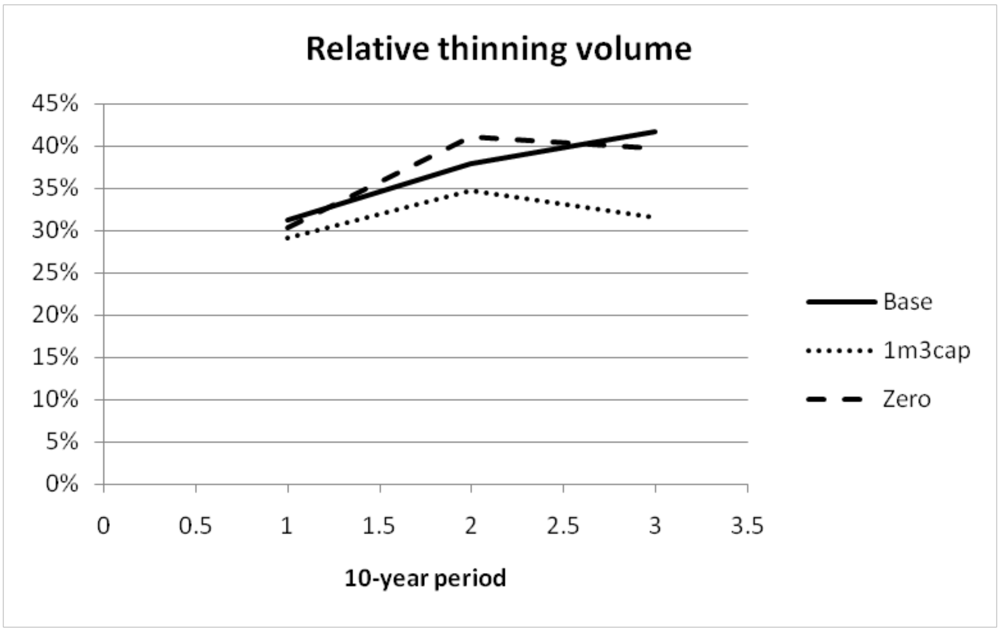

Fig 6.3 Relative thinning volume over three 10-year periods for different scenarios with the SMAC model.

The above conclusion is corroborated by an inspection of the long term projections. The initial drop in total harvests over the first decades in scenario *1m3cap* results in high removals in 10-year period's 7-11 (Figure 6.4a). Except for the first two decades, the relative share of thinning out of the total harvest is about 10% higher in *Base*. A prolonged rotation period and less thinning should result in relatively more timber in the long run. This is also confirmed in the patterns shown in Figure 6.4b.

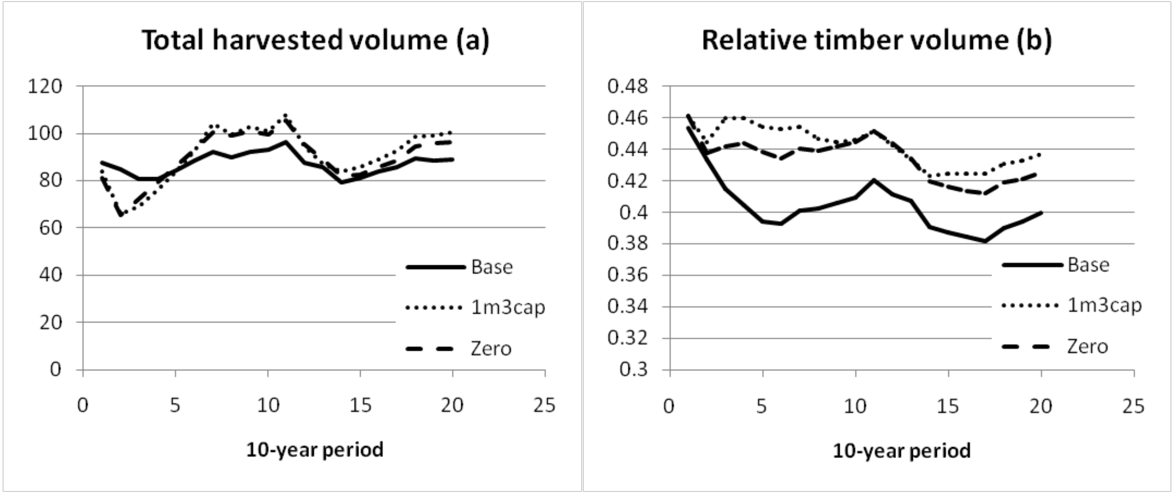

Fig 6.4 Total harvest (a) and relative timber (b) volume over a 200 years for different scenarios with the SMAC model.

The effects on the carbon balance of the different scenarios are gauged in Table 6.4. The initially reduced harvests in scenario *1m3cap* compared with *Base* results in more carbon stored in the forest. This increase in standing volume compared with the initial stock is sustained even though harvests in scenario *1m3cap* exceed those in *Base* after period 6. The harvest figures in Table 6.4 measure the accumulated carbon content of harvested trees. The figures in the row Sum can thus be interpreted as the sequestration that would result in case all harvested trees could be stored safely. It should be noted that these figures could not be compared with those presented for scenario *1m3cap* in Table 4.6 for several reasons. The most important is that the harvests are here reduced instead of increased, contrary to the calculations underpinning Table 4.6.

Table 6.4. Difference between scenario *1m3cap* and *Base* in stock (initial volume of the period) and harvest (accumulated from year 1 to the beginning of each 10-year period) in Mt C

	10-year period																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Stock	0	8	54	89	110	124	129	119	112	106	105	98	98	111	117	123	129	131	129	124
Harvest	0	-6	-38	-56	-62	-62	-53	-31	-13	6	21	42	56	58	68	78	88	101	118	138
Sum	0	2	16	32	48	62	76	88	100	112	126	140	153	169	185	201	216	232	247	262

7. Stand level

7.1 Approach

The purpose of the stand level analysis is to examine how optimum silviculture would depend on the different wood prices identified in the scenarios employed in this study. Because of the nature of the stand level model, the economic parameters such as wood prices are kept constant over the rotation. Different prices are analysed by assuming that forests are grown in different economic conditions: one where the *Base* scenario prices apply, and another where alternative prices apply. Prices do not change during the forest rotation because that would have made the effects intractable as different stands would have encountered different prices over time. Therefore, the stand level results should be seen as long-term steady state solutions giving an overall picture about the impacts of price changes on optimum stand management.

7.2 SMA-stand level optimization-simulation system and input data

7.2.1 Description of the model

The effect of increased demand of sawn timber for the optimal forest management at the stand level was studied by using the simulation-optimization system SMA (Valsta and Linkosalo 1995). The SMA system contains intermediate cuttings and rotation as decision variables, and optionally, planting density. The timing and intensities of precommercial and commercial thinnings as well as the rotation length are solved simultaneously so that the objective function is maximized. Thinning type can also be optimized to deliberate accuracy.

The objective function (1) for the forest owner/manager maximizes the discounted net returns over an infinite time horizon with rotation age T and includes (at time t, whenever there is a cut) road-side value returns from intermediate and final cuts, h_t, logging costs, l_t, and regeneration costs, w, all discounted at rate r. For the years without a cut, h_t and, l_t are equal to zero.

$$\max \pi = \left[\sum_{t=0}^{T} (h_t - l_t)(1+r)^{-t} - w \right] \frac{1}{1-(1+r)^{-T}} \tag{1}$$

Equation (1) computes the stumpage returns, net of regeneration costs, before taxes and other administrative costs.

Non-linear, non-differentiable optimization (Hooke and Jeeves 1961) in the SMA software (Valsta and Linkosalo 1995) is utilized to find the optimum thinning and rotation solutions. To improve robustness (to better identify globally optimal solutions), the algorithm is complemented by random search phases at the initialization of restarts and after locating a candidate optimum solution, as described in Valsta (1992).

Following Roise (1986), Valsta (1987, 1992), and Haight and Monserud (1990), the optimization problem is formulated as a static, nonlinear programming problem in the control variable space:

$$\max_{\mathbf{u}} \quad g(\mathbf{u} \mid \mathbf{x}_0) \tag{2.1}$$

subject to:

$$\mathbf{u} \in \mathrm{U} \tag{2.2}$$

$$\mathbf{x}_0 \text{ given} \tag{2.3}$$

where g: $\mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}$ is the objective function (Eqn. 1) that computes the net present value based on initial stand state $\mathbf{x}_0 \in \mathbb{R}^m$ and control variables $\mathbf{u} \in \mathbb{R}^n$. The control variable vector **u** consists of the time to the first thinning, times between thinnings and intensities as well as types of thinnings, the time to the final harvest after the last thinning, and planting density. The number of thinnings is set exogenously for each optimization. Runs are repeated for several numbers of thinnings, and the number of thinnings that provides the optimum is chosen.

The stand projection system in SMA is based on individual-tree, distance-independent growth and mortality models (Hynynen 1993, 1995a, 1995b, 1995c), also used in the Finnish MELA system (Siitonen et al. 1996) for national timber resource projections. Timber returns are computed by deducting logging costs from road-side values as in Cao et al. (2006). Amounts of wood assortments are predicted with models that use tree characteristics (species, diameter, height) (Laasasenaho and Snellman 1983). Harvesting costs are computed using the models by Kuitto et al (1994). As input, these models use average tree size by species and tree type (saw log tree, pulpwood tree), the amounts harvested by product classes and the amount harvested per hectare. Based on the input, the models compute productivity (m^3/hour) in cut-to-length harvesting for felling and hauling. Productivity combined with hourly cost rate provides the logging costs.

7.2.2 Parameters

The parameter values to be identified include biological and economic parameters. To compute the effects of management on forest biomass (amount of carbon) we used biomass expansion factors that give total tree biomass relative to stem volume. Other types of forest ecosystem carbon were excluded from the analysis, with an imputed assumption that those were not significant for the research questions. The biomass expansion factors used in this study were 0.7051 Mg/m^3 for Scots pine and 0.8139 Mg/m^3 for Norway spruce (Lehtonen et al. 2004). The share of carbon in dry weight of biomass was assumed to be 0.5.

We used a 3 % real discount rate. The minimum size of a tree for saw logs was 17 cm dbh and 12 m height. The saw log price premium based on tree breast-height diameter was chosen to Finnish conditions based on Paajanen (1997) which correspond to Swedish conditions (Valsta 2000). The regeneration method was assumed to be planting and the fixed cost for both planting and tending of seedlings was set to 1000 €/ha including all treatment cost up to the first commercial thinning.

The hourly harvesting cost rates were 67.23 € and 47.06 € for felling and hauling, respectively. Other fixed parameters were 200 meter hauling distance, 20 meter strip road distance, 4 meter strip road width, and the load sizes of 12.8 and 11.6 m^3 for saw log and pulpwood load, respectively. Additionally, a minimum total cost of 420 €/ha was assigned for each harvest time and used if the total harvest costs would have been less.

7.2.3 Scenarios examined

We provide numerical results for the scenario *1m3cap* and the *Base* case scenario (see Ch. 5). Price changes in other scenarios are so modest that most likely they would not have any significant impact on forest management. Prices used in our analysis are outputs from the EFI-GTM model. As noted above, stand level results describe steady states instead of some particular year or time period. Prices for year 2030 are applied as they take into account the long term impacts on the forest sector. The price for coniferous saw logs is 50.3 €/m^3 and for coniferous pulpwood 35.7 €/m^3 in the *Base* scenario. In the scenario *1m3cap* the corresponding prices are 105.5 and 29 €/m^3. These prices are road-side prices including bark. Compared to the *Base* case, the price for coniferous saw logs is thus increased by 110% while the price for coniferous pulpwood is decreased by 19%.

For spruce-dominated forests, stand-level analyses were made for both high fertility Oxalis-Myrtillus type (OMT) and medium fertility type (MT) sites (Cajander, 1949) by using two plots measured in southern Finland. For Scots pine, computations were performed for three plots. One of them represents the MT site type and two the VT site type.

For both price alternatives (*Base* and *1m3cap*) computations were made for management options with different amounts of thinnings. For Norway spruce one to four thinnings were applied, and for Scots pine three to five thinnings were applied. Results consist of stand development, i.e., thinning timing, intensity and rotation length, as well as average total volume and amounts of pulp wood and logs on the average per hectare over the rotation. The use of biofuel was not considered. Soil expectation value based on 3% real discount rate was used as an objective function and the optimal number of thinnings was determined by choosing the alternative with the highest SEV. Under economic regularity assumptions, these solutions then lead to the maximization of the forest owner's wealth considering an infinite time perspective (Johansson and Löfgren 1985, p 74-75).

7.3 Results

The most interesting question in the stand-level analysis in this study was how much optimal forest management would change if the demand for sawn wood increased notably thus changing the wood prices. Based on the computations made, the change in prices predicted by the EFI-GTM model (Section 5.3) would cause a significant change in the optimal treatment schedule for spruce dominated stands, especially for the most productive stand type (OMT, H_{100} = 33 m). This can be seen in Table 7.1 which illustrates the optimal management strategy in both *Base* and *1m3cap* scenarios, and the differences between these two cases. The change in the price relation extended the rotation by eight years, increased the optimal number of thinnings from one to two, scaled up optimal planting density and increased both the average volume and the production of saw logs per hectare and simultaneously decreased the production of pulp wood.

Table 7.1. Optimal management in the OMT spruce stand and difference between the *1m3cap* and *Base* scenarios

Site	Case	SEV	Average Volume	m3/year	Logs/ year	Pulp wood /year	Planting density	Rotation length
OMT	*Base*, 1 Thinning	2256	139	8.4	4.5	3.8	2068.6	70.8
OMT	*1m3cap*, 2 Thinnings	3928	162	8.8	5.1	3.6	2416.2	78.9
Difference		**1672**	**23**	**0.4**	**0.6**	**-0.2**	**347.6**	**8.1**

Compared to the *Base* scenario, in the *1m3cap* scenario the first thinning occurs several years earlier. A second thinning becomes optimal and takes place ten years before the final felling.

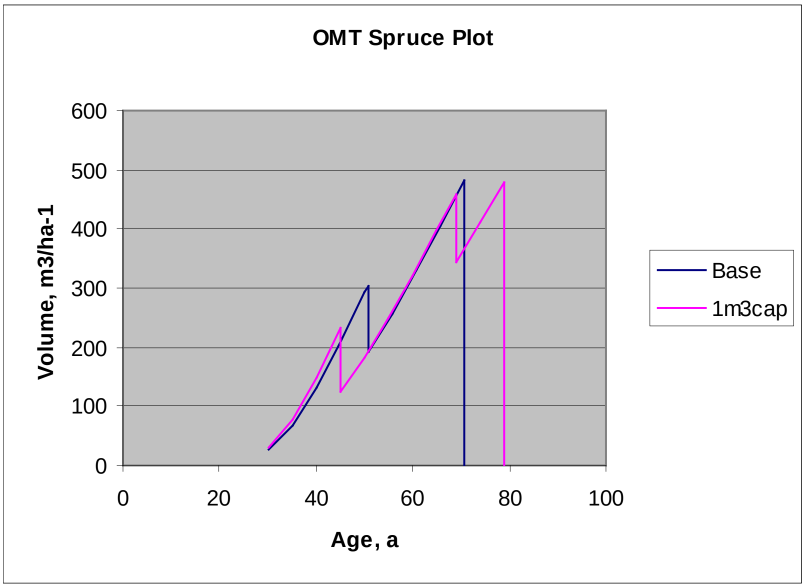

Figure 7.1. Timing of thinnings and rotation length at the OMT spruce stand.

For the stand belonging to medium fertility class (MT, *Myrtillus* type), changes were somewhat smaller: for both the *Base* and *1m3cap* scenarios a one-thinning option was optimal and the price shock did not increase the optimal planting density. A change in price relation caused only a slight increase in average volume and a small decrease in the amount of pulp wood, but did not change the average amount of saw logs, even though the rotation age was lengthened by six years (Figure 7.2).

Table 7.2. Optimal management in the MT-spruce stand and difference between the *1m3cap* and *Base* scenarios

Site	Case	SEV	Average Volume	m3/year	Logs/ year	Pulp wood /year	Planting density	Rotation length
MT	*Base*, 1 Thinning	921.4	119	5.9	3.1	2.7	1508	79.8
MT	*1m3cap*, 1 Thinning	1810.5	121	5.7	3.1	2.6	1508	85.9
Difference		889.1	2	-0.2	0	-0.1	0	6.1

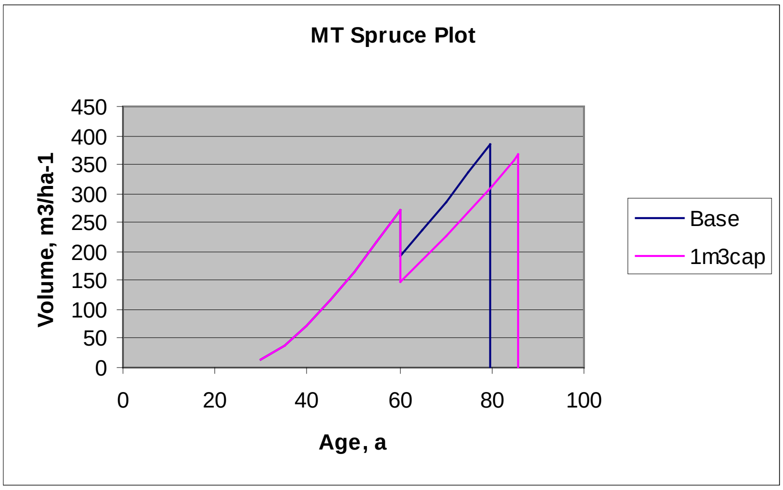

Figure 7.2. Timing of thinnings and rotation length at the MT Spruce stand.

For Scots pine, the effects were also somewhat different among plots and fertility classes. For two plots (MT and VT1) the optimum number of thinning increased from four to five due to an increase in saw log price (Figs 7.3 and 7.4). Rotation age was increased by 4-7 years for these plots. On the other hand, rotation length was shorter in the case of higher saw log prices for the VT plot for which the optimal amount of thinnings was the same for both *Base* and *1m3cap* scenarios (Fig.7.5). It should be noted that net present value was quite similar for three to five thinnings, especially in the *Base* case. For all plots, thinnings took place earlier in the *1m3cap* scenario in order to increase the amount of saw logs over the rotation.

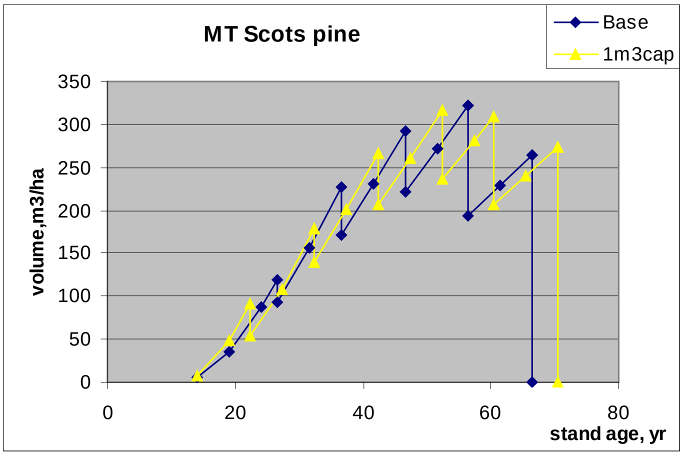

Figure 7.3. Timing of thinnings and rotation length at the MT Scots pine stand.

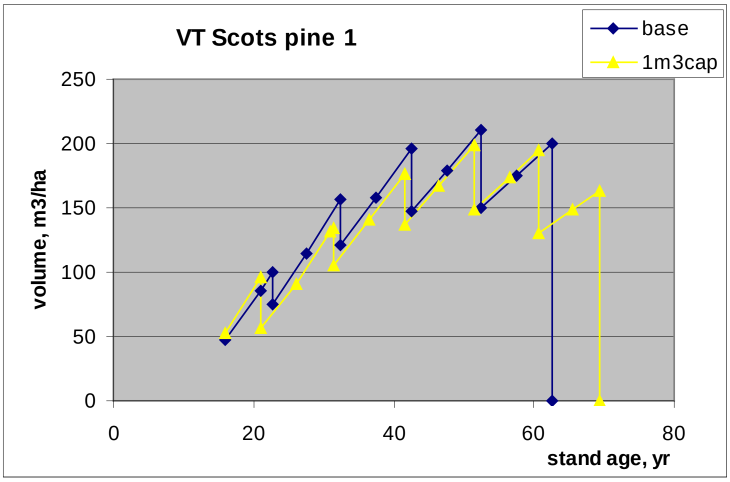

Figure 7.4. Timing of thinnings and rotation length at the VT Scots pine stand 1.

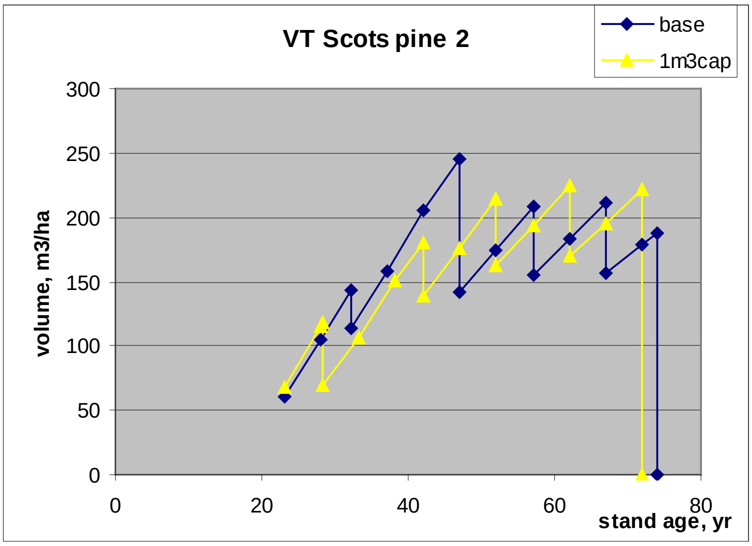

Figure 7.5. Timing of thinnings and rotation length at the VT Scots pine stand 2

The annual supply of Scots pine saw logs was increased by 0.1-0.7 m^3/ha. On the other hand, the supply of pulpwood was decreased. Thus, the impact on total supply varied from slightly negative to slightly positive. A relatively small increase per hectare may at aggregated level provide a relatively large increase in saw log supply. For example, if a 0.6 m3 ha-1 year-1 increase on the spruce OMT stand is aggregated to the Uppsala County level in southern Sweden, we end up getting 47,700 m3 more saw logs from this area of 6,989 km2 on annual basis (Uppsala county has 255 000 ha spruce from which 52% H100>28m) (Skogsstyrelsen 2007).

Table 7.3. Optimal management in the MT-Scots pine stand and difference between the *1m3cap* and *Base* scenarios

Site	Case	SEV	Average Volume	m3/year	Logs/ year	Pulp wood /year	Planting density	Rotation length
MT	*Base*, 4 Thinnings	2720	144	8.2	4.6	3.5	2495	66.5
MT	*1m3cap*, 5 Thinnings	5823	153	8.4	5.3	2.8	3487	70.4
Difference		**3103**	**9**	**0.2**	**0.7**	**-0.7**	**992**	**3.9**

Table 7.4. Optimal management in the VT Scots pine stand 1 and difference between the *1m3cap* and *Base* scenarios

Site	Case	SEV	Average Volume	m3/year	Logs/ year	Pulp wood /year	Planting density	Rotation length
VT	*Base*, 4 Thinning	1509	111	5.9	3.1	2.6	2296	62.5
VT	*1m3cap*, 5 Thinnings	3219	108	5.6	3.2	2.3	2578	69.3
Difference		**1710**	**-3**	**-0.3**	**0.1**	**-0.3**	**282**	**6.8**

Table 7.5. Optimal management in the VT Scots pine stand 2 and difference between the *1m3cap* and *Base* scenarios

Site	Case	SEV	Average Volume	m3/year	Logs/ year	Pulp wood /year	Planting density	Rotation length
VT	*Base*, 4 Thinning	1235	118	5.8	2.9	2.8	2587	74
VT	*1m3cap*, 4 Thinnings	2691	114	5.8	3.3	2.4	2895	72
Difference		**1456**	**-4**	**0.0**	**0.4**	**-0.4**	**308**	**-2**

Impacts on average volume, and thus the average carbon stock in standing biomass, over rotation also varied between plots. For two Scots pine plots, representing VT type, the carbon stock was lower in the scenario with higher saw log price. The decrease was 4-5 t CO_2/ha. On the other hand, for more fertile Scots pine stand, the average carbon stock was increased by 12 t CO_2/ha. For the more fertile spruce stand the increase was 9.4 t CO_2/ha while at the MT spruce stand the difference was minor. Overall, the impacts were quite small. However, in cases where average volume is smaller but saw log production increases, the total climate change mitigation effect may also be positive due to material substitution and longer lifecycle of wood products manufactured from larger stems (see Chapter 4).

In the computations reported above, planting density was optimized. We also performed computations with fixed planting density based on the plot characteristics. When planting density is fixed, the number of trees is considerably lower. Less flexibility implies less modification in forest management. For Scots pine, the changes in rotation length were very minor. Average volume and thus carbon stock were lower in scenarios with high saw log price for all plots. The results are compared and discussed further in Chapter 8.

8. Discussion

In this study, we analysed climatic gas emission implications of increased wood use in building construction. For this purpose, we developed a new preliminary approach of integrated modelling. The complexity of the issue required the linking of a wood substitution model, a forest products market model and forest management models on both stand and regional levels. Applying the model framework, we endeavoured to determine what would happen to the roundwood supply and demand, growing stocks of forests, forest management practices, and the overall carbon balance in Sweden, if the use of wood in building construction increased from the current level.

In the first stage of the modelling system, the global impacts of the increased demand for wooden construction material on the forest product markets were simulated with the EFI-GTM model. This gave us projections for saw log and pulpwood prices, demand and supply in Sweden and globally up to year 2030. In the second stage, the prices were used as an input in a regional forest model and a stand level model to simulate the optimal forest management and the resulting harvests at the country and stand level. Whereas the regional model could be characterised as a medium term transition model, the stand model supplied long run steady state results. For technical reasons, it was not possible to feed the entire path of annual prices obtained from the EFI-GTM to the stand level or forest region model and to simulate the dynamic behaviour with the prices changing annually over time. The forest management steady state model operated with a single price used for the whole time horizon, while in the forest regional model the forest owners were exposed to new prices during each 5-year period.

Looking at the results it appears that the more modest scenarios *Sweden* and *Finland* have limited implications in terms of C emission reductions. This goes for both the effects in the construction sector and in the forest. The building design is, however, shown to be quite important. Going to the extreme scenario *1m3cap*, the emission reductions are about 20 times as large as scenario *Finland*, the most carbon efficient of scenarios *Sweden* and *Finland*. How large the net emission reduction will be for this scenario is unclear, however, since the assessment of the forest carbon storage by the regional model is completely out of phase with the increased demand for construction wood. It can be noted that in terms of carbon, the build up of stock in the Swedish forests during the first 30 years matches in magnitude the gains in the construction sector while at the same time having different harvest volumes. The reduced emissions for Sweden in the construction sector assumes an increase of Swedish harvests for the first 23 years of 137 million m^3 while in the regional forest model the harvests for the first 30 years in Sweden are reduced by 186 million m^3 compared with scenario *Base*).

The steady-state results from the stand level model imply that when the amount of saw logs is increased, the average carbon storage in the forest might decrease for Scots pine. Computations performed by Pingoud et al. (2008) for Finnish forests were based on current silvicultural recommendations in Finland and their modifications. They showed that it is possible to increase both the average carbon stock in forests and the supply of saw logs by increasing the rotation length and basal area compared to current silviculture. However, at some point, increasing the rotation starts to decrease the annual supply of saw logs, due to decreasing growth rate. Thus if real rotation lengths are longer than the one recommended, it might not be possible to increase the supply of saw logs by only postponing the final felling without other changes in management. In this study the analyses were made assuming even-aged management regimes for both spruce and pine dominated stands. For spruce, however, it could be possible that due to increasing demand of sawn wood, higher prices for saw logs in relation to pulp wood could cause a transition towards continuous cover forestry with single tree selection cuttings and primary emphasis on log-sized wood production.

Concerning the integrated modelling framework, there are still several problems to be solved after the present pilot study. The discussion will here focus on the consistency between the EFI-GTM and the forest regional model (the Swedish matrix model SMAC) on the one hand, and between the forest regional model and the stand level model (the Finnish SMA model) on the other. Consistency between the construction scenarios and the EFI-GTM model is built into the system as the result of the former being an assumption in the latter. In reality one would also expect that there is a feedback loop between prices established at the timber markets back to the wood construction scenarios. However, this interaction is not included in the current model system (cf. Figure 3.1).

Econometric studies and the theories behind them suggest a positive correlation between timber supply and prices. Thereby, non-negative price-harvest elasticities were applied in the EFI-GTM model assuming the myopic forest owners do not see how the markets will evolve in the future. Our results suggest that saw log prices increase due to the high demand in the booming sawnwood industry, while the pulpwood prices drop because of sawmill chips streaming abundantly into the market.

With the forest regional model, the harvest levels for saw logs deviated from those projected by the EFI-GTM. Unlike in the EFI-GTM, the immediate harvests decreased when the saw log prices increased due to forest owners postponing their harvests in order to increase the future saw log yield and thereby income. The SMAC model only considers the supply of timber, and despite the behavior represented being optimal for the forest owners', it is unlikely that the timber supply path generated by it would match the market saw log demand in the short-run. SMAC does not incorporate export/import aspects and the economic challenge of covering the short-term demand from the existing Swedish forest industries. Therefore, the model gives lower fellings in Sweden in the first 2-3 decades compared to the EFI-GTM results because, seen from the forestry side, it is more profitable to postpone harvest given the assumed increase in saw log prices.

The EFI-GTM and the SMAC model accommodate different assumptions on what the market players know about the future. The EFI-GTM assumes that the agents have no foresight to the future or that they assume that any period in the future is identical to that of today. The SMAC model assumes perfect foresight. Although the latter assumption finds support in the economic literature, both assumptions can be seen as rather extreme ones, when looking at the conduct in the timber markets. The reality is likely to be somewhere in between the two. Nevertheless, for an internally consistent analysis of the optimal forest management and forest sector demand for roundwood, a dynamic model like e.g., FASOM, with simultaneous demand and supply mechanism would be needed. Another option would be to integrate the SMAC model, or a simplified version of it, and the EFI-GTM into the same model. Sallnäs and Eriksson (1989) provide an example of the use of the SMAC model in an integrated analysis to find market clearing prices. Another, more simple approach to avoid this difference between EFI-GTM and the SMAC results would be to run SMAC with both prices and volumes of saw logs and pulpwood fixed until 2030 according to the EFI-GTM results, so that only the forest management (silviculture and harvesting operations) are decided endogenously.

Whether these options come available or not, we find that addressing the following questions would improve the usefulness of the approach integrating EFI-GTM and SMAC in the future analyses:

- Should the SMAC operate with single year instead of 5-year periods in order to make it easier to link and interpret the time series? This would demand a recalculation of the transition probabilities of the SMAC model but is otherwise structurally not complicated.
- What price expectation hypothesis should be used? The myopic price expectation (future prices the same as today's prices) used in this study or perfect expectations (in reality meaning perfect foresight)?
- Since the SMAC model assumes profit maximizing forest owners there is an initial adjustment of harvests due to the fact that certain forests in reality are not managed only with consideration of maximum profit. The effect is that first period harvests in the SMAC model hardly correspond to realistic figures. This could be approached with some kind of adjustment mechanism, such as the entropy measure suggested by Sallnäs and Eriksson (1989). With perfect foresight the problem might not be that difficult since supplied quantities will automatically adjust themselves between periods.
- Should fuel wood be integrated as a separate assortment? It would certainly add to the validity of the analysis, although it complicates matters as it tends to influence the supply relation between timber and pulpwood. It would also make it easier to discern where carbon content of forest residues should be calculated, either in the house construction model or the forest model. With the current set up there are obvious risks of double counting.
- Should the SMAC model be open for the possibility to adapt stand establishment (investment activities)? The stand level model shows this to be quite important (see Ch. 8).
- Finally, the EFI-GTM model could potentially be supplied with cross-price elasticities, describing the effect of supply of one commodity when the price of another changes. However, it is also obvious from the SMAC model results that supply conditions vary over time, also within the 30 year time frame used here. Thus, one would need a cross price matrix that was updated each time period. Still, econometric estimation of cross-price roundwood price elasticities is rather difficult.

Turning to the relation between the SMAC regional model and the SMA stand model a high degree of consistency could be observed. Higher saw log prices implicate longer rotations and increased production of saw logs in the long run. The results from the SMA model should be viewed as long term effects starting from young stands. For older stands, the supply of saw logs cannot be increased by earlier thinnings. By postponing final fellings the amount of saw logs could be increased in medium term but short term supply would decrease.

9. Conclusions

The conclusions of the report can be divided into those associated with the practical effects, and those that pertain to the modelling system. On the practical side the results indicate the following:

- An increase of wood framed buildings would reduce net carbon emissions in the construction sector.
- The total net carbon emission effect was not analyzed because the models used do not yield consistent results.
- The changes in the price relations between sawnwood and pulpwood indicated by the EFI-GTM lead in the forest regional model to a change in the management programs towards prolonged rotations, leading to a medium term reduction of sawnwood supply.
- The long term steady state analyses indicate small differences in carbon stock due to the price increases predicted by the scenarios. Saw log output increases, but is in most cases balanced by a similar reduction of pulpwood. Rotations are prolonged and for several stand types the number of thinning is increased. However, biofuel use is not considered here.

The modelling system in this report represents an ambitious effort to combine models from different disciplines into one coherent system. Regarding the overall structure, it works and could be a valuable basis for further analysis. However, the main focus of the project has been to test the system in order to discover inconsistencies and gaps. The following experiences can be gained from the exercise:

- Linking the wood construction scenarios with the EFI-GTM model, however demanding, succeeds without major problems. The resulting demand for sawnwood can be distributed among countries by the EFI-GTM model in consistency with the construction scenarios.
- The most problematic part of the system appears to be the linkage between the EFI-GTM and the forest regional model. In particular, cross-price elasticities between saw logs and pulpwood is an issue for the former whereas the latter has to consider more realistically the short-term fluctuations caused by export/import possibilities of logs and the short-term wood demand from existing forest industries. Also, it would also be advantageous to have the same time resolution in both models.
- None of the models – the sector, regional or stand model – explicitly include biofuels. Given the growing importance of the biofuel market it would be desirable to adjust the models such that one could study the effects of changing demand and supply relations on economic indicators and forest management activities.
- The detailed stand level model and the regional forest model could be better integrated with each other. Specific examples include some growth related models that are currently missing in the regional model, and the input of stand management prescriptions from the stand model into the regional model.
- The overall consistency relies on a number of common parameters that defines boundary conditions, such as discount rates in different sectors and carbon emission factors in the energy sector.

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Appendix

Generic project application: Integrated analysis of the potential contributions of the forestry sector to mitigating climate change

Summary of project

Climate change is a major long-term environmental threat facing humanity. Forestry and the forest products industry can play an important role in mitigating the effects caused by increased atmospheric CO_2 levels. This can be done by increasing the use of forest-based bioenergy, and substitution of wood in place of non-wood materials in e.g. the construction sector.

A number of studies in the Nordic countries show that substantial contributions to climate change mitigation can be achieved by each of these means. However, there have been few integrated analyses of forest management and substitution strategies. More study is needed to understand the strong interdependences between various mitigation measures. For instance, increased long-term sequestration of carbon in forest biomass reduces the biomass quantities available for bioenergy or material substitution of fossil fuels or carbon-intensive materials. Other interdependencies are transmitted by the price mechanism such that increased use of wooden construction material will tend to increase timber prices, resulting in more intensive forest management. The long time scales further complicate comparisons of strategies: whereas timber can substitute for fossil fuel today, the use of wood in construction will affect energy use in different sectors immediately, and also fossil fuel substitution when the house is eventually demolished a number of decades from now. A large geographic scope, such as a regional or global setting, is needed in order to assess impacts on supply and demand over time.

A pilot project conducted from 2006 to 2008 endeavoured to link forestry models (at the stand and landscape levels) and biomass substitution models (of biofuels and wood material). That effort laid a solid analytical foundation, demonstrated the viability of the proposed approach and pointed out possible improvements needed. The purpose of the current project is to build on the results of the pilot project to develop an integrated analysis of potential measures in the forest sector for climate change mitigation, and develop robust policy recommendations for forest management and forest biomass use. Specifically, this project will: (i) expand and refine the linkage of models of forest management on the stand and landscape levels and models of wood and biofuel substitution, (ii) identify missing models and linkages, and create the necessary models to produce a comprehensive analytical framework, (iii) implement a regional level application of the framework with improved scenarios of material and energy substitution, and (iv) develop policy recommendations based on economic, biological, technological and political issues related to the implementation of forest sector activities to optimize the greenhouse gas mitigation of the sector.

Background[1]

Previous analyses of carbon stock changes or wood substitution have generally focused on individual aspects of using forestry to mitigate climate change. There has been little research conducted on integration between forest management and substitution strategies, although the importance and need of such research has been pointed out (Gustavsson et al. 2005b). To date, only

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[1] For reference list, see main text.

limited effort has been focused on a modelling framework that allows the integrated analysis of the forest sector to determine beneficial strategies for mitigating climate change.

Managing forest stands for increased carbon emissions reductions results in a different silvicultural guideline from normal economical use of forests as well as an increased demand for forest products. Zhou (1999) and Pohjola et al. (2007) suggested that increased carbon sequestration in forests is achieved by increasing growing densities and rotation length. These results neglect the use of wood to substitute for fossil energy intensive materials and fossil energy. Taking substitution into account will typically change the optimum timber assortment composition and the rate at which carbon is passed through the forest ecosystem. Stand level analyses using a simulation-optimization model such as the SMA software (Valsta and Linkosalo 1995) allow for optimum combination of the different goals in silviculture.

Incorporating carbon storage into forest planning at the regional scale clearly affects forest management by e.g. changing clear felling priorities (Hoen and Solberg 1994). When carbon storage in forest biomass is given a monetary value, without a corresponding value given for the substitution benefits of wood products, harvest levels will decline and this effect is more pronounced in areas with low production (Backéus et al. 2005). The study included forest biofuel at low local prices without price elasticity (e.g. due to changed cost for carbon mitigation) and not substitution of fossil energy intensive materials. Petersen et al (2004, 2005) used the GAYA/JC model to connect forest planning with climate change mitigation impacts based on forest and forest products use. The model permits an analysis of the impacts of including energy and material substitution effects in carbon benefits. Studies on forest or regional level are performed using an integrated analysis and planning system like the Heureka-system (Lämås and Eriksson 2003).

Increasing the use of wood material in construction is a potential option for reducing net CO_2 emission because of the relatively low fossil energy needed to manufacture wood products compared with alternative materials, the increased availability of bio fuels from wood by-products that can be used to replace fossil fuels, and the storage of carbon in wood building materials. Furthermore, using biomass for direct substitution of fossil fuels or fossil fuel-intensive materials provides permanent and cumulative reduction in CO_2 emission, whereas sequestration or conservation of carbon is typically limited so that the carbon sinks always saturate in the long run.

A growing body of knowledge also supports that wood-based material typically result in lower energy use and CO_2 emission compared to other materials such as concrete, brick or steel (Koch 1992; Buchanan and Honey 1994; Buchanan and Levine 1999; Börjesson and Gustavsson 2000; Lippke et al. 2004; Gustavsson and Sathre 2004, 2005; Petersen and Solberg 2005). Gustavsson et al. (2005a) developed a method to compare the net CO_2 emission from the construction of concrete- and wood-framed buildings. The method, applied to two buildings in Sweden and Finland, includes carbon accounting from emissions due to fossil fuel use in the production of building materials; the replacement of fossil fuels by biomass residues from logging, wood processing, construction and demolition; carbon stock changes in forests and buildings; and cement process reactions. They found the most important contributor to the lower CO_2 balance was the recovery of wood residues, including logging, processing, construction and demolition wastes, for use as biofuel to replace fossil fuels. Pingoud and Perälä (2000) estimated the maximum wood substitution potential in new building construction in Finland. The results indicated that nearly twice as much wood material could have been used in Finland in 1990 compared to the amount that was actually used. Most substitution studies, however, are lacking an active integration between wood demand from the industry and timber supply from the forest.

A preliminary case study integrating forest management, carbon sinks and substitution was performed in Pingoud et al (2006), which analyze the impacts of various forest management strategies on both carbon stocks, and substitution. The supplies of sawnwood, pulpwood and energy wood were given as input into the framework similar to Gustavsson et al (2005a), to estimate the impacts of replacing concrete houses with wooden houses on emissions and carbon stocks. The results showed that the quality of the wood produced (sawlogs, pulpwood, fuelwood) had substantial impact on the substitution potentials. Some substitution factors were found to be greater than one, implying that relative emission reduction is larger than the carbon content of the stemwood itself. Consequently, maximizing the biomass production does not necessarily lead to the maximal substitution benefits. According to the results, there could be win-win solutions in the long run: both higher substitution benefits and higher carbon storages might be obtained by the same forest management strategy in some cases.

The CORRIM consortium in North America (e.g. Perez-Garcia et al 2005) analyzed different management alternatives for individual stands, taking into account the whole lifecycle from forest to wood products in housing. According to CORRIM results, management strategies with lower forest stock and rotation lengths and higher biomass yield gave clearly the best overall greenhouse gas benefits. The difference is partly explained by their assumption that small-diameter wood was used as raw material for long-lived products in construction, such as wood-based panels. This illustrates the importance of the mixture of wood raw materials, and their varying potential uses, on the resulting climate impact.

Eriksson et al. (2007a) conducted a broad system analysis of carbon stocks and flows in trees, soil, wood products, and substitutable materials and fuels. They found that overall carbon emissions were lowest when forests were managed intensively, with shorter rotation periods, to produce construction materials. The substitution effect of using wood instead of non-wood materials had the greatest single impact on the overall carbon balance. Removing harvest residues for use as biofuel led to avoided fossil emissions that were 7-10 times greater than the reduced soil carbon stock.

A Swiss study (Taverna et al 2007) examined the impacts of different forest management and wood use strategies on CO_2 sinks and CO_2 emissions. The analysis was performed by using a forest model, a wood flux model of the timber industry, and a model of carbon stocks and substitution effects, which are linked. The analysis covers sequestration in wood products and substitution of both energy and materials. The analysis is made for Switzerland, but the impacts of products used abroad are also estimated. Both short and long term impacts are analyzed. The models are simulation models; economic decision making is not involved in the analysis.

This project builds on the work carried out in a pilot project financed by SNS and conducted from 2006 to 2008. In the pilot project, the authors of this proposal developed rough scenarios of increased wood construction and estimated the impact of material substitution on the total carbon balance of forests and wood-product chains. The scenarios were meant to illustrate the greenhouse gas mitigation potentials of combined material and energy substitution. By such scenarios, we demonstrated the trade-offs and synergies between forest management on one hand, and the substitution effects of avoiding fossil carbon emissions due to increased wood material use and forest-based bioenergy production on the other hand. We identified the most important interactions between sub-models, and the linkages that are crucial to developing the integrated modelling framework we propose in the current project.

Project objectives

A comprehensive analysis of different forest management and wood substitution strategies for climate change mitigation will benefit from the integration of forest management models on stand and regional levels and as well as the consideration of wood substitution in place of fossil fuels and non-wood materials. Implementation issues, including appropriate forest management regimes and the consequences for future international agreements in the area, are central and should also be covered. The scope must range from the occurrence of natural resources to the services required by end users.

Integrated analyses are the outcome of a major research undertaking that rests on a well established, integrated and multidisciplinary analytical framework. The current project follows and builds on a pilot project that established a basic framework and conducted a preliminary regional-scale analysis. In the current project, both the analytical framework and the scenario analysis will be expanded and refined, resulting in a more comprehensive study. Furthermore, policy issues will be thoroughly addressed, resulting in policy recommendations for forest management and substitution strategies to reduce net greenhouse gas emission. The following activities are envisioned:

1. Existing models of forest management on stand and forest level, forest product market models, and models of wood substitution will be combined. The analytical framework established in the pilot project will be expanded and refined. The consistency of the linkages between the models investigated, and missing models and linkages, will be identified and ensured.

2. A regional-level application of the framework, with refined scenarios of material and energy substitution, will be developed. This application will determine the greenhouse gas mitigation potentials of the European forestry sector as a whole, including carbon stock changes in forest ecosystems and wood products and avoided emissions due to the wood substitution as fuel and material. Issues of global-level application of the framework will be identified and discussed.

3. Implementation issues will be examined, resulting in policy recommendations to promote the optimal use of forest resources for climate change mitigation. These issues include, inter alia, energy and carbon taxation, forest management regimes for different forest sector usage strategies, the technical and economic potentials for increase wood product use, regional and global trade in forest products, and the impacts of post-Kyoto climate change mitigation protocols.

Research plan

This research project consists of three interrelated elements: the development of a comprehensive analytical framework, the description of regional wood use scenarios, and the investigation of relevant implementation issues.

1. Comprehensive analytical framework

In this project, several models representing different parts of forest sector are linked in order to cover the life-cycle of wood. Existing models to be integrated in this project include (a) forest stand model, (b) forest regional model, (c) forest product market model, and (d) wood substitution model. Figure 1 illustrates the relationships between the various models.

a) In the *stand level model* the forest owner maximizes the discounted net income from timber production over time, subject to economic and ecological parameters. The stand level model provides the rotation age, and timing and intensities of thinnings with given targets or economic incentives with changes in timber prices.

b) In the *forest regional model* simulations for the forest growth are made for sample plots from e.g. National Forest Inventory. Guidelines for forest management are received from the stand level model. The simulations are performed numerous times and then used as input to an optimizing model where demands for e.g. harvest level for the whole region are set.

c) The *forest product market model* links regional forest resources and wood and forest based bioenergy supply, the forest industry production and the market demand for forest products and wood-based bioenergy. Such models exist for Norway (NTM II, see Bolkesjø and Solberg (2006)) and Finland (SF-GTM).

d) The *wood substitution model* determines the micro-level carbon balance associated with wood use in house construction. Model inputs are the amounts of building materials needed to build a wood house and a reference house, built mainly in some other materials than wood. The model outputs include the carbon emissions from producing the building materials, the avoided fossil carbon emissions from using processing residues and demolition wood for bioenergy, and the amount of tree biomass needed to produce the building materials.

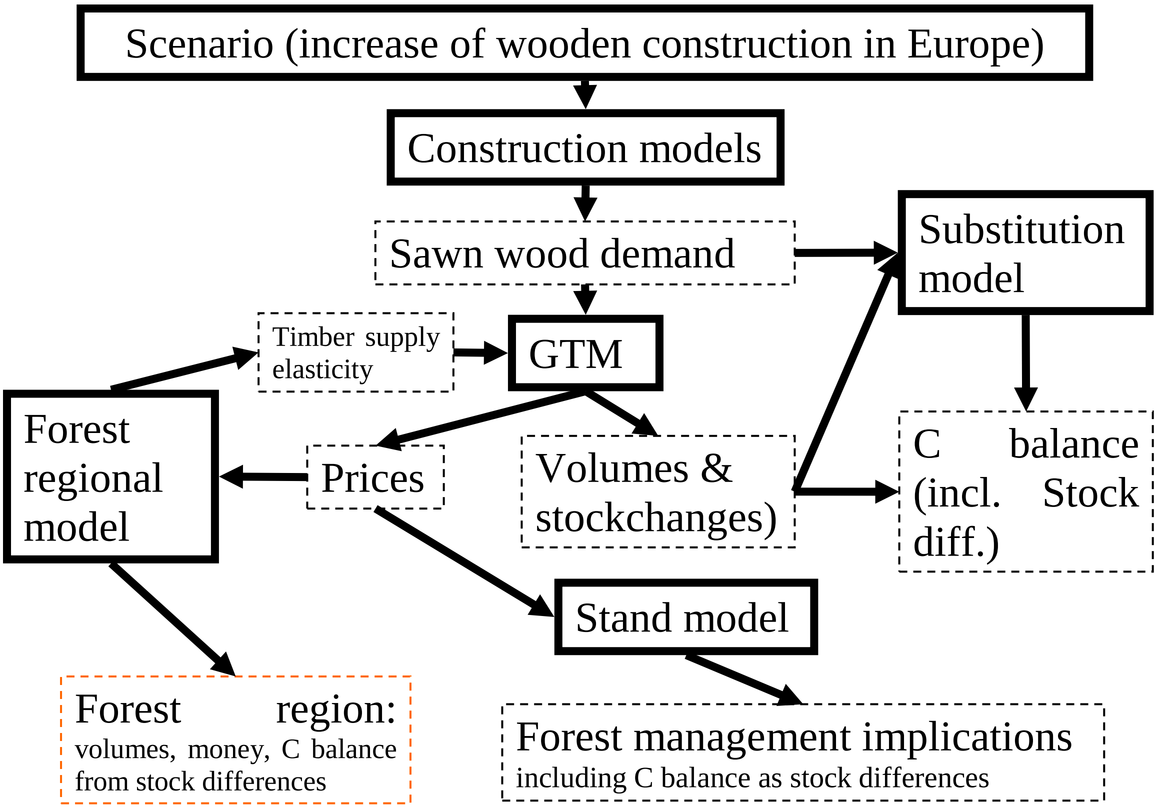

Figure 1: Schematic diagram of the relationships between different forest-based models.

2. Wood substitution scenarios

Scenarios are a means to illustrate the greenhouse gas mitigation potentials of combined material and energy substitution. In the pilot project, we provided rough scenarios on the impact of material substitution in construction on the total carbon balance of forests and wood-using chain, based on existing scenarios of increased wood construction. In the current project, more sophisticated scenarios will be developed. Through such scenarios, the trade-offs between carbon stock in forest biomass and avoidance of fossil carbon emissions due to increased wood material and bioenergy production can be demonstrated and quantified. By identifying the most important interactions the scenarios will assist in developing the integrated modelling framework. Scenario development will also occur alongside the analysis of implementation issues. In this way, scenarios of expanded use of wood in construction will be compatible with expected diffusion patterns, anticipated obstacles, and required incentive measures. The different scenarios will be compared from both carbon balance and economic terms.

Given the scenarios for increase in wood construction in Nordic countries, the substitution effects in the construction sector will be discussed, such as the demand of various timber species. Forest models will be used to evaluate possible needs for modifying forest management in order to respond the new level of demand. The implied demands of timber species will be implemented on a regional scale to quantify the accumulated effect on carbon storage, harvested timber and biofuels over time. The price responses will be estimated with a market model.

While the scenarios will focus on the European region, they will take into account issues of different scales, e.g. national and global levels. The scale of the analysis, from the micro to macro level, requires the consideration of differing issues. The aggregate use of forest land will depend on the competing demands for the various products and services that the forest can provide, and the alternative materials available. This will differ between a marginal change in product use (i.e. the consideration of a single product substitution) and a structural change in society's production and consumption patterns. An effective analysis will integrate the dynamics of forest processes and economic markets to identify interdependencies, such as those transmitted by the price mechanism such that increased use of wooden construction material will tend to increase timber prices, resulting in more intensive forest management.

Carbon dynamics differ substantially as the scale increases from the forest stand level to the landscape level. Within a managed forest stand a characteristic curve can be traced over time: carbon is quickly bound in tree biomass during stand establishment and growth, then eventually accumulates at a decreasing rate, then is removed during a harvest disturbance, followed by reestablishment of the subsequent rotation. At the landscape level, the total carbon balance at any time is the aggregate of the balances of a multitude of stands, each at a different stage of its rotation. The maximum carbon stock at the landscape level is thus lower than the maximum at the stand level, because not all the individual stands will hold the maximum stock at the same time. A substitution analysis on the micro-level can analyse wood flows in terms of their relation with the production of an individual stand, while a scenario involving macro-level forest use must consider flows on the landscape level.

3. Implementation issues

Implementation issues are the third and final focus of the project. The goal is to develop policy recommendations based on economic, biological, technological and political issues related to the development and implementation of forest sector strategies to reduce net greenhouse gas emission. Implementing the new measures in the construction and forestry sectors might involve economic instruments like carbon taxes or subsidies, legislation, recommendations or information.

Increasing the climate benefits of the forestry sector may involve expanding the geographic scope of wood substitution. By exporting wood or wood products from forest-rich areas to be used in applications that result in the highest CO_2 emission or energy use reductions per unit of biomass, the total impact of the available supply of wood could by increased. The inter-European and intercontinental trade in wood-based products and fuels is currently increasing. This process would be encouraged by the wider establishment of economic policy instruments for climate change mitigation, which tend to economically favour wood-based materials.

The spatial distribution of the climate impacts or benefits of material substitution will be investigated. Because the forest growth, wood processing, material use, and waste disposal will occur at different sites, and possibly different countries, there may be political implications of the substitution. This type of analysis offers an essential perspective in the event that carbon accounting of wood products is included in national obligations in post-Kyoto agreements beyond 2012.

Deliverables

The specific deliverables of this project include:

- Articles in peer-reviewed scientific journals,
- Papers presented at international and national conferences,
- A technical report describing the concepts, models and linkages of the analytical framework, and the results of the scenario analysis providing a regional level application of the framework,
- The network of researchers participating in this project will diffuse the results informally among a wide professional audience of colleagues and contacts.

Time frame:

The project will have aduration of 4 years.

Participants:

The research group combines the knowledge from various Nordic countries (Sweden, Finland and Norway) and disciplines (forest economics, economics, system analysis, engineering). The research organisations that are currently involved are SLU, Mid Sweden University, VTT Technical Research Centre of Finland, METLA, UMB, Norsk Treteknisk Institutt, and the University of Helsinki.