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Assessing the Integrated Climatic Impacts of Forestry and Wood Products

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Managed forests serve as a store of carbon (C) and a renewable source of energy and materials. By using forest products as substitutes for fossil fuels or non-renewable materials, emissions from fossil C sources can be displaced. The efficiency of emissions displacement depends on the product, its lifecycle and the fossil-fuel based reference system that is substituted. Forest management practices have an impact on C stocks in biomass and on the annual supply of products and their mix. There are trade-offs between sequestering C stocks in forests and the climatic benefits obtained by sustainable forest harvesting and using wood products to displace fossil C emissions. This article presents an integrated, steady-state analysis comparing various equilibrium states of managed forests and wood product pools that represent sustainable long-term forestry and wood-use strategies. Two climatic indicators are used: the combined C stock in forests and wood products and the fossil C emissions displaced annually by harvested wood products. The study indicates that long-term strategies could be available that are better according to both indicators than forestry practices based on the existing silvicultural guidelines in Finland. These strategies would involve increasing the basal area and prolonging rotations to produce more sawlogs. Further, the climate benefits appear to be highest in case the sawlog supply is directed to production of long-lived materials substituting for fossil-emission and energy intensive materials and recycled after their useful life to bioenergy.

Keywords managed forests, silvicultural guidelines, carbon stocks, harvested wood products, energy and material substitution, displacement of fossil carbon emissions
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1 Introduction

Carbon (C) sequestration and substitution are greenhouse gas (GHG) mitigation options provided by managed forests. Reducing harvests and wood supply has a temporary positive impact on the C stock in forest. On the other hand, wood use, substituting for energy-intensive materials or fossil fuels, can displace fossil C emissions and contribute to GHG mitigation too, and, in addition, wood products sequester C. Thus there are trade-offs between the two mitigation options, sequestration and substitution. One key parameter is the fossil C displacement factor (Schlamadinger and Marland 1996) describing the units of displaced fossil C by one unit of C in harvested wood biomass. In a theoretical sensitivity analysis at stand level, Marland and Schlamadinger (1997) compared two alternative ways to manage forest plantations for greenhouse gas mitigation: 1) C sequestration to forest and 2) sustainable forest harvesting to displace fossil fuels. Which of these options is preferred depends on the growth rate, fossil C displacement factor and the time frame under which C balance is considered.

Harvesting decreases wood biomass stocks. This C loss is not compensated by substitution benefits due to bioenergy and wood products in the short term, as the displacement factor calculated for the whole biomass extracted in harvest is usually less than 1. Under sustainable forest management re-growth of new biomass during the next rotation, however, makes the C balance positive over the course of time, leading to a cumulative net benefit in emissions reductions.

C sequestration potentials in existing forests are case-dependent and can be substantial, because the average biomass stock in a managed forest with an economically feasible rotation length is generally low compared with the maximum stock in unmanaged forests. Old-growth forests in temperate and boreal regions can continue to accumulate C for very long time periods (Luyssaert et al. 2008), although the accumulation rate might decline over time.

The C sequestration mechanism is based on the net growth of biomass stocks, while the substitution mechanism is related to the biomass flux that can be sustainably harvested from forests. The fundamental difference between sequestration and substitution mechanisms is that the substitution mechanism can be continuously applied as long as forest management is carried out on a sustainable basis. This leads to permanent and thus cumulative emissions reductions: the use of wood fuels instead of fossil fuels prevents C release into the atmosphere from the stable tectonic stocks. The C sequestration mechanism is based on the net growth of biomass stocks, while the substitution mechanism is related to the biomass flux that can be sustainably harvested from forests.

In this article, forest management and wood use strategies with long-term benefits both in C sequestration and fossil C substitution are discussed. For the analysis the C balance of the whole wood cycle starting from forest management to end-use must be integrated. The substitution benefit is proportional to the wood supply multiplied by the displacement factor. Forest management strategies have an impact both on wood yield and on quality, and specifically, on what share of biomass can potentially be used with a high displacement factor. In our study we use silvicultural data from boreal forests and realistic estimates of displacement factors for wood in alternative end-uses. Forest management and wood use practices specify the long-term average C stock in forests and wood products and the substitution potentials due to wood use cycles.

We assume that sustainably managed forests at landscape level are in the long term in equilibrium. We compare management strategies whose biomass stocks and annual wood supply are constant but differ in their equilibrium stocks, annual wood supply and substitution benefits. Two distinct targets are considered: 1) maximization of C stocks of forests (and wood products) and 2) maximization of annual climatic benefits from substitution. These targets are partly contradictory, but synergies could still be found. In our study we assess in which cases it would be possible to identify forest management and wood-use strategies that would improve the existing practices according to both criteria: the total C stocks in forests and wood products and the displaced emissions.

2 Previous Studies

Separate studies considering either C sequestration potentials of forests (e.g. van Kooten et al 1995, Hoen and Solberg 1997, Pohjola and Valsta 2007, Hoen and Solberg 1994, Sohngen and Brown 2008, Sohngen and Sedjo 2006, Richards and Stokes 2004) or climatic benefits of wood products have provided valuable information on their mitigation potential and the impact of policy instruments. Climatic and other environmental benefits of wooden construction materials are reported on different scales considering single products or building components (e.g. Petersen and Solberg 2003, 2004, Lippke and Edmonds 2006), entire buildings (Gustavsson et al. 2006, Perez-Garcia et al. 2005a), and national level impacts (Buchanan and Honey 1994, Buchanan and Levine 1999, Pingoud and Perälä 2000, Werner et al. 2005, Taverna et al. 2007, Upton et al. 2008). Micro-level analysis of substitution between wood products and alternative materials in Norway and Sweden has been reviewed by Petersen and Solberg (2005). An extensive synthesis of nearly 50 substitution studies and a meta-analysis to estimate the fossil C displacement factors for wood use in construction was carried out by Sathre and O'Connor (2008).

Separate studies of either forests or wood products might however lead to conflicting policy recommendations due to the potential trade-offs between the sequestration and substitution options. The strong relationship between those two has recently been taken into account in integrative studies linking supply and demand for wood. Integrative modelling studies differ from each other in many respects, including the definition of system boundaries, consideration of marginal impacts (e.g., on emissions from fossil fuels), description of system dynamics and the choice of the initial condition of the C stocks, as well as the modelling techniques (simulation, optimization), the elaborateness and focus in modelling, and the scale of analysis.

Among integrative studies Perez-Garcia et al. (2005b) and Eriksson et al. (2007) tracked C stocks and emissions from the growth of timber to its end-use, and provided time paths and estimates of the amounts of C in different biomass pools for a given time interval. Upton et al. (2008) and Hennigar et al. (2008) also included the C pool of wood products in landfills in their analysis. Hennigar et al. (2008) base their study on optimizing the physical amounts of timber and C stored. Petersen et al. (2004) presented an analysis based on economic optimization and including the C payments from sequestration and substitution. All these studies have included C stocks in both forests and wood products, as well as material substitution in construction, but the use of pulpwood and paper products has been excluded. However, there have been some essential differences in modelling substitution benefits. Eriksson et al. (2007) and Perez-Garcia (2005b) utilized detailed descriptions of wood products as material substitutes based on real cases, while Hennigar et al. (2008) used theoretical displacement factors that varied in the study, and Seidl et al. (2007) explicitly considered only energy substitution. Our study differs from earlier integrative analysis in some important aspects. The steady-state method differs, for instance, from Perez-Garcia et al. (2005b), Eriksson et al. (2007) and Hennigar et al. (2008), who estimated the detailed C dynamics of a stand and its wood use cycle (time path). The advantage of our method is that the results are not sensitive to the time period chosen or to the initial system state. Our approach is similar to that applied by Liski et al. (2001), but we substantially broaden that analysis by adding the substitution impacts using realistic model parameters. On the wood-use side, we explicitly include all timber assortments, namely sawlogs, pulpwood and energy wood, and their uses.

3 Methodology, Models and Data

3.1 Methodology to Integrate Forests and Use of Wood Products

The basic methodological idea is to compare steady states where growth equals the removals from the forest and the inflow to the wood product pool equals the decay flow. We consider a steady-state forest to be a normal forest that is composed of even-aged, fully-stocked stands representing a balance of age classes, such that

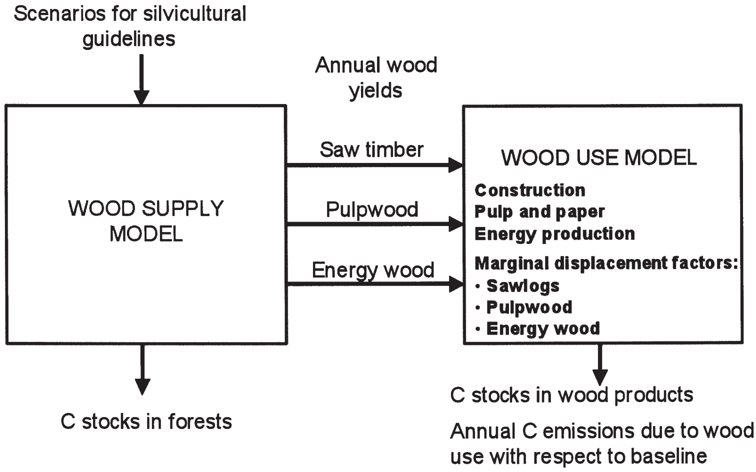

Fig. 1. Framework of analysis. Steady-state models, their linkage and information flows.

for a specified rotation period, one age class can be harvested in each year. At the end of the rotation, the stands that were harvested first in the cycle would be ready for harvesting again. Thus, our focus is on the landscape level rather than on individual stands. The normal forests under comparison differ in their management practices, equilibrium C stocks and the resulting annual supply of different wood commodities. Further, the wood supply contributes to the potential for displacing fossil C emissions via the wood use chains, and together with the assumed lifetime of wood products to their equilibrium C stocks. On the wood demand side, we assume the same material function to be fulfilled either by wood products or their substitutes, depending on the annual supply of wood. In our case study we compare a small number of alternative *scenarios* in their C balance. By a *scenario* we mean a management regime applied to the normal forest and its associated wood-use chains determined by the annual wood supply. The approach provides information about the long-term effects of changing forest management strategies, although it does not show the optimal way of reaching the ideal state starting from existing tree stands.

The framework of our analysis is illustrated in Fig. 1. The analysis is supply-driven, starting with the formulation of scenarios for silvicultural guidelines. Different management regimes are implemented in the *wood supply model* to obtain the annual wood yields for sawlogs, pulpwood and energy wood in each scenario and the C stock of the normal forest associated with the scenario is estimated. Timber yields are used as inputs in the *wood use model* by which the displaced fossil C emissions due to the wood-use cycles of sawlogs, pulpwood and energy and the equilibrium C stock of wood products are calculated in each scenario.

3.2 Marginal Fossil C Displacement Factor

In estimation of the displaced fossil C emissions we do not use the original displacement factor presented by Schlamadinger and Marland (1996) but its slight modification called *marginal* displacement factor. Let us consider two systems having the same function or providing the same service: a fossil fuel based reference system, **RS**, and another one, **WS**, based on more intensive use of wood biomass (Fig. 2). The systems could provide energy services or they could additionally include some other functions such as housing. Essentially, they must provide the same services to be comparable. The reference system could, for instance, represent a business as usual (BAU) or baseline situation with minor use of wood.

The system **RS** may *also* need a small amount of wood biomass (C flux W) for its operation, for

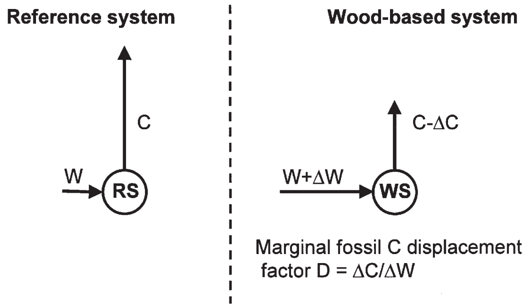

Fig. 2. Definition of the marginal fossil C displacement factor D. W and W+ΔW are the wood-based C flows into the reference system and the wood-based system, respectively, and C and C-ΔC are the fossil C emissions of the systems.

example wood materials used in concrete houses, or W can be zero, which would be the case in energy production using fossil fuels. The system **WS** needs wood-based raw material W+ΔW for its operation and its associated fossil C emissions are C-ΔC. The *marginal* fossil C displacement factor D that describes the *reduction* in fossil C emissions in proportion to the *additional* biomass use ΔW is given by:

$$D = \Delta C / \Delta W \qquad (1)$$

Note that D could also be negative, in case the wood-based system is worse than its reference.

3.3 Wood Supply Model

The growth functions used in the wood supply model are based on empirical data and realistic alternative forest management practices in Finland. The forest resource data consist of two tree species, and both are grown as single species forest areas. To analyze variation between sites and stands, we utilize management simulations of 8 Scots pine stands and 4 Norway spruce stands. The stands were measured in the field before the first thinning and their further development was simulated using the MOTTI simulator (Hynynen et al. 2005) for different rotation lengths and thinning intensities. The MOTTI simulator uses individual-tree, distance-independent growth models and provides detailed outputs on growth, mortality and yields of wood assortments as well as economic returns.

The forest management alternatives (scenarios) are generated by varying the final harvest age and thinning intensity. These silvicultural changes impact the growth rates, yields of wood assortments and stumpage returns. The wood supply from the forest is divided into three categories: sawlogs, pulpwood and energy wood. The relative proportions of sawlogs, pulpwood and energy wood and their total annual wood supply vary between the scenarios, but in each individual equilibrium scenario the wood supply is constant over time.

The forestry practice in Finland largely follows silvicultural recommendations given by the Forestry Development Centre Tapio (Tapio 2006). We took these recommendations as the basic silvicultural regimes. By increasing growing densities and/or rotation lengths, variations in the regimes were generated that provided alternatives for the analysis of GHG mitigation. When the amounts of wood produced during each silvicultural regime are divided by their respective rotation lengths, we obtain average annual wood yields per hectare for a fixed forest area. The different regimes can then be compared. Annual yields are provided for sawlogs, pulpwood and energy wood. Energy wood is collected from the final harvest in all scenarios, and the amount of energy wood is calculated using biomass expansion factors provided by Lehtonen et al. (2004). It is assumed that 70% of the available energy wood is actually transported from forest and utilized. The potential energy wood from pre-commercial thinning is excluded from our analysis.

Each simulation of the MOTTI simulator can start with a built-in initial stand or a given initial tree list and site characteristics. We decided to base our computations on a set of measured plots in order to account for the variation between forests in wood production and the reaction to different regimes. The plot data were from stands before the first commercial thinning so that the silvicultural regimes could be differentiated. Plot-level results were averaged for use in further analysis. All the stands can be considered successfully regenerated in terms of the established density of commercially viable tree species when viewed against the silvicultural recommendations. The initial stand data are provided in Appendix 1. The wood yields are converted to biogenic C fluxes by assuming that the softwood density is equal to 0.4 t/m^3 and its C content is 0.5. Energy use and emissions of silvicultural operations are not included in the estimates of marginal displacement factors, as they have found to be small (1–2%) compared to the amount of wood produced over the rotation (Karjalainen et al. 1994, Manriquez 2002, Sonne 2006).

3.4 Wood Use Model

The annual constant wood supply from normal forests, i.e. sawlogs, pulpwood and energy wood, is assumed to be consumed in house construction, papermaking and energy, respectively. The impact of wood supply on the annual C emissions is calculated using the marginal displacement factors, which are estimated in the wood-use model.

The basic assumption in the wood-use model is that the same social functions, i.e. the same housing area, paper production or energy service, will be fulfilled in each scenario, regardless of the wood supply. The above services will be provided *partly* by using conventional fossil fuel-based technologies and energy and *partly* by their wood-based substitutes, but the share of wood-based services is determined by the wood supply. For instance, both wood- and concrete-frame houses are assumed to be built using sawlogs as a raw material, but the proportion of wood-frame houses increases in scenarios with a higher sawlog supply. The total amount of houses constructed annually remains the same regardless of the scenario. The demolition of old wood products is proposed to be in balance with the new products coming into the wood products pool, so that the product stock is constant within each scenario and is determined by the estimated lifespan of wood materials. Further, it is assumed that no wood biomass will be disposed into landfills, which is compatible with environmental regulations of the European Union.

3.4.1 Emissions and C Stocks of Wood Products

We compare the alternative steady state scenarios in terms of their C stocks and the changes in their annual fossil C emissions due to substitution. The objective is to compare them to a baseline rather than presenting them as absolute emissions. For each of the three wood commodities with their specific end-uses, the displacement factors D are determined. The changes in annual fossil C emissions of scenario i with respect to a baseline scenario are then calculated in the model by Eq. 2:

$$\begin{aligned} C_i - C_{base} = &- D_s * (W_{s,i} - W_{s,base}) \\ &- D_p * (W_{p,i} - W_{p,base}) \\ &- D_e * (W_{e,i} - W_{e,base}) \end{aligned} \qquad (2)$$

where C_i are the total annual fossil C emissions of sawlog, pulpwood and energy wood chains in scenario i; C_{base} are the corresponding emissions of the baseline scenario; D_s, D_p, D_e are the marginal fossil C displacement factors of sawlogs, pulpwood and energy wood; $W_{s,i}$, $W_{p,i}$ and $W_{e,i}$ are the annual supplies of sawlogs, pulpwood and energy wood in scenario i; and $W_{s,base}$, $W_{p,base}$, and $W_{e,base}$ the corresponding supplies in the baseline scenario. As we are calculating the displacement factors with respect to the wood raw material used, they also include fossil C displacement due to by-product flows (e.g. from sawlogs) used for bioenergy.

In our analysis, one of the wood supply-demand scenarios, corresponding to the current silvicultural recommendations in Finland and providing the lowest sawlog supply, was defined as the baseline scenario. In this scenario, only concrete-frame houses are built containing a small amount of wood materials. The higher sawlog supply in the remaining scenarios is used to increase the proportion of wood-frame houses, functionally equivalent to the concrete ones. The terms $(W_{p,i} - W_{p,base})$ and $(W_{e,i} - W_{e,base})$ can also be negative, because the increase in the sawlog supply in some scenarios leads to a lower supply of pulpwood or energy wood. The wood supply from forests is presented as tons of C biomass per hectare of forest.

The C stock for scenario i is the steady state stock of wood materials in housing, corresponding to the sawlog supply in scenario i. The C stock in paper products is assumed to be negligible compared with stock of construction and was not considered. The steady state C stock of wood products in scenario i is calculated by multiplying the constant wood supply (in tons of C per ha of forest) by the assumed lifespan of wood materials.

3.4.2 Marginal Displacement Factor of Sawlogs

The marginal displacement factors for sawlogs are calculated based on the results of the Finnish-Swedish case study by Gustavsson et al. (2006), in which the greenhouse gas impacts of the construction of wood-frame multi-storey houses were compared with their functionally equivalent concrete-frame houses. The marginal displacement factor describes the relative reduction in annual emissions when the share of wood-frame houses is increased in proportion to concrete-frame ones. It is assumed that the lifespan of concrete- and wood-frame houses is the same and that the same percentage of their decommissioned wood materials is used to produce bioenergy.

Sawlogs are assumed to be processed to sawn wood and wood-based panels to be used in construction. The associated wood-biomass flows, including energy production, are illustrated in Fig. 3. Particle board is assumed to be produced from residues from sawmill and plywood manufacture. The remaining processing residues, including bark from logs, are assumed to be used for bioenergy. No residues are assumed to be used for pulp and paper.

A wood-frame house requires essentially more wood materials. In a concrete house some wood is used, for example, in roofs, windows and fittings. The marginal displacement factor of sawlogs is calculated by Eq. 3:

D_S = (fossil C emissions of building a concrete house – fossil C emissions of building a wood house) / (biogenic C in the *additional* amount of sawlogs over bark needed to build a wood-frame house instead of a concrete one) (3)

The fossil C emissions in Eq. 3 include all emissions from the manufacture of construction materials (wood products, concrete, metals) and displaced fossil C emissions due to the bioenergy use of wood waste (bark, sawmill residues, construction and demolition waste) during the whole lifecycle of a house. The factors also depend on the supposed marginal fossil fuel, i.e. coal or natural gas, that bioenergy substitutes for. In contrast to Gustavsson et al. (2006), in the present study the impacts of the parallel sawlog and energy wood chains (harvest residues from forests such as foliage and branches) are treated separately and distinct displacement factors are derived for each chain.

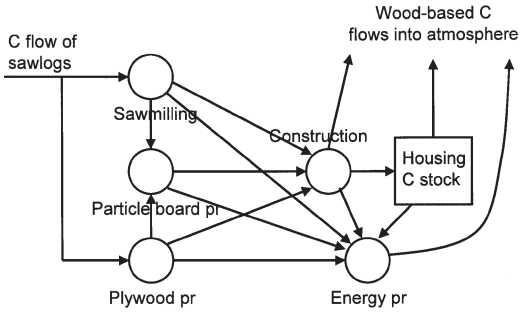

Fig. 3. Wood-based C flows for sawlogs. Energy production also comprises internal bioenergy production within wood processing. The flow chart applies to both wood- and concrete-frame houses: only their flow rates differ.

3.4.3 Marginal Displacement Factor of Pulpwood

Pulpwood is assumed to be used both for pulp and paper manufacture and energy the material flows shown in Fig. 4. Recycling of paper is not considered.

Unlike the case of wood materials or bioenergy, it is difficult to find realistic substitutes for paper products in general. For newspapers there are viable alternatives such as internet-based newspapers or in the foreseeable future also e-papers and e-readers. However, it is not straightforward to assess their climatic impacts compared to conventional printed media (an example of such a study is Moberg et al. 2009). Hence, we assume that pulp and paper production is constant in all the wood supply scenarios to maintain the same function, i.e. the same paper consumption in each scenario, and the change in pulpwood yield

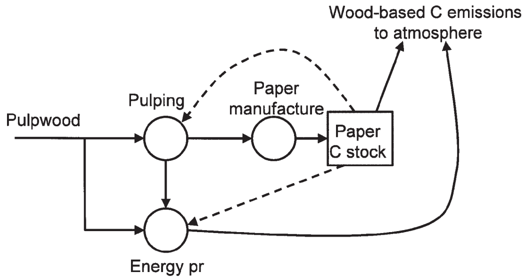

Fig. 4. Major wood-based C flows for pulpwood.

affects bioenergy production based on pulpwood. The model is designed somewhat unrealistically so that in the base scenario pulpwood is used both in paper and bioenergy production, allowing us to analyze the circumstances in which the pulpwood yield is reduced. Hence, the marginal displacement factor D_p for pulpwood is assumed to be the same as for energy wood and equal to the change in emissions due to the energy use of wood divided by the biogenic C content of the pulpwood used for energy:

D_p = (fossil C emissions of the fossil fuel chain – fossil C emissions of the pulpwood chain used for energy) / (biogenic C in pulpwood over bark used for energy) (4)

In the above Eq. 4 it is assumed that the same end-use energy is produced by pulpwood or alternatively by its fossil substitute.

3.4.4 Marginal Displacement Factor of Energy Wood

This displacement factor D_e is calculated based on assumptions of the percentage utilization of harvest residues, on boiler efficiency and on the fossil energy demand in the recovery and transport of the biomass. Energy wood harvested from either thinning or final cuttings is assumed to be used as bioenergy to replace fossil fuels.

D_e = (fossil C emissions of the fossil fuel chain – fossil C emissions of the energy wood chain) / (biogenic C in energy wood) (5)

3.4.5 Data and Assumptions in Calculating Displacement Factors

The same parameters for wood and fossil fuel cycles are used as in Gustavsson et al. (2006). The data on embodied energy in construction materials, which are needed in the estimation of emissions in Eq. 3, are originally from Fossdal (1995). All the data and assumptions used in calculation of the displacement factors are listed in Appendix 2.

Following Gustavsson et al. (2006), the fossil fuel used in the manufacture of construction materials (wood and non-wood) is assumed for the sake of simplicity to be oil. In sawmills, however, the main process fuel is assumed to be wood residues. The manufacture of construction materials also requires electricity. A coal-fired condensing plant is assumed to present a good estimate for the so-called *marginal* electricity in the Nordic electricity markets at present. The use of marginal electricity can be justified in a displacement study, where marginal changes with respect to a reference are considered, for instance, due to the additional supply of bioenergy or decreased demand for electricity. Natural gas-fired generation, being an approximation of the emissions from future marginal electricity, is also considered for comparison. The emissions of fossil fuels are from the full fuel cycle, including the average 'upstream' emissions from processes such as mining or drilling, refining and transportation of the fossil fuel. Wood fuels are assumed to replace coal and, for comparison, also natural gas.

3.5 Scenarios

The silvicultural regimes designed for this study allow us to examine how increasing rotation length and growing density affects wood yields and climate change mitigation.

The alternative forest management strategies are:

- BASE silvicultural guidelines issued in Finland, rotation based on average diameter
- S20 increase of rotation by 20 years
- S40 increase of rotation by 40 years
- S20BA increase of rotation by 20 years and increase of basal area by 4 m^2/ha

S40BA increase of rotation by 40 years and increase of basal area by 4 m^2/ha

In the base case representing the current silvicultural guidelines for Finnish forests (Tapio 2006), the average rotation lengths of the sample plots are 75 and 57 years for Scots pine and Norway spruce, respectively. The rotations were based on attaining the recommended average diameter at breast height, defined by tree species and site quality. The recommendations also define stand basal areas before and after thinning, as functions of dominant height, by species and site. The basal area increase was defined as an equal change in basal area before and after thinning. Thus, in the four alternative scenarios cuttings are postponed, resulting in higher C stocks in forests. This allows us to evaluate the implications of strategies to increase C stocks for substitution and avoided emissions. In the energy wood scenario, the bioenergy potential of the stands includes the energy wood from pre-commercial thinning in addition to energy wood from final felling.

4 Results

Forest management influences the steady state C stock in forest biomass and annual wood production and the relative share of sawlogs, pulpwood and energy wood. This, in turn, determines the potentials of displacing fossil C emissions on the wood-use side, where in all scenarios the same social functions are assumed to be fulfilled and the C stock in biomass products. The numerical results of alternative scenarios consist of 1) the estimated annual wood yield from both a normal pine- and spruce-growing forest, 2) the steady-state C stocks in forests and wood products, and 3) the change in annual fossil emissions of the wood-use chains with respect to the baseline, with 2) and 3) both being indicators of the greenhouse gas benefits of the alternative scenarios.

4.1 Auxiliary Variables for Calculating Climatic Benefits

4.1.1 Wood Yields from Forests

In the case of Scots pine (Table 1), an increase in rotation (from the average of 75 to 95 and 115 years) reduces the annual total yield, implying that 75 years was closest to the rotation with the maximum mean annual increment (M.A.I.). Sawlog yields are highest for middle rotation lengths, whereas pulpwood yields are highest with the shortest rotation. An increase in growing densities (4 m^2 per hectare in basal area before

Table 1. Average wood yields in silvicultural regimes.

Scenario	Scots pine regime	Sawlog yield	Pulpwood yield	Total stem wood yield	Final harvest energy wood
			m^3/ha/yr		t/ha/yr
BASE	Base	3.41	2.49	6.02	0.61
S20	+20yr	3.54	2.08	5.71	0.49
S40	+40yr	3.40	1.87	5.35	0.49
S20BA	+20yr + 4m^2	3.86	2.29	6.23	0.59
S40BA	+40yr + 4m^2	3.75	2.08	5.90	0.59
	Norway spruce regime	Sawlog yield	Pulpwood yield	Total stem wood yield	Final harvest energy wood
			m^3/ha/yr		t/ha/yr
BASE	Base	3.67	2.36	6.32	0.86
S20	+20yr	4.52	1.76	6.49	0.75
S40	+40yr	4.97	1.35	6.49	0.82
S20BA	+20yr + 4m^2	4.90	2.22	7.28	0.87
S40BA	+40yr + 4m^2	5.55	1.72	7.40	0.94

and after thinning) increases both the sawlog and pulpwood yield.

In the case of Norway spruce (Table 1), the annual total yield increases with the first 20 year increase in rotation but then remains constant, except for the higher stand density, where the annual total yield continues to increase with the second 20-year increase in rotation. The annual yield of sawlogs increases with the lengthening of the rotation period (from 57 years up to 97 years). Pulpwood yields decline with increasing rotation but, compared to the baseline, are greater with a higher stand density. Overall, yields are greater in Norway spruce plots compared to Scots pine. This is because, on average, they are located on more productive soils.

The amount of energy wood obtained in final harvests depends on how much growing stock there is at the time of the final harvest. This depends on the timing of the final harvest relative to the last thinning.

4.1.2 *Marginal Fossil C Displacement Factors*

Results with marginal displacement factors for sawlogs, pulpwood and energy wood, calculated using Eqs. 3–5 and data described in Appendix 2, are presented in Table 2. The marginal displacement factor for sawlogs is significantly larger in the Swedish case than in the Finnish case. One explanation for this is obviously the structural differences between Finnish and Swedish wooden houses. The Finnish house with frame and façade in wood contains much more wood per square metre than a Swedish house with a stucco façade and only bearing frames in wood. Thus the highest substitution benefits from wood material appear to come from the frame material, i.e., the highest unit benefits are attained if a wooden frame is used instead of a concrete one and the benefits are relatively lower from façade material. Note that when the displacement factors are larger than 1, then the relative reduction in emissions is higher than the C content of the saw logs.

Table 2. Marginal fossil C displacement factors for the three wood commodities: sawlogs, pulpwood and energy wood, calculated based on the study by Gustavsson et al. (2006).

		Marginal fossil fuel	
		Coal	Natural gas
Sawlogs (multi-storey house, Sweden)	D_s	2.05	1.52
Sawlogs (multi-storey house, Finland)	D_s	1.31	0.91
Pulpwood (constant p&p prod, rest of wood to bioenergy)	D_p	0.89	0.50
Energy wood	D_e	0.89	0.50

4.2 Climate Benefits

4.2.1 *C Stocks in Forests and Wood Products*

Lengthening the rotation and increasing the den-

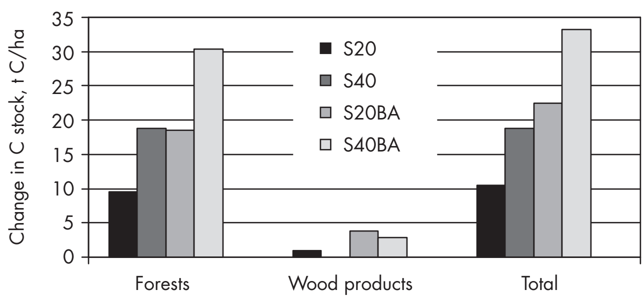

Fig. 5. Change in C stocks (t C/ha) in forests and wood products in various wood-supply scenarios compared to the BASE scenario, in the case of Scots pine and a Swedish house.

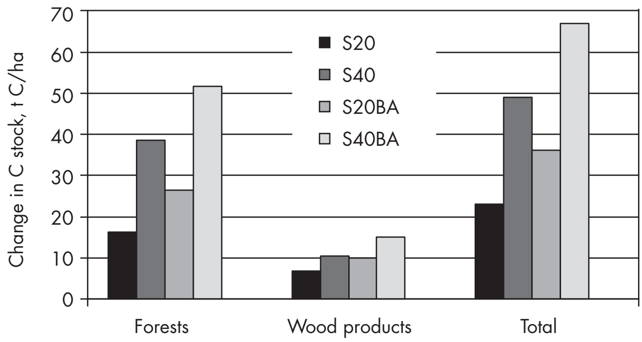

Fig. 6. Change in C stocks (t C/ha) in forests and wood products in various wood-supply scenarios compared to the BASE scenario, in the case of Norway spruce and a Swedish house.

Table 3. C stocks in forests (Scots pine vs. Norway spruce stands), in wood products and in total. The share of wooden houses from all houses maintained, their housing area and total housing area maintained by 1 ha of forest (Swedish house case). (Note that in the BASE scenario only concrete frame houses are constructed, but wood is still used in interior design such as fittings).

Scots pine Scenario	C stock forests t C/ha	C stock wood products t C/ha	Wooden houses %	Housing area in wooden houses m^2/ha	C stock total t C/ha
BASE	47.64	35.72	0	0	83.35
S20	57.10	36.74	7	101	93.84
S40	66.47	35.72	0	0	102.19
S20BA	66.18	39.59	25	383	105.77
S40BA	77.98	38.57	19	282	116.55
		Maintained housing area by 1 ha of forest = 1506 m^2 (i.e. 1.27 houses)			

Norway spruce Scenario	C stock forests t C/ha	C stock wood products t C/ha	Wooden houses %	Housing area in wooden houses m^2/ha	C stock total t C/ha
BASE	41.16	38.18	0	0	79.34
S20	57.31	45.03	42	677	102.34
S40	79.65	48.66	64	1036	128.31
S20BA	67.50	48.06	61	976	115.56
S40BA	92.90	53.30	93	1494	146.19
		Maintained housing area by 1 ha of forest = 1610 m^2 (i.e. 1.35 houses)			

sity increased the C stock in forests compared to the base case for both tree species (Table 3). The relative stocks with respect to the BASE scenario are presented in Figs. 5 and 6. The C stock was largest in scenario S40BA with the prolonged rotation period and increased basal area. The increase in the C stock was larger for Norway spruce than for Scots pine.

The stock in wood products was largest in scenario S40BA for Norway spruce, while for Scots pine the stock was largest in scenario S20BA, in which the rotation length was increased by only 20 years in addition to increasing the density. The C stock in wood products is directly proportional to the sawlogs produced. It is also proportional to the estimated lifespan of houses, which was assumed be 100 years. The results are presented here for the Swedish case only, but the Finnish case is very similar in terms of C stocks. As a whole, the differences between the scenarios are larger in forest stocks than in wood product stocks.

The impacts (of modified silviculture) on C stocks were notably larger in the case of forests than for wood products. However, the *absolute* level of the C stock seems to be high in the wood-use chain of sawlogs when the end products are in long-term use, being even the same magnitude as the stock in Norway spruce forests. This is, however, likely to be an overestimation, as the 100 years lifespan of wooden buildings is also applied to wood materials, although their lifespan is usually shorter due to the need for renovation during lifetime of the building. This applies specifically in the Finnish house case with wooden façade materials, whereas the lifespan of the bearing frames can be the same as that of the building. If the renovation cycles were included in our analysis, less wood could have been used for new construction of houses and the housing stocks per forest hectare would have been lower.

4.2.2 *C Emissions from Wood-Use Chains with respect to the Baseline*

The changes in annual emissions of wood-use chains for the alternative scenarios are illustrated in Figs. 7 and 8. For Scots pine (Fig. 7), the total emissions are increased compared to BASE in scenarios S20 and S40, in which only the rotation length is increased. The increase in the sawlog yield in scenarios S20 and S40 is so small that despite the large absolute value of its displacement factor, the climatic benefits of the sawlog chain cannot compensate for the decreasing pulpwood and energy wood supply and their lowered climatic benefits as bioenergy. In scenarios where also the basal area is increased, the total emissions are reduced, most when the rotation is increased by 20 years

For Norway spruce (Fig. 8), both an increase in the rotation length and in basal area implies growth in the sawlog supply and thus a considerable decrease in emissions from sawlogs due to strong substitution effects. On the other hand, the emissions due to pulpwood are increased, because the pulpwood yield decreases and thus the production of bioenergy also decreases. The increase in emissions does not, however, exceed the decreased emissions due to sawlogs, because of the smaller displacement factor pulpwood. The annual reduction in total emissions of the three wood-use chains is highest in scenario S40BA.

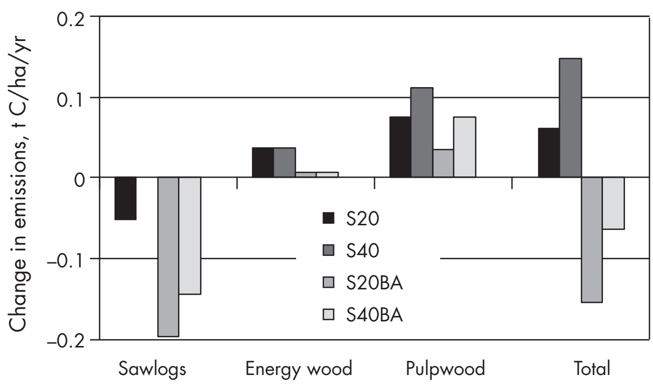

Fig. 7. Change in annual fossil C emissions (t C/ha/yr) from the use of sawlogs, energy wood and pulpwood,and in total in various wood-supply scenarios compared to the BASE scenario in the case of Scots pine, a Swedish house and coal as a marginal fossil fuel.

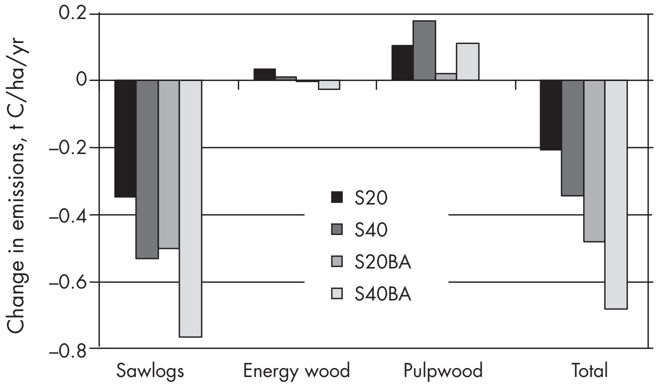

Fig. 8. Change in annual fossil C emissions (t C/ha/yr) from the use of sawlogs, energy wood and pulpwood, and in total in various wood-supply scenarios compared to the BASE scenario in the case of Norway spruce, a Swedish house and coal as a marginal fossil fuel.

Table 4. Impact of changing the marginal fossil fuel: coal vs. natural gas. Change in annual fossil C emissions (per unit of forest area) from the sawlog chain and in total in various wood-supply scenarios *with respect to* the BASE scenario. (Normal Norway spruce forests; sawlogs used in the Finnish house case).

	Sawlog chain		Wood use total	
Marginal fuel	Coal	Natural gas	Coal	Natural gas
	t C/ha/yr			
S20	–0.22	–0.16	–0.08	–0.08
S40	–0.34	–0.24	–0.15	–0.13
S20BA	–0.32	–0.22	–0.30	–0.21
S40BA	–0.49	–0.34	–0.41	–0.29

Table 5. Impact of changing the marginal fossil fuel: coal vs. natural gas. Change in annual fossil C emissions (per unit of forest area) from the sawlog chain and in total in various wood-supply scenarios *with respect to* the BASE scenario. (Normal Norway spruce forests; sawlogs used in the Swedish house case).

	Sawlog chain		Wood use total	
Marginal fuel	Coal	Natural gas	Coal	Natural gas
	t C/ha/yr			
S20	–0.35	–0.26	–0.21	–0.18
S40	–0.53	–0.40	–0.34	–0.29
S20BA	–0.50	–0.37	–0.48	–0.36
S40BA	–0.77	–0.57	–0.68	–0.52

The decrease in emissions when deviating from BASE is clearer for Norway spruce than for Scots pine, because the sawlog yield could be significantly increased for Norway spruce according to our growth models. Because the marginal displacement factor for sawlogs is especially high in the Swedish case, an increase in the sawlog supply creates substantial reductions in emissions.

An average displacement factor could be estimated for the whole wood material harvested. Calculating the factor D by dividing the emission reduction due to sawlogs, pulpwood and energy wood by the total amount of C in biomass harvested (including the below ground biomass and forest residues not used for energy), we would in the most favourable case (Swedish house, coal as the marginal fossil fuel) obtain a displacement factor between 1.0 and 1.2.

In Tables 4 and 5 the impact of the assumed marginal fossil fuel (coal vs. natural gas) on annual emissions is shown in the case of normal forests of Norway spruce. Because the displacement factor for sawlogs is lower in the Finnish house case than in the Swedish case (Table 2), the decrease in emissions per unit of forest area with respect to the BASE scenario is also lower in the former case.

Emission reductions due to wood construction with respect to the functionally equivalent concrete construction can also be estimated per square metre of housing area. The results are presented for Finnish and Swedish houses in Table 6. The estimated emission reductions of wood construction in proportion to concrete result from lower embodied emissions from wood building materials and the bioenergy use of sawlog by-products, construction waste and demolition waste from wood buildings. The same data for the sawlog chain are used in Table 6 as in Tables 4 and 5, but the emission reductions here are allocated to the functional unit in wood end-use, namely housing area.

The climate benefits per square metre of housing area are higher for the Finnish house case, although the displacement factor in the Swedish case is better. This is because much more wood is used in a Finnish house and proportionally more biomass is also available (sawlog by-products, wood waste) for bioenergy, reducing the emissions with respect to the functionally equivalent concrete house. In Table 6 the climatic benefits are divided over the whole house lifecycle (100 yrs). Thus the annual emission reduction multiplied by 100 yrs gives the climate benefit per m^2 of building in wood instead of concrete.

Table 6. Annual change in fossil C emissions of a wooden house with respect to a concrete one per unit of housing area. Marginal fossil fuel: coal vs. natural gas. (The numbers below are approximately the same for both tree species.)

	Coal	Natural gas
	kg C/m^2 housing area/yr	
Finnish case	–1.11	–0.78
Swedish case	–0.51	–0.38

4.2.3 Win-Win Scenarios

For Scots pine both scenarios S20BA and S40BA are win-win with respect to the baseline. However, scenario S40BA has the highest C stocks (Fig.5) whereas S20BA creates the highest annually displaced emissions (Fig.7) so among the four alternative Scots pine scenarios there is no win-win. The displaced emissions in scenario S20BA is of the order of 0.1 t C/ha/yr higher than in S40BA. On the other hand the difference in C stocks between scenario S40BA and S20BA is of the order of 10 t C/ha, which would mean that the imbalance in C stocks between S40BA and S20BA would be compensated by the higher displaced emissions S20BA in as much as 100 yrs.

In case of Norway spruce all the alternative scenarios are win-win in proportion to the baseline. In addition the scenario with the highest C stocks S40BA (Fig. 6) also appears to cause the highest annually displaced emissions (Fig. 8) forming a win-win scenario among the alternative scenarios.

5 Discussion and Conclusions

In our study we present a method to assess long-term climatic benefits of forest management strategies and the associated wood-use chains. This kind of steady-state analysis can also give suggestions of the direction in which the existing forest management practices and wood use should be changed to improve overall climatic benefits from forestry, and what could be the best options for sustainable forestry in the long term. An advantage of the steady-state assumption is that the somewhat arbitrary choice of the initial state of the system (e.g. mature stock or forest land after a regeneration cut) can be circumvented. The steady state is assumed to be a reasonable landscape-level approximation of managed forests under ongoing activities.

Our study indicates that win-win solutions could be obtained by changing forest management practices with respect to the existing silvicultural recommendations (Tapio 2006) and increasing wood use in housing construction. However, using our method we are not able to answer the question of how the most favourable scenarios should be reached starting from the baseline corresponding to the existing recommendations. The issue of time paths is beyond the scope of the present study. On the landscape level, increasing the rotation lengths of individual stands would lead to sequestration of C, but would simultaneously reduce the wood supply, and lower substitution benefits would temporarily be obtained. The problem of combining changes in stocks and annual emissions is related to the time path question. There is no obvious way to merge these two impacts as it would need the knowledge of societal preferences on stock changes and annual emissions. One way of merging these two impacts was presented in Valsta (2007) and Valsta et al. (2008) but we chose not to utilize that approach as it assumes that the societal preferences can be reduced to a simple time preference (interest rate).

The potential for substitution benefits is related to the quality of the raw material and how efficiently wood biomass can be used during its lifecycle. The obtained emission reductions per unit of biomass are generally higher if harvested biomass can be used both for material and energy substitution; and possibly even higher if it can be materially recycled during its lifetime and only finally used for energy. Wood that can only be used for energy obviously has lower unit benefits in emissions reduction. Hence, it is understandable that the potential displacement factors of sawlogs, pulpwood and energy wood differ from each other. When the average displacement factor calculated for the whole tree biomass is larger than one such as in the Swedish case of this study, the C loss due to harvest on stand-level would be directly compensated by the displaced emissions due to wood materials. In this case the C payback time (cf. Gibbs et al. 2008) for wood use would be zero. By increased utilisation of bioenergy the displaced emissions could be even higher.

However, in theory, some wood materials could also be more energy- and emission-intensive than their non-wood-based functionally-equivalent substitutes, so the efficiency of material substitution could be very case-specific in character. Note that the general idea of substitution implies a certain baseline relative to which we estimate emissions. The definition of this baseline, for instance the reference technology or reference fuel, is not straightforward and in reality it could also change over time because of technological developments.

Electronic media as a substitute for paper could be included in the pulpwood scenarios, but the displacement factors would be related to a large number of case-dependent assumptions (Moberg et al. 2009). The web-based media appeared to have climatic impacts of the same order of magnitude as conventional printed media, but tablet e-paper somewhat lower, which would mean that the displacement factor of pulpwood could be negative in this case.

One of our results is that simply maximizing the annual biomass production does not necessarily lead to the highest substitution benefits in the form of reduced fossil C emissions. Based on the results of our study, forest management strategies that lead to high sawlog production could have the greatest substitution benefits. This result is somewhat different from those of the CORRIM consortium (Perez-Garcia et al. 2005b), according to which management strategies with lower forest stocks, shorter rotations and a higher biomass yield clearly gave the best overall greenhouse gas benefits (including the whole lifecycle from forest to wood products in housing). One obvious explanation for this difference is that in the CORRIM analysis low-diameter wood (pulpwood size) was also used as a raw material for long-lived products in construction, such as wood-based panels. Their analysis is appropriate to the local conditions in which small-diameter wood was not directed to pulp production or just bioenergy. Additionally, the range of rotations was much larger in Perez-Garcia et al. (2005b), and our alternatives would fall around their middle alternatives.

There are also substantial uncertainties concerning the parameters of the wood use chains in our numerical examples. Displacement factors of sawlogs are only estimated from two specific cases of wood construction that even differ from each other significantly. Further, wooden construction materials are assumed to be produced only from sawlogs in our case examples, whereas low-diameter roundwood could also serve as a raw material for climatically beneficial long-lived wood products, such as OSB-based I joists (see CORRIM studies, e.g. Perez-Garcia et al. 2005a), or the small amount of wood-based panels used in the Finnish and Swedish houses of our case examples. The wood-use chains in our study are somewhat unrealistic, as we assume that sawmill residues are not used as a raw material for pulp, contrary to the common practice in Finland or

Sweden, but this would not change the estimated marginal substitution impacts.

We have calculated the marginal displacement factors for the basic timber assortments harvested from forests. These dimensionless factors are illustrative in describing the changes in fossil C emissions in proportion to the amount of biogenic C transported from harvest sites. They do not include C sequestered into wood products. It must be emphasized that the factors for sawlogs are marginal, which means that we are considering an additional change in emissions in proportion to the additional amount of logs harvested from forests. Further, the additional sawn wood made from logs is assumed to be used in the new construction of wood-frame multi-storey houses instead of concrete-frame ones (which also contain some wood materials in our cases).

Our computed results are naturally dependent on the alternatives used. For another set of silvicultural alternatives, increasing the growing density or rotation length will lead to different changes in the production of the wood assortment and, hence, different amounts of displaced emissions. However, our methodology itself can be applied to other cases in various parts of the world, our main objective being to demonstrate the steady-state methodological approach.

A limitation in our modelling study is that soil C is not included. In reality the equilibrium soil C stock is influenced by production of litter and forest residues left on site (Liski et al. 2001), which are factors varying in our alternative forest management scenarios. Especially intensified biomass extraction from forests for bioenergy would certainly decrease the soil C pool in the long term, but there would be significant uncertainties in quantifying the soil C balance by existing models (Palosuo et al. 2008).

The use of a marginal fossil fuel or electricity with higher specific emissions than the average electricity mix is justified, when we assume that the additional supply of bioenergy will have an impact on the use of the most emission-intensive marginal energy sources (e.g. coal condensing power in the Nordic power market). To illustrate the sensitivity of the displacement factors to the chosen marginal fuel, natural gas is considered in addition to coal.

In our study we have considered steady states, representing sustainable long-term forest management and wood use strategies. However, the urgency of mitigation will most likely highlight climate policies in the near future that would give rapid assistance in stabilizing atmospheric greenhouse gas concentrations. In some cases, transient forest management strategies based on the utilization of sinks might be an efficient short-term option. It can be outlined that this type of short-term sequestration option, materialized in prolonged rotations, could be combined, depending on the present age-class distribution of managed forests, with a growing supply of sawlogs in the future and higher substitution potentials. It could represent a dynamic win-win strategy for managed forests, which in the longer term would approach some favourable steady state, as considered in our study.

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Appendix 1. Wood Supply Model Motti: Initial Forest Stand Data Used in Simulations

Table A1.1. Main characteristics of the stands. Site quality is expressed as dominant height predicted for age 100. Plots were located between lat 60.5–61.5N and lon 25–26E. The stands were tended to 1800 trees/ha at the beginning of simulation.

Plot number	Dominant height at age 100, (m)	Plot age (years)	Number of trees (ha^{-1})	Average (basal area weighted) diameter (cm)
Scots pine				
1	22.6	15	4800	5.7
2	23.6	11	2990	6.8
3	24.5	11	2732	5.4
4	24.8	11	2790	7.1
5	25.2	13	2917	5.2
6	27.9	12	4333	8.7
7	28.3	11	2603	4.4
8	28.6	11	2740	4.9
Norway spruce				
1	28.5	12	4788	3.9
2	29.3	10	2902	5.1
3	29.5	11	3636	5.9
4	30.7	11	3118	6.6

Note: 70% of energy wood from final felling assumed to be used for energy.

Appendix 2. Wood Use Model: Assumptions and Data Required for Calculating the Marginal Displacement Factors.

Table A2.1. Properties of wood.

Softwood density	0.4 t/m^3
C content in DM (dry matter)	50%
Share of bark in logs	10%

Table A2.2. Biofuel properties.

	Moisture content	Specific heat	Share of energy use	Oil use: recovery and transport [a)]
	%	MJ/kg	%	%
Wood (dry)	0	19		
		MJ/(kg DM)		
Chips and sawdust (sawlogs)	50	16.6	100 [b)]	1
Bark (sawlogs)	60	15.3	100	1
Pulpwood	50	16.6		5
Energy wood from final felling [c)]	60	15.3		5
Construction waste	15	18.6	100	1
Demolition waste from wood materials	15	18.6	90	1

[a)] Primary energy of oil in proportion to heat value of wood fuels (note: harvest and transport of sawlogs included in primary energy use of building materials (Fossdal))
[b)] Share of energy use but excluding raw material used for wood-based panels
[c)] Foliage, branches etc

Table A2.3. Fossil fuels.

	Fuel lifecycle Specific fossil C emission	El. production Conversion efficiency	Wood fuel conversion efficiency in proportion to fossil fuel
	kg C / GJ	%	%
Coal	30	40	100
Natural gas	18	50	96
Oil	22		98

Table A2.4. Specific end-use energy of the main construction materials and CO_2 emissions from cement production (Fossdal 1995). Material use in the wood houses and the (fictitious) functionally equivalent concrete houses (Gustavsson et al. 2006).

Main construction materials	Specific end-use energy of main construction materials			CO_2 from cement production	Construction materials delivered to site						
					CASE: Viikki, Finland[c)]			CASE: Växjö, Sweden[d)]			Material losses
	Electricity[a)]	Fossil fuel[b)]	Wood fuel		Wood house	Concrete ref. house	Wood house – Concrete house	Wood house	Concrete ref. house	Wood house – Concrete house	
	MJ/kg	MJ/kg	MJ/kg	g/kg	kg	kg	kg	kg	kg	kg	%
Macadam (Dk-study)	0	0.068			14726	0	14726	315400	315400	0	0
Concrete (crushed gravel)	0.1125	0.7375		60	192768	2044862	–1852094	226497	1372528	–1146030	2
Mortar	0.13	0.85		99	118	118	0	25684	23895	1789	5
Lightweight blocks	0.3	1.9			0	0	0	4204	4204	0	5
Iron/steel	3.11	3.06			21892	18843	3048	18487	29855	–11368	15
Aluminium	64.1	42.4			0	0	0	1	1	0	5
Copper	2.3	15.9			0	0	0	530	530	0	5
Zinc (data for copper)	2.3	15.9			0	0	0	148	148	0	5
Lumber	0.47	0.54	2.07		114273	25259	89014	66108	36608	29500	10
Particleboard	1.4	0.61			29480	10066	19414	19874	19341	533	10
Plywood (particle board)	1.38	0.61			16310	0	16310	23619	21953	1667	10
Insulation	1.1	10.2			24782	10573	14209	22532	10597	11935	7
Glass	0.72	6.7			0	0	0	4364	4364	0	5
Plasterboard	0.52	4.61			154730	24863	129867	99144	27922	71222	10
Paper (papp swe.)	4.8	17			79	0	79	2376	2376	0	5
Plastic (PVC)	8.44	47.69			2380	2264	116	2078	2040	38	5
Paint	4.6	8			8283	370	7913	1117	1117	0	5
Putty (fillers)	0.8	5.5			11807	14707	–2899	4248	4248	0	5
White goods (iron/steel)	3.11	3.06			0	0	0	3027	3027	0	5
Sanitary ware	7	6			0	0	0	584	584	0	0
Ceramic tiles (brick)	0	2.2			0	0	0	1269	1269	0	5

a) Assumed transmission losses of the electricity grid, 2%, must be added to above numbers
b) Assumed fossil fuel in production of building materials: oil

c) Viikki, usable floor area 1175 m^2, only materials which differ in wood and concrete houses are given. Note: The lifetime of all houses is assumed to be 100 years
d) Växjö, usable floor area 1190 m^2