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Article

Potential Roles of Swedish Forestry in the Context of Climate Change Mitigation

Tomas Lundmark [1,]*, Johan Bergh [2], Peter Hofer [3], Anders Lundström [4], Annika Nordin [5], Bishnu Chandra Poudel [6], Roger Sathre [7], Ruedi Taverna [8] and Frank Werner [9]

[1] Department of Forest Ecology and Management, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden

[2] Swedish Forest Research Centre, Swedish University of Agricultural Sciences, 230 53 Alnarp, Sweden; E-Mail: johan.bergh@slu.se

[3] GEO Partner AG, Baumackerstrasse 24, 8050 Zurich, Switzerland; E-Mail: hofer@geopartner.ch

[4] Department of Forest Resource Management, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden; E-Mail: anders.lundstrom@slu.se

[5] Department of Forest Genetics and Plant Physiology, Swedish University of Agricultural Sciences (SLU), 901 83 Umeå, Sweden; E-Mail: annika.nordin@slu.se

[6] Ecotechnology and Environmental Science, Mid Sweden University, Akademigatan 1, 83 125 Östersund, Sweden; E-Mail: bishnu.poudel@miun.se

[7] Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA; E-Mail: rsathre@lbl.gov

[8] GEO Partner AG, Baumackerstrasse 24, 8050 Zurich, Switzerland, E-Mail: taverna@geopartner.ch

[9] Werner Environment & Development, Idaplatz 3, 8003 Zurich, Switzerland; E-Mail: frank@frankwerner.ch

* Author to whom correspondence should be addressed; E-Mail: tomas.lundmark@slu.se; Tel.: +46-70-6317412 Fax: +46-18-672000.

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Abstract: In Sweden, where forests cover more than 60% of the land area, silviculture and the use of forest products by industry and society play crucial roles in the national carbon balance. A scientific challenge is to understand how different forest management and wood use strategies can best contribute to climate change mitigation benefits. This study uses a set of models to analyze the effects of different forest management and wood use strategies in Sweden on carbon dioxide emissions and removals through 2105. If the present Swedish forest use strategy is continued, the long-term climate change mitigation benefit will correspond to more than 60 million tons of avoided or reduced emissions of carbon dioxide annually, compared to a scenario with similar consumption patterns in society but where non-renewable products are used instead of forest-based products. On average about 470 kg of carbon dioxide emissions are avoided for each cubic meter of biomass harvested, after accounting for carbon stock changes, substitution effects and all emissions related to forest management and industrial processes. Due to Sweden's large export share of forest-based products, the climate change mitigation effect of Swedish forestry is larger abroad than within the country. The study also shows that silvicultural methods to increase forest biomass production can further reduce net carbon dioxide emissions by an additional 40 million tons of per year. Forestry's contribution to climate change mitigation could be significantly increased if management of the boreal forest were oriented towards increased biomass production and if more wood were used to substitute fossil fuels and energy-intensive materials.

Keywords: forest growth; harvest; substitution; carbon dioxide; abroad; in-country

1. Introduction

Most of the Swedish boreal forest landscape has been actively managed for at least the last 100 years. Today, managed forests in Sweden are a rich asset, and are increasingly recognised as a key natural resource to administer for climate change mitigation. Throughout the 20th century, the growth of Swedish forests has been larger than the annual forest harvest [1]. As an effect of active management, improved silviculture and increased standing volume, the growth and potential harvest of Swedish forests have also increased. For these reasons, the amount of carbon stored in the forest ecosystem has increased while simultaneously providing an increasing stream of wood raw materials for use by society.

A sustainably managed forest can contribute to the reduction of carbon dioxide (CO_2) emissions to the atmosphere in several ways: through the carbon sink into the forest biomass and soil, the increasing storage of carbon in harvested wood products and the use of wood as a substitute for fossil fuels and energy-intensive materials. Wood biomass from sustainably managed forests has generally been considered to be "carbon neutral", in that its use for bioenergy has zero net carbon emissions since the emissions released in its utilization for energy are subsequently captured in forest re-growth [2]. This view has recently been challenged by stand-level lifecycle analyses suggesting that the use of wood for biofuels will result in a drawdown of the forest stock and thereby a net reduction in the carbon captured in forests [3–5]. In contrast, Poudel *et al.* [6] showed both short- and long-term carbon balance benefits due to silvicultural practices to increase forest growth on the landscape level. The opposing views on the climate change mitigation effects of forestry and the use of forest-based products seem to relate to the temporal and spatial system boundaries adopted in the different analyses. CO_2 emissions, whether from biomass or fossil fuels, accumulate in the atmosphere and contribute to climate change. However, fossil fuel emissions represent permanent transfers from geologic carbon storage, while biogenic emissions are part of the biospheric carbon cycle that the photosynthetic capacity of the Earth's vegetation allows. Comprehensive lifecycle analyses integrating biological and technological processes can identify appropriate long-term approaches to carbon management through land-use. It is important to define the geographical scale used in such analyses, as a forest landscape has different carbon dynamics than a forest stand. In Sweden, large landscapes are managed as forest systems, where management activities in one stand are coordinated with activities elsewhere in the system. Hence, a steady flow of harvested wood will not be possible in sufficient volumes from an individual stand, but can be obtained from a landscape-level system. The same applies for carbon emissions, as sequestration in one stand offsets emissions from another.

The main focus of this study is to comprehensively analyze the relation between forest management, the use of forest products, and the carbon balance of the Swedish forest sector. The following carbon stocks and flows are included in the analysis:

- carbon stock in the forest ecosystem;
- carbon stock in long-lived wood products;
- fossil emissions from forest management, logistics and wood product processing;
- substitution effects through the avoidance of the production and disposal of (generally more energy-intensive) non-wood products;
- production emissions from the pulp and paper industry;
- substitution effects due to the imports and exports of pulp and paper;
- substitution effects of avoided use of fossil fuels due to energy recovery from fuel wood and residues from wood processing, chemical pulp processing, waste wood and paper.

Using a model cluster, we simulated the long-term (until the year 2105) carbon balance effects of three scenarios combining different forest management practices and biomass use alternatives for all managed forests in Sweden. In the simulations we considered the imports and exports of forest products between countries, which include the transfer of product carbon stocks and substitution benefits [7]. Because Sweden exports a substantial part of its forest products, this is a very important aspect of total carbon balance analyses that has not been considered in previous Swedish studies.

2. Materials and Methods

2.1. Swedish Forestry Overview

Sweden has 28.4 million hectares of forest of which approximately 22 million hectares are actively managed for multiple uses. In the current Swedish model of forestry, the Forestry Act stipulates equal importance for production and environmental goals in the managed forest landscape. Hence, all forest owners are obliged to sustain wood production while at the same time conserving biodiversity, enhancing recreational needs, protecting waters and soils and mitigating climate change. Clear-cut forestry has been the dominant silvicultural system in Sweden since the 1950s. The clear-cut silvicultural system has an even-aged stand structure that follows a cyclic harvest-and-regeneration pattern on the stand level. The length of the rotation period is normally set to optimize average forest production. To obtain a long-term sustainable flow of timber from the forest, an even age-class distribution on the regional and national level has been a long-term target in forest policy.

The forest standing stock in Sweden has nearly doubled over the last century. Currently, the average growth rate of Swedish forests is 5.1 cubic meters ha^{-1} $year^{-1}$ [1]. A number of studies have suggested that changes in management practices can lead to substantial (>50%) increases in forest growth, which would increase the long-term future potential of biomass harvest [6,8,9].

Forestry and forest products have long been a key resource for the Swedish economy [1]. National forest inventories have regularly been made since 1923 [10]. As a result, Sweden has a unique set of long-term data describing the forest resource on regional as well as national bases. Together with a long tradition of analyzing the consequences of different management practices [11,12] and well developed tools for the modeling forest growth [13], Sweden is well suited for analyzing the climate mitigation effects of active forest management in the boreal region.

2.2. Scenarios and Assumptions

Changes in silvicultural practices affect forest growth, carbon stock and the long-term potential of harvesting biomass for consumption. In this study, three different forest management scenarios were considered to represent different forest management strategies (Table 1). The scenarios are based on previously published scenarios developed by the Swedish Forest Agency. For each scenario the highest sustainable harvesting level was calculated, *i.e.*, the level of felling was based on growth level in every period. The probability for natural disturbances was the same for all scenarios and based on data from the Swedish National Forest Inventory.

Table 1. Overview of scenarios analyzed in this study.

Scenario name	Forest management	Biomass harvest	Biomass use
Baseline	Current (forestry conducted as today)	Stem-wood, bark and 15% of residues	Construction, interior works, industrial wood for energy, pulp and paper
Baseline increased harvest	Current management, more tree biomass is utilized compared to today	Stem-wood, bark, 35% of slash (tops, branches, and needles), 20% of stumps	As for baseline but with increased use of forest residues for bioenergy
Increased growth	Forest growth increases substantially, sustainable felling level increased by 50%	Stem-wood, bark, 35% of slash (tops, branches, and needles), 20% of stumps	As for baseline increased harvest, additional wood is used for construction and bioenergy.

The baseline scenario describes the forest management with current silvicultural practices in Swedish forestry [12]. In general practice, forests are managed as even-aged stands with one or two pre-commercial thinnings and two to three commercial thinnings before a final clear-cut harvest. The rotation length varies between 60–120 years depending on site conditions. It was assumed that 15% of harvest residues during the final harvest are retrieved for bioenergy. Environmental considerations were taken according to Swedish forest policy including 5% green tree retention [14].

The baseline increased harvest scenario applies the same silvicultural practices and environmental considerations as those of the baseline scenario. The difference lies in the amount of residues harvested for bioenergy use. Here we assumed that all final fellings include the removal of 35% of harvest residues and 20% of the stumps.

The increased growth scenario assumed an intensified silviculture with the aim of increasing forest growth and subsequently the harvest. Green tree retention levels were the same as in the other scenarios. Traditional Swedish silvicultural measures intended to increase forest yield were applied, including increased intensity in regeneration efforts and increased use of forest fertilisation [9]. We assumed that all extra growth is harvested, so that the development of the carbon stock in the standing biomass is expected to be similar for all scenarios despite different growth and harvest levels. The level of harvested residues and stumps was the same as in baseline increased harvest.

In all scenarios, it was assumed that the pulp and paper markets are relatively stable, while markets for solid wood products and bioenergy have the potential to grow in the future (Table 2). For the baseline increased harvest and increased growth scenarios it was assumed that additional biomass is used for bioenergy and/or construction. All additional biomass for bioenergy was assumed to be consumed in Sweden according to political goals [15], while the majority of the additional timber in the increased growth scenario was assumed to be exported.

Table 2. Overview of scenarios and assumptions for forest product harvest, consumption, and foreign trade.

Description	**2005**	**2035 ***					
Scenario		Baseline		Baseline increased harvest		Increased growth	
Harvest (million t dry matter)							
Stem wood	31.20	35.10	+12%	35.10	+12%	48.60	+56%
Slash	1.60	1.70	+3%	3.80	+140%	3.80	+140%
Stumps	0.00	0.00	0%	1.70	New	1.70	New
Consumption (million t dry matter)							
Construction, interior works, other wood products	2.30	2.50	+12%	2.50	+12%	3.50	+56%
Pulp and paper	2.10	2.30	+12%	2.30	+12%	2.30	+12%
Total fuel wood	8.10	8.80	+8%	12.60	+55%	21.50	+165%
Foreign trade (million t dry matter)							
Export of wood products	7.90	8.90	+12%	8.90	+12%	12.60	+60%
Export of pulp and paper	13.70	15.10	+11%	15.10	+11%	15.10	+11%
Import of wood products	7.10	7.10	Constant	7.1	Constant	7.10	Constant
Import of pulp and paper	2.10	2.30	+12%	2.30	+12%	2.30	+12%

* Linear increase from 2005 to 2035; afterwards, constant.

This study considered three phases in the scenario modeling. Phase one (years 1900 to 2005) represents actual forest management in Sweden during the period, including the imports and exports as well as the use of forest biomass within Sweden. Due to the long residence time of solid wood products in construction, the calculations start in the year 1900. The consumption and foreign trade figures from 1900 to 2005 were taken from various statistical sources [16–35].

The second phase (years 2006 to 2035) represents the period in which the different forest management practices according to the three scenarios are implemented. For all scenarios, forest growth and maximum sustainable harvest were modeled. The use of harvested biomass was according to assumptions presented in Table 2.

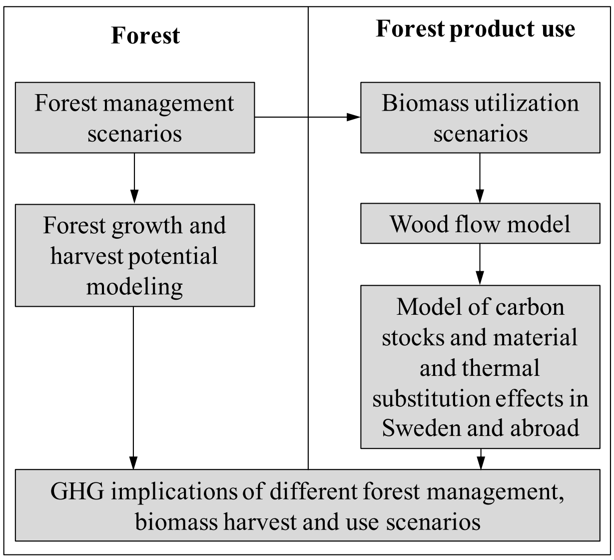
The third phase (years 2036 to 2105) assumed that the consumption and foreign trade remain constant after 2035 to allow various components of the model to approach a steady state, due to the long lifetime of many wood products and the long response time in the forest ecosystem in relation to growth and yield.

In addition to Swedish forestry and wood use, we accounted for the effects of the international wood products trade, *i.e.*, the carbon stocks of wood are accounted for where they are situated (contrary to, *e.g.*, as a legacy for the country where the wood was grown). The assumptions for accounting carbon benefits abroad included that domestic wood is stored in various products abroad, foreign wood is stored in various products in Sweden, and wood residues arising from the processing of imported and exported semi-finished wood products both in Sweden and abroad, which can be used to generate energy. We assumed that the production emissions of the imported semi-finished wood products arise abroad, similar to the case of exported products, whose production emissions were assumed to arise in Sweden. Exported finished products were assumed to replace conventional products manufactured abroad, and *vice versa*. The carbon stock changes in the forest and in wood products were compared with the year 1990. For the substitution effects, the entire wood flow, including that from the past, is considered, *i.e.*, the wood that was harvested earlier than 1990 that is leaving the pool of harvested wood products in a specific year, was also included.

2.3. Modeling Approach

A broad, integrated system analysis approach was adopted covering lifecycle greenhouse gas (GHG fluxes of forestry and forest biomass utilisation [7,36]. Independent models representing different parts of the system were clustered to quantitatively estimate system-wide effects (Figure 1).

Figure 1. Modeling cluster for estimating GHG implications of forestry and biomass utilisation practices.



2.3.1. Modeling of Forest Growth

The modeling of forest management and subsequent growth was carried out with the HUGIN system. This system is a regional-level strategic planning model that forecasts timber yield and possible harvest level [13]. It is a deterministic simulation model with some stochastic components built in, and is based on data from the Swedish National Forest Inventory (NFI). A basic assumption was that the natural site productivity and the climate conditions remain unchanged for all scenarios during the studied period. The growth simulators were constructed to be valid for all forestland in Sweden, for all types of stands and within a wide range of management alternatives. The growth period for the simulators was five years, and after each period a volume was obtained by applying static form height functions. To estimate the net growth for each period, functions for mortality and ingrowth (trees passing 5 cm diameter in breast height) were used. The effect of thinning was estimated by means of thinning response functions based on experimental data [35]. Age for final felling, stem number after pre-commercial thinning, thinning schedules and other recommendations for the management of each plot were determined from site index classes according to the Swedish Forest Act [37]. The level of final felling was based on the growth level in every period, and the state of the forest. Functions used to determine tree biomass were developed by Marklund [38,39] and Petersson and Ståhl [40].The total carbon stock in standing forest biomass was also estimated using HUGIN. The output values included above and below ground biomass, and are described as amounts of stem-wood, stem-bark, needles, branches, tops and stumps including coarse roots. The HUGIN model is described in more detail in Lundström and Söderberg [13].

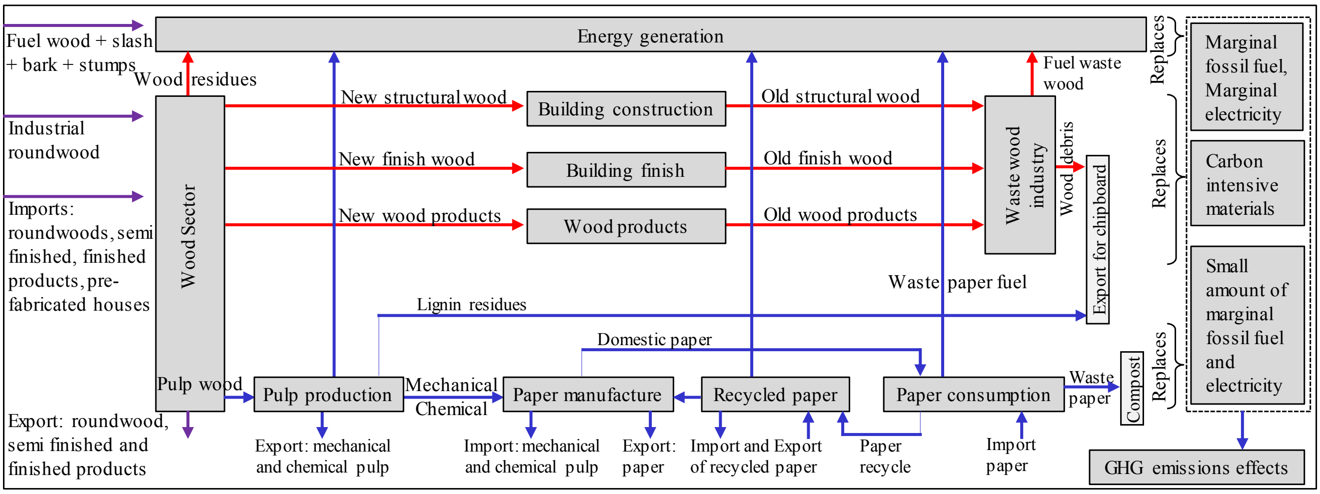
2.3.2. Modeling of Soil Carbon

Soil carbon stock has been monitored in Swedish forests since the start of Swedish forest soil inventories in 1961 [41]. The relations of soil carbon stock changes as a result of changes in actual standing tree volumes and harvests have also been established based on Swedish forest inventory data since 1926 [42]. Based on these measurements and dynamic soil carbon modeling, it is evident that the soil carbon stock in the managed forest landscape has been steadily increasing over the years, and is expected to increase further in the future [42]. We used the same approach for soil carbon modeling as Ågren *et al*. [42] but assumed no difference in soil carbon dynamics between the different scenarios. On average, the increase in soil carbon was estimated to be 7 g C m^{-2} $year^{-1}$ from 1926 to 2004. Since the highest sustainable harvesting level is assumed for the different scenarios from 2005 onwards, the increase in the biomass stock levelled off and the increase in the soil carbon for the later phases was lower, on average 4 g C m^{-2} $year^{-1}$.

2.3.3. Modeling of Wood Flows

A wood flow model for the Swedish forest industry was developed through the adaptation of an existing model for Switzerland. This material flow model was then implemented in the software SIMBOX and is explained in detail in Taverna *et al.* [36]. It incorporates all the relevant wood use in the Swedish consumer product cycle, including the wood sector, building stock, the paper cycle and the various forest energy, wood residue and waste wood stocks (Figure 2). All waste wood was assumed to be recovered according to the Swedish strategy for sustainable waste management [43]. The exports and imports of forest-based products were included in the modeling.

Figure 2. Model system of the Swedish timber industry and wood flows. The green arrows denote raw materials; blue arrows denote pulp and paper cycle; and the red arrows denote biomass use for materials and energy.



The input flows included industrial round wood, fuel wood, including slash and stumps, imports made by the timber industries, including all types of forest products, imports of pulp, recovered paper for paper production and paper imports for final consumption. Changes in wood product stocks were calculated by means of dynamic modeling using different service lifetimes of the products (see Table 3). The output flows included exports made by the timber industries, exports of pulp and paper and exports of lignin residues and debris.

2.3.4. Modeling of Carbon Stock Changes in Wood Products

Carbon stock changes in wood products were based on the wood flows generated by the SIMBOX model and were converted into total annual carbon stock changes based on wood flows per inhabitant. The carbon stock changes in wood products occurring in-country were quantified as the difference between the carbon flows entering a pool and those leaving the pool in the same year. The carbon stock changes in wood product were modeled as a cohort model based on the average service life of the product (Table 3). A mean lifetime of the product was defined for each process that ranges between zero (for no stock) to 80 years (for wood use in the construction of buildings) (see Table 3). Carbon pool changes in the pulp and paper cycle were modeled in a similar way as the other wood products. According to the wood flow model, the domestic paper cycle consists of various processes; it was assumed that only the process "paper consumption" leads to the storage of paper and respective carbon.

The total carbon stock changes in wood products, including pulp and paper in Sweden was calculated by summing the carbon stock change in buildings and other wood product-related flows, including within the pulp and paper cycle. The carbon stock changes within Sweden and outside the country due to foreign trade were calculated. The global effects were calculated as the sum of the effects in-country and the effects outside the country.

Table 3. Average service life of the wood products considered in the study.

Description	Average service life	Reference
In-country		
Building construction	80 years	[7,44]
Interior works including furniture	30 years	[7,44,45]
Other wood products (formwork)	10 years	[7,44]
Recovered wood for energy storage time	3 years	[7]
Energy biomass from forest and industrial residual wood	2 years	[7]
Abroad		
Imported or exported houses/furniture	50 years	[7]
Imported or exported ¾-fabricates	50 years	[7]
Imported or exported semi-fabricates	50 years	[7]
Imported or exported round wood	30 years	[7]
Imported or exported residual wood	10 years	[7]
Exported recovered wood	25 years	[7]
All recovered post-consumer wood as recovered waste wood for energy purposes	3 years	[7]
Industrial residual wood that results abroad from pre-processing of wood products	2 years	[7]
Imported or exported industrial residual wood that results from further processing	2 years	[7]

2.3.5. Modeling of Material Substitution

It was assumed that wood products replace more energy-intensive consumer products resulting in material substitution. In addition, it was assumed that forest residues and stumps as well as industrial wood-based residues result in direct substitution of fossil fuels, *i.e.*, energy substitution. The effects of material substitution were modeled on a building element basis, distinguishing structural elements, interior works and other wood products. The approach taken in this study to quantify the substitution of materials on a building element basis considered the functionality aspects of the elements in a building, and quantified the GHG emissions related to the production of the wooden element and its substitute, including the associated impacts from their transportation, mounting, maintenance and deconstruction. The specified products were defined to represent functionally equivalent wood and non-wood building elements under Swedish conditions and are illustrated in Hofer *et al.* [46]. The GHG emissions for the production and processing of all wood and non-wood products were calculated in SimaPro software based on the Ecoinvent 2.0 database [47], using the lifecycle assessment (LCA) method described in International Organization for Standardization (ISO) guidelines, ISO 14040 and ISO 14044 [48,49]. Therefore, the GHG emissions associated with raw material extraction, production, use, maintenance and disposal of a product were accounted for. The Swedish electricity consumption mix was used for domestic processes, and the Union for the Coordination of Transmission of Electricity (UCTE) mix was used for all processes occurring abroad. In terms of the effects arising from material substitution, a distinction was made between two temporally varying substitution effects:

substitution effects during production that also cover eventual replacements, and substitution effects during waste disposal.

In addition to the temporal dynamics, the spatial differences are also important for accounting for the carbon benefits of the substitution effects, *i.e.*, whether they occur in-country or abroad. For this purpose, import shares of the most important wood products were defined for the allocation of production emissions to abroad or in-country. As a general rule, emissions from transportation of exports were attributed to Sweden, and emissions from the transportation of imports into Sweden were attributed to the exporting country. In the case of domestic production and consumption, the substitution effect of a wood product was calculated as the difference between the GHG emissions generated by the wood product and its competitive non-wood product over their lifecycles [50]. The GHG potentials were calculated taking into account the radiative forcing effect of all gases for which a global warming potential (GWP) has been specified by Intergovernmental Panel on Climate Change (IPCC) [51].

2.2.6. Modeling of the Substitution Effects and Emissions from the Pulp and Paper Cycle

The emission and substitution factors for the pulp and paper cycle were derived from the Ecoinvent 2.0 database [52]. All relevant processes were adjusted to Swedish conditions including the electricity mix. A modeling approach was chosen for the analysis of the pulp and paper chain in order to link the wood flow model with the existing Lifecycle Inventory (LCI) data for pulp and paper in Ecoinvent. The modeling was performed in two separate processes. First, available data on integrated paper production processes were disaggregated by subtracting the respective raw material supply and pulp production processes. Then, the geographical attribution of emissions was made for all processes based on a detailed analysis within SimaPro. As there is no reasonable substitute for paper, only emission factors for the national production and consumption were considered. We assumed that the national consumption of pulp and paper develops in the same way in all scenarios. The two most important pulp types, mechanical and chemical, were considered in the analysis. Three different paper types using fresh fiber (newsprint, wood-free coated, corrugated board) and three using recycled fibers (with deinking, without deinking, cardboard) were included. These types of papers and the respective datasets were selected to represent the average GHG emissions related to the production of newsprint paper, other graphical paper and cardboard/paperboard.

We assumed that substitution effects are related to the exports and imports of pulp and paper, resulting in a geographical shifting of production-related emissions. Exports of pulp, paper and recovered paper substitute the production of respective pulp types abroad and result in increased domestic emissions. Similarly, imports of pulp and paper lead to reduced domestic production, but increase the production-related emissions abroad. The effect of domestic pulp and paper production for domestic use was excluded from the analysis, because it was assumed to be equal for all scenarios.

2.2.7. Modeling of the Substitution Effects of Energy Recovery

The use of forest biomass can result in the direct substitution of fossil fuels, if used in a thermal power plant or for co-generation in combined heat and power (CHP) plants. The biomass used may include harvest residues, stumps, industrial wood processing residues, exported energy biomass, imported energy biomass, post-consumer wood and exported wood as post-consumer wood abroad. The substitution factors used in the analysis were calculated by weighting the substitution factors for thermal energy and thermal energy/electricity from CHP generation according to the share of a specific wood flow going into each of the two use options.

The emission factors for wood and fossil fuel combustion were taken from the Ecoinvent 2.0 database [47]. In the case of wood fuel, Swedish LCI data on forestry processes were used for the wood input. The substitution effect of the additional thermal use of wood was quantified based on the marginal technologies used for the production of heat. We assumed that these marginal technologies are fossil fuel-based technologies [53,54]. Swedish energy statistics indicate that the industrial and district heating sectors consume 27% of fossil fuel in the form of coal, oil and fossil gas [55]. The emissions related to the combustion of fossil fuel were calculated as direct emissions, emissions from refinery processes and emissions from transportation and extraction. We assumed that the direct emissions from combustion occur in Sweden, and emissions from refinery processes occur both in Sweden and abroad. The respective shares were calculated based on the relative share of nationally produced fuel compared to the sum of nationally produced fuel plus imports. The emissions from exploration, extraction and long-distance transport of fuels occur outside Sweden, as Sweden does not have its own fossil fuel extraction. In the case of fossil fuels being used abroad, all related GHG emissions were considered to occur abroad.

The substitution factors for waste wood combustion considered the emissions associated with the avoided combustion of fossil fuels only. Forestry processes, as well as the transportation to the incinerator and the burning processes were already included by the model as fossil fuel emissions associated with the disposal of materials. For the calculation of the substitution factors for co-generation, it was assumed that the overall efficiency of a CHP plant is 75% of the net calorific value of its wood input; 75% of the usable energy is heat and 25% is electricity. It was assumed that heat replaces the average marginal mix of fossil fuels used for thermal energy generation in Sweden, and the electricity replaces marginal technology used to produce electricity consumed in Sweden. The final substitution factors were derived by weighting the substitution factors for heat and CHP generation according to the share of a specific wood flow going to each of the two use options. A more detailed description of substitution factor calculation is in Hofer *et al.* [46].

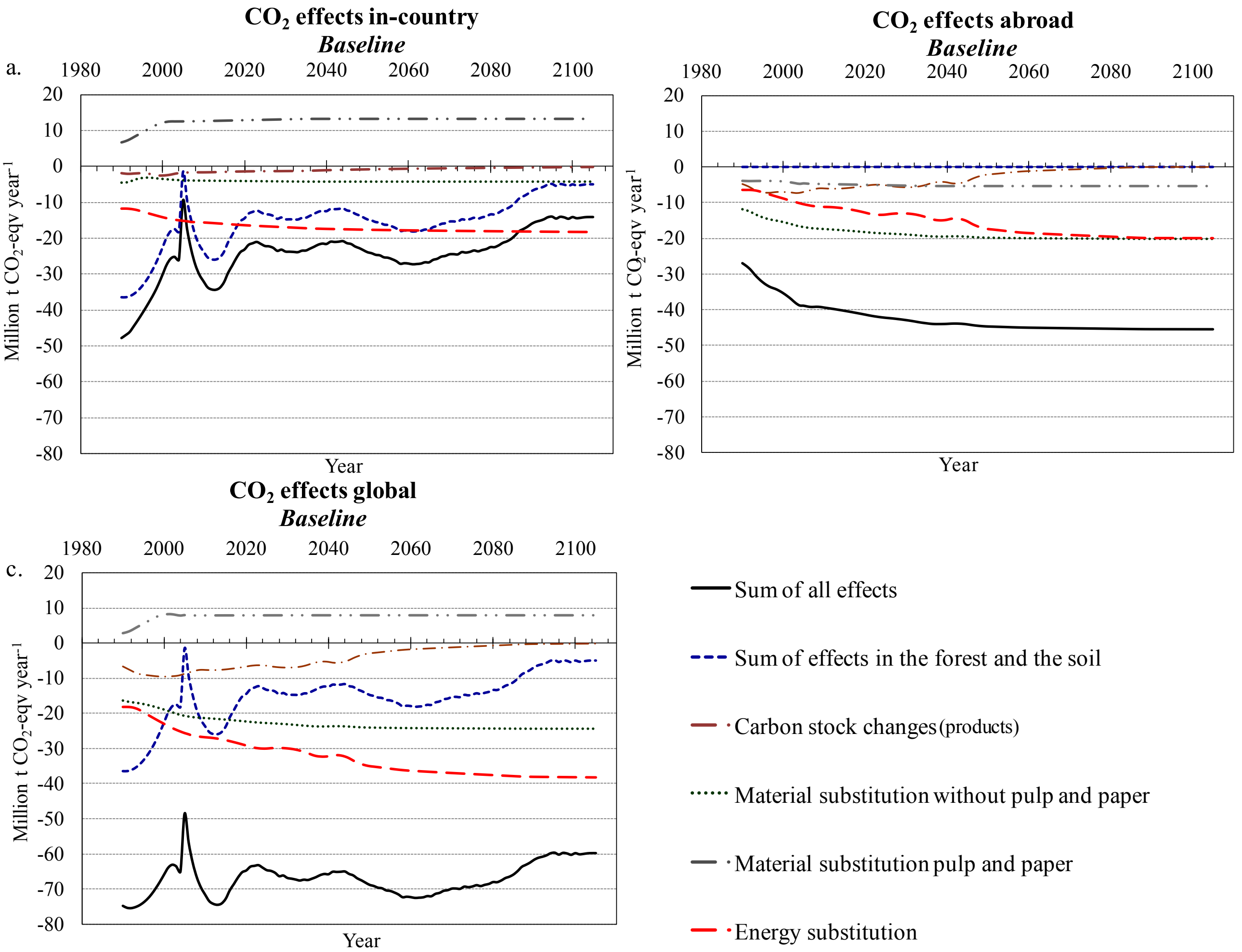
2.2.8. Modeling of Energy Substitution Resulting from the Pulp and Paper Cycle

The amount of fuel consumption in the pulp and paper industry may vary considerably [52]. We assumed that energy lignin (from pulp production), black liquor as well as the waste fiber fraction from the processing of recovered paper are entirely used within the pulp and paper industry. A second process resulting in (external) energy substitution effects was the incineration of waste paper. The substitution factors for domestic waste paper incineration were derived as the GHG emissions from waste paper collection and incineration minus the substituted amount of heat and electricity resulting from co-generation. It was assumed that municipal waste incinerators have only half the energy efficiency of a waste wood incinerator, from which the emission/substitution factors were derived. Abroad, no additional substitution effect occurs, due to the energy use of pulp and paper originating from Sweden. It was assumed that the net consumption of pulp and paper abroad does not change due to different import/export scenarios for Sweden.

3. Results

For the baseline scenario, the total avoided CO_2 emissions within Sweden at the end of the study period were estimated at 14 million t CO_2-eqv year^{-1}. When considering the period 1990–2105, the accumulated CO_2 reduction was 2800 million t CO_2-eqv. However, the CO_2 reduction effect was larger abroad where it reached 46 million t CO_2-eqv year^{-1} at the end of the study period, with an accumulated CO_2 reduction of 4900 million t CO_2-eqv for the period 1990–2105. Hence, with a global perspective, the present Swedish forestry practices result in reduced and avoided CO_2 emissions on the order of 60 million t CO_2-eqv year^{-1}, according to the assumptions made in this analysis. This is a similar magnitude as Sweden's currently reported annual CO_2 emissions, which were 61 million t CO_2-eqv year^{-1} in 2011 [55]. Material and energy substitution and carbon stock changes in forest and soil accounted for the majority of the total effect (Figure 3).

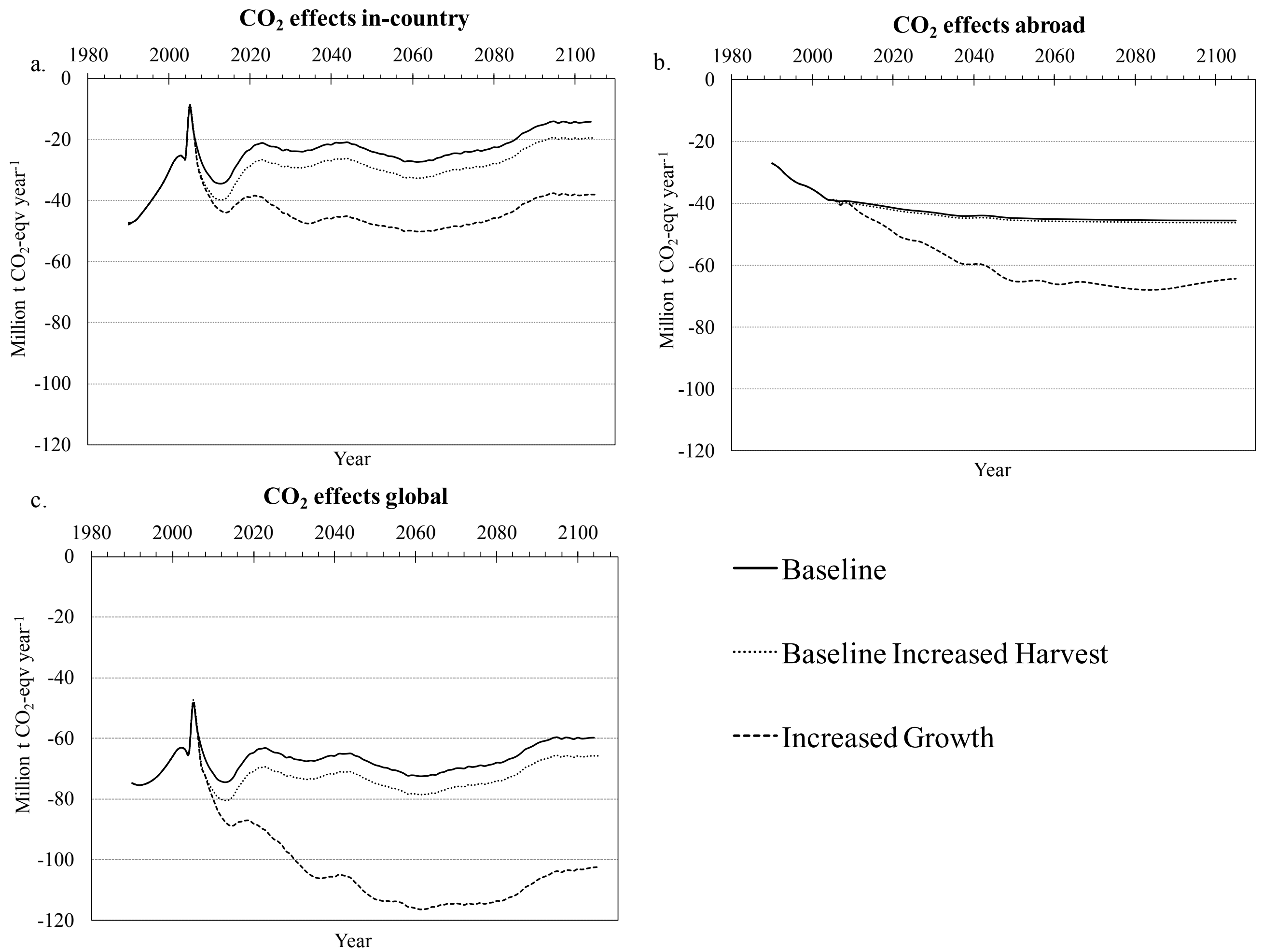
Figure 3. The CO_2 reduction effect in the baseline scenario, in-country (**a**), abroad (**b**) and globally (**c**), due to Swedish forestry (the effects from all types of carbon stock changes are shown). Negative values represent reductions of atmospheric CO_2.



The peak in 2005 was due to a major storm-felling, which caused significant forest biomass loss from the forest and was a source of CO_2 emissions. A majority of the storm-felled forests were harvested, but all of the timber, pulp-wood and fuel wood were not used in the same year; thus the substitution values could not compensate for the effects in the forest. It is also noteworthy that the material substitution effect from pulp and paper was negative, *i.e.*, since it was assumed that there were no actual substitute to pulp and paper, this use of forest biomass resulted in net emissions of CO_2.

For the scenarios with higher biomass yields, the positive climate impact was larger. The total emissions reduction at the end of the study period for the baseline increased harvest and increased growth scenarios were 66 million t CO_2-eqv year^{-1} and 103 million t CO_2-eqv year^{-1}, respectively, compared to the baseline scenario of 60 million t CO_2-eqv year^{-1}. When considering the period 1990–2105, the accumulated CO_2 reduction was 8200 million t CO_2-eqv for the baseline increased harvest scenario and 11,200 million t CO_2-eqv for the increased growth scenario, respectively, compared to 7700 million t CO_2-eqv for the baseline scenario (Figure 4).

Figure 4. The overall CO_2 reduction effect for in-country (**a**), abroad (**b**) and globally (**c**) for different scenarios; baseline (solid line), baseline increased harvest (dotted line) and increased growth (dashed line).



The average CO_2 emissions reduction effect per cubic meter of harvested biomass for the baseline and increased growth scenarios were 466 kg and 546 kg, respectively, at the end of the study period.

The marginal effect of the extra wood harvested in the increased growth scenario was higher, 719 kg CO_2 per cubic meter of harvested biomass (Table 4). This was mainly due to the increased substitution effects, since the additionally harvested wood was assumed to be used primarily for construction and energy purposes.

Table 4. The average CO_2 emissions reduction effect for one cubic meter of biomass during the later part of the studied period (2035–2105), calculated as the annual global reduction of CO_2 emission divided by the annual harvest of wood for the baseline and increase growth scenarios. The marginal effect of an extra cubic meter produced in the increased growth scenario during the later part of the studied period (2035–2105) is based on the assumption that the additionally harvested wood is mainly used for construction and bioenergy (see also Table 1).

Forest management scenarios	kg CO_2-eqv reduction m^{-3} of harvested biomass
Baseline	466
Increased growth	546
Increased growth, marginal effect	719

4. Discussion

Swedish forests are a rich natural asset, and Swedish forestry can contribute in many ways toward reduced emissions of GHGs to the atmosphere. Throughout the 20th century, the growth in Swedish forests has been higher than the annual extraction of timber [56]. For this reason, the growing stock and, therefore, the volume of carbon sequestered in the forest ecosystem have increased due to active cultivation of forest resources. At the same time as growing stocks have risen, the felling potential has also increased. Annual felling today is approaching annual growth, which means that the build-up of timber reserves is not as strong as before. The International Union of Forest Research Organizations (IUFRO) has observed the immense potential of the forest sector to mitigate climate change at low cost, and it is important that we understand how different forest management and wood use strategies influence the mitigation of climate change [57]. In order to describe the total climate benefit of forest utilization, the uses of wood raw material must be taken into consideration and the geographical perspective must be on the landscape scale or larger. By taking into account how forestry is conducted, how much renewable raw material can be harvested in a sustainable manner and how and where this raw material is used, the overall climate benefit of forestry can be estimated. This study shows that the present Swedish forestry practices result in reduced and avoided CO_2 emissions on the order of 60 million t CO_2-eqv year^{-1}, according to the assumptions made in this analysis. It also demonstrates that there is an additional future mitigation potential to be utilized if land use were more oriented towards increased forest production. With a sustainable increase in harvested biomass of approximately 50%, the additional mitigation potential of the increased growth scenario is estimated to be more than 40 million t CO_2-eqv year^{-1}. The modeling approach used here to assess the impacts of wood pools and substitution effects within Sweden and outside Sweden is not directly related to the reporting and accounting framework of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol. In this context, some double-accounting could occur if a country that exports harvested wood products to Sweden would follow the same approach as has been used in this study.

An alternative strategy to mitigate climate change is to cease cultivation of the forest, *i.e.*, stop felling in order to allow all forests to mature and the forests' carbon stocks to increase over time. In the short term this can be an efficient strategy. Our study shows that the average CO_2emissions reduction effect in a managed forest is on the order of 500 kg CO_2 m^{-3} of harvested biomass use. Since one cubic meter of biomass contains carbon corresponding to 700–900 kg CO_2, depending on the wood density, increasing the standing volume of the forest would be a more efficient measure to mitigate climate change as long as the standing volume of the forest can continue to increase. Focusing solely on increasing carbon stocks in this way is, however, a limited climate mitigation strategy, since it is not possible to store unlimited quantities of carbon in the forest. If this method were to be applied, timber reserves in Sweden would initially increase, but would eventually reach a new equilibrium between growth and natural attrition. When this balance is reached, the "uncultivated forest landscape" would, in principle, be CO_2 neutral, *i.e.*, it neither sequesters nor releases carbon to any significant extent. Another effect would be that possibilities for the sustained harvesting of forest biomass for consumption would be eliminated. Consumption must then either decrease or be met with something other than renewable forest products, *e.g.*, more energy-intensive materials, fossil fuels or other energy sources. Cessation of harvesting and the build-up of forest carbon stocks also carries considerable risks, due to the occurrence of wildfire, storms or insect-caused tree mortality [58]. The sharp decrease in the forest carbon stock in 2005, as an impact of a large storm, shows that natural forest disturbances can cause significant CO_2 emissions, and that increasing growing stocks is not without risk. The findings from this study show that Swedish forestry contributes to obtaining significant long-term climate benefits both in-country and abroad; the latter being more important. This may lead to a further increasing expectation for Swedish forest residues and industrial wood processing residues to be utilised as bioenergy, and the demand for woody bioenergy material may also increase in a global market [59].

This study demonstrates the long-term significance of the substitution effects when using forest biomass. Substitution benefits varied considerably in this study depending on whether biomass was used for pulp and paper, solid wood products or bioenergy (Figure 3). These results are broadly consistent with what has been presented in other studies. Sathre and O'Connor [60] performed a meta-analysis of GHG displacement factors of wood product substitution and found that most of the substitution factors in the studies were in the range of 1.0 to 3.0 units of fossil C emission avoided per unit of C in a wood product. Using simple assumptions [61] to convert this range to the units shown in Table 3, wood product substitution may reduce emissions by 500 to 1400 kg CO_2 per cubic meter of harvested biomass. The substitution factors calculated in this study (Table 4) are within the lower half of this range and are comparable to John *et al.* [62], who analyzed a multi-story building in New Zealand, and to Pingoud and Perälä [63], who analzsed wood use throughout the Finnish construction sector. The meta-analysis by Sathre and O'Connor [60] identified sources of variation in substitution effects, including the consideration of biomass co-products and the post-use fate of wood products. Closer integration of energy and material flows among the forestry, energy, construction and waste-management sectors has the potential to reduce total net CO_2 emissions per unit of available biomass, thus increasing substitution benefits [64].

Large amount of carbon are stored in Swedish forest soils, but the carbon stock and its short-term changes may vary considerably between sites [65]. Long-term tracking of carbon stock in Swedish forest soils indicates a steady increase over time, and a positive relationship between forest growth and carbon accumulation in the soil is normally found [45]. Soil carbon accumulation can also be negatively affected if additional biomass is harvested [66,67], as in the scenarios in this study where additional residues and stumps are assumed to be harvested. Despite this, we decided to use a similar soil carbon dynamics for all scenarios, since present knowledge on soil carbon dynamics in relation to different management scenarios is limited. It is possible that this has resulted in an overestimation of the carbon balance for the baseline increased harvest scenario, since increased biomass harvest has been shown to decrease soil carbon stores in Swedish forest soils if a complete removal of needles, branches and tops were applied [66,67]. In this study, however, the removal levels were considerably lower and the differences between scenarios were modest. It is also possible that the carbon balance is underestimated for the increased growth scenario, since there normally is a positive relationship between forest growth and soil carbon accumulation [42,67].

It is obvious that there are considerable uncertainties in a complex modeling exercise like the one presented here, and much of the detailed results will depend on the assumptions made. Forest growth has been modeled by using a well-known and tested model, HUGIN, which has been used for numerous studies of the consequences of different forest management scenarios on regional and national levels in Sweden [6,9,11,12,68]. The statistics of the import, export and use of forest-based products are robust in Sweden, giving a representative estimate of the past uses of the forest resources. The biomass substitution effects have been estimated using the best information available for this purpose. The assumptions that increased supply of biomass from the forest will be used mainly for bioenergy and construction are based on outlook studies [59] and the fact that Sweden has a sustained political goal of further increasing the use of renewables in the energy system [15]. Thus, we argue that the results can be seen as realistic.

5. Conclusions

By using wood flow modeling of the potential production and use of Swedish forest products, carbon accounts of the effects both in-country and abroad have been calculated. The main conclusions from this study are that: (i) current forestry practices in Sweden and the use of forest products in-country and abroad cause an annual reduction in global CO_2 emissions almost equal to the total annual GHG emissions in Sweden, relative to a scenario where no forest-based products are available; (ii) the benefits of CO_2 reduction occur mainly abroad and not in-country as a result of the high share of exported wood products from Sweden and the higher substitution effect abroad; and (iii) more intensive silvicultural methods can increase forest production and would be an effective way to further reduce emissions of CO_2.

Based on the results of this study, it is evident that the effects of forest production and the trade of wood products are important considerations in determining the total climate benefit. To optimize the domestic Swedish CO_2 balance, wood resources should be used for solid wood products (sawn wood, wood-based panels, *etc.*) or energy generation, rather than for pulp and paper production. From a global perspective and in the long term, the energy and material substitution effects are much more important than the stock change effects. The substitution effects, which depend on continuing harvests from sustainably managed forests, create durable and sustainable mitigation of CO_2 emissions. This study is offered to help researchers, policy makers, forest managers and civil society to understand the likely long-term effects of forest management policies and practices in reducing global GHG emissions.

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Author Contributions

Initial idea and financing of the research: Tomas Lundmark and Annika Nordin, data compilation and evaluation: all authors, manuscript drafting: Tomas Lundmark, Johan Bergh, Peter Hofer, Annika Nordin, Bishnu Chandra Poudel, Roger Sathre, Ruedi Taverna and Frank Werner.

Conflicts of Interest

The authors declare no conflict of interest.

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