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CARBON BALANCE IMPLICATIONS OF
FOREST BIOMASS PRODUCTION POTENTIAL

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Cover photo: Different stages in forest management and product use, Sweden, ©Bishnu Chandra Poudel

Printed by Mid Sweden University, Sundsvall, Sweden, 2014
To my beloved parents
Ram Prasad & Sabitri
CARBON BALANCE IMPLICATIONS OF FOREST BIOMASS PRODUCTION POTENTIAL

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Abstract

Forests in boreal and temperate forest-ecosystems have an important function since they sequester atmospheric carbon by uptake of carbon-dioxide in photosynthesis, and transfer and store carbon in the forest ecosystem. Forest material can be used for bio-fuel purposes and substitute fossil fuels, and supply wood products, which can replace carbon- and energy-intensive materials. Therefore it is vital to consider the role of forests regarding today’s aim to mitigate climate change. This thesis assess (i) how climate change affects future forest carbon balance, (ii) the importance of different strategies for forest management systems, and biomass production for the carbon balance, (iii) how the use of forest production affect the total carbon balance in a lifecycle perspective, and (iv) how the Swedish carbon balance is affected from the standpoint of both the actual use of forest raw material within Sweden and what Swedish forestry exports. The analysis was made mainly in a long-term perspective (60-300 year) to illustrate the importance of temporal and also the spatial perspective, as the analysis includes stand level, landscape level, and national level.

In this thesis, forestry was considered a system. All activities, from forest regeneration to end use of forest products, were entities of this system. In the evaluation, made from a systems perspective, we used life-cycle analysis to estimate carbon stock in different system flows. Different forest management systems and forest production were integrated in the analyses. Different forest management scenarios were designed for the Swedish forest management in combination with the effect of future climate change: (i) intensive forest practice aiming at increased growth, (ii) increased forest set-aside areas, changes in forest management systems for biomass production, and (iii) how the use of forest production affect the total carbon balance (construction material, bioenergy and other domestic use).
The results showed that future climate changes and intensive forest management with increased production could increase the biomass production and the potential use of forest raw material. This has a positive effect on carbon storage for the forest carbon stock, litter production and carbon storage in the ground etc. and help mitigating carbon-dioxide. Increased forest set-aside areas can increase the short-term carbon stock in forest ecosystems, but will reduce the total long-term carbon balance. The net carbon balance for clear-cut forestry did not differ significantly from continuous-cover forestry, but was rather a question of level of growth. Most important, in the long term, was according to our analysis, how forest raw material is used. Present Swedish forestry and use of forest raw material, both within Sweden and abroad, reduce carbon-dioxide emissions and mitigate climate change. The positive effect for the total carbon balance and climate benefit take place mostly abroad, due to the Swedish high level of export of wood products and the higher substitution effects achieved outside Swedish borders. One strategy is to increase production, harvest and change the use of Swedish forest raw material to replace more carbon intensive material, which can contribute to significant emission reduction. Carbon-dioxide mitigation, as a result of present Swedish forestry, was shown to be almost of the same level as the total yearly emission of greenhouse gases. The total carbon benefit would increase if the biomass production and felling increased and if Swedish wood products replaced carbon intensive materials.

This thesis shows also that, by changing forest management, increase the growth and the use of forest raw material and export of forest material we can contribute to even larger climate benefits. In a long-term perspective, the substitution effects and replacement of carbon- and energy-intensive materials are of greater significance than carbon storage effects in forests. A more production oriented forestry needs to make balances and increase the prerequisite for biological diversity, improve recreation possibilities, and protect sensitive land areas and watersheds.

Climate benefits, from Swedish forestry, are highly dependent on policy decision-making and how that can steer the direction for the Swedish forestry.

**Keywords:** forest management, silviculture, clear-cut forestry, continuous-cover forestry, substitution, total carbon, climate benefit, climate change.
Sammanfattning

Skogen i boreala och tempererade skogseksystem fyller en viktig funktion eftersom de minskar atmosfäriskt kol genom upptagning av koldioxid vid fotosyntesen och upplagring av kol i den egna biomassan, och genom att överföra kol till andra delar av skogseksystemet, som också kan upplagra. Skogsrävara kan användas för biobränsleändamål och ersätta fossila bränslen samt tillhandahålla träprodukter, som kan ersätta kol- och energiintensiva material. Denna typ av substitution innebär att utsläppen av fossil kol till atmosfären kan minska. Det är därför viktigt att beakta skogens roll vad gäller dagens strävanden att mildra klimatförändringen. I denna avhandling utvärderas (i) hur klimatförändringar påverkar skogens kolbalans i framtiden, (ii) hur olika skogsskötselstrategier, skötselsystem och biomassaframställning påverkar skogens kolbalans, (iii) hur användandet av skogsprodukter påverkar kolindragningen i det första, (iv) hur Sveriges kolbalans påverkas om man beaktar den verkliga användningen av skogsprodukter i Sverige och tar hänsyn till import och export. Analysen har gjorts främst för ett längre tidsperspektiv (60-300 år) för att belysa det viktiga tidperspektivet men även det rumsliga perspektivet då analyserna innefattar ståndortsnivå, landskapsnivå och nationell nivå.

Skogen har i denna avhandling betraktats som ett system. Alla verksamheter, från återplantering till skogsprodukter, har utgjort enskilda enheter i detta system. Utvärderingen, gjord från ett systemperspektiv, används livscykelanalyser för att redovisa kolindragningen för olika systemflöden. I avhandlingen har olika skoggårdsanalyser och skogsproduktionsanalys integrerats i livscykelanalyserna. Olika skoggårdsscenario konstruerades för att jämföra skogsbruket i kombination med effekten av framtida klimatförändringar; (i) intensiv skoggårdsmed syftet att öka tillväxten, (ii) ökad areal för bevarande av skog, förändringar i skoggårdsmed för biomasaframställning och (iii) hur användandet av skogsprodukter påverkar den totala kolbalansen (konstruktionsmaterial, bioenergi och annan inhemsk användning).

användandet av skogsråvara, såväl inom Sverige som utomlands, kan minska koldioxid- emissionerna ytterligare och innebär redan idag att betydande emissioner av koldioxid undviks. Den positiva effekten på den totala kolbalansen och klimatnyttan sker då främst utomlands som ett resultat av Sveriges höga exportnivå av trävaror samt den högre substitutionseffekt vi erhåller utanför Sveriges gränser. En strategi som ökar produktionen, uttaget och ändrar användningen av svensk skogsråvara för att ersätta mer kolintensiva material, kan bidra till betydande utsläppsminskningar. De utsläpp av koldioxid som redan undviks till följd av det nuvarande svenska skogsbruket visade sig vara nästan av samma dignitet som Sveriges totalt årliga nettoutsläpp av växthusgaser. Den totala kolvinsten skulle öka om biomassaproduktionen och avverkningen ökade och om svenska träprodukter ersatte kolintensiva material.

Denna avhandling visar på möjligheterna att ändra skogsskötseln, öka tillväxten, användandet av skogsråvara och export av skogsråvara för att bidra till än större klimatvinster än dagens. I ett långt tidsperspektiv, är substitutionseffekterna och ersättnings av kol- och energiintensiva material av större betydelse än kollagringseffekterna i skog. Ett mer produktionsinriktat skogsbruk kommer att innebära fler och svårare avvägningar mot andra intressen och värden i skogen, inte minst för att bevara biologisk mångfald, förbättra rekreationsmöjligheterna och skydda känsliga markområden och vattendrag.

Klimavinsterna från den svenska skogen är i högsta grad beroende av politiskt beslutsfattande och hur detta kan styra skogsbruksprogram.

Nyckelord: Skogsskötselsystem, trakthygesskogsbruk, kontinuitetsskogsbruk, substitution, livscykelanalys, klimatnytta, klimatförändringar
Acknowledgements

This is a story about a person who grew up in the foothills of the mountains of Nepal and started a journey towards higher education. His initial motives for higher education were cultivated in a small agrarian family. His journey, starting from primary school to this point, has not always been an easy one as he experienced many upheavals throughout the time. He kept sailing his boat with patience so that he could end up in a beautiful coast. Looking back, he found that the turning point was the start of bachelor's of forestry education in 1999. He would never have imagined then that, after fifteen years, he would be defending his PhD thesis. During this long journey, he happened to meet many nice people who should be acknowledged here for what they have provided along the way, increased his motivation, provided valuable suggestions and encouraged to reach the PhD defense.

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I have dedicated this thesis work to my parents: Ram Prasad (father) and Sabitri (mother), who dreamed about my higher education, provided sound values, and showed the path. This thesis is the result of their invaluable support throughout the journey. Since my high schooling time, I have been deprived of closeness to them, family members and relatives. I owe special thanks to my mother-in-law, Laxmi. I hope this thesis brings happiness to all of us.

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Bishnu Chandra Poudel
Östersund, May 2014
List of Papers

This doctoral thesis is based on the following papers:


# Table of contents

Abstract ......................................................................................................................... i  
Sammanfattning ........................................................................................................... iii  
Acknowledgements ....................................................................................................... v  
List of Papers ............................................................................................................... vii  
Table of contents ......................................................................................................... ix  
Figures ......................................................................................................................... xi  
Tables ........................................................................................................................... xiii  
Abbreviations and definitions ....................................................................................... xiv  

## 1. Introduction

1.1 Background ............................................................................................................. 1  
1.2 Motivation for the study ......................................................................................... 4  
1.3 Previous studies ..................................................................................................... 6  
	1.3.1 Forest biomass production and harvest ....................................................... 6  
	1.3.2 Soil carbon stock ......................................................................................... 7  
	1.3.3 Substitution of fossil fuels and carbon-intensive materials ...................... 8  
	1.3.4 Carbon accounting of transfer of forest biomass ................................... 9  
1.4 The research context ............................................................................................ 9  
1.5 Objective and scope of this thesis ........................................................................ 12  
1.6 Outline of the thesis ............................................................................................ 13  

## 2. Concept and state-of-the-art in forest biomass production, harvest and utilization

2.1 Forest biomass production and carbon ................................................................. 16  
2.2 Climate change and forest biomass production .................................................... 17  
2.3 Forest management and silviculture .................................................................... 17  
2.4 Forest biomass harvest and use .......................................................................... 19  

## 3. Methodological framework

3.1 The systems concept ............................................................................................. 21  
3.2 Methodological framework .................................................................................. 22  
3.3 Forest management, product harvest and conversion ........................................ 24  
3.4 The material life cycle and energy systems ........................................................ 25  
3.5 Activities included in the analysis ...................................................................... 27  
3.6 Study area ........................................................................................................... 27  
3.7 Scenarios and assumptions ................................................................................ 28  

## 4. Forest production, forest biomass pools and harvest

4. Forest production, forest biomass pools and harvest ............................................. 32
Figures

Figure 1  World CO₂ emissions by fossil fuel use 1971–2010 [Source: (OECD/IEA, 2012a)] ................................................................. 1

Figure 2  The forestry sector’s role in minimising net GHG emissions to the atmosphere. [Source: (Nabuurs et al., 2007)] ................................................................. 4

Figure 3  The outline and the workflow of the thesis, arrows denote the work flow. .................................................................................. 14

Figure 4  The relations of appended papers corresponding to the objectives as a schematic diagram (Papers I–IV). ................................................................. 15

Figure 5  Schematic carbon stock development of aboveground biomass under clear-cut and continuous-cover systems [Source: (Böttcher, 2007), from (WBGU, 1998)] ................................................................. 18

Figure 6  Schematic diagram of carbon flow during forest production and biomass utilization. .................................................................................. 23

Figure 7  Study areas in this thesis, Sweden (a) Paper III, (b) Paper I and II. ............. 28

Figure 8  Annual biomass productions at the beginning and end of the study period for Reference and Climate scenarios ................................................................. 36

Figure 9  Annual biomass production at the beginning and the end of the study period for Reference, Environment, Production and Maximum scenarios (Paper II).... 37

Figure 10  The biomass harvests for Reference, Environment, Production and Maximum scenarios (Paper II). ................................................................. 38

Figure 11  The development of litter carbon stock for CF+, CF, CF100 and CCF80 scenarios (Paper IV). ................................................................. 41

Figure 12  Average annual carbon emission reduction (Tg C year⁻¹) for the whole study area as a result of whole-tree (WT) and stem-wood (SW) biomass use to replace fossil fuels and non-wood construction materials (Paper II)...................... 46

Figure 13  Differences in cumulative total carbon balance (Tg C) between the Climate and Reference scenarios (Paper I)................................................................. 48

Figure 14  Differences in cumulative carbon emission reduction (Tg C) between the Climate, Environment, Production and Maximum scenarios and the Reference scenario for each 10-year period (Paper II). ................................................................. 49

Figure 15  The CO₂ reduction effect in the Baseline scenario, in-country (a), abroad (b) and global (c), as an effect of Swedish forestry. ................................................................. 49
Figure 16 The overall CO₂ emission reduction effect for in-country (a), abroad (b) and global (c) for different scenarios; Baseline (solid line), Baseline Increased Harvest (dotted) and Increased Growth (dashed).

Figure 17 Cumulative total carbon balance in (a) CF and (b) CCF100 scenarios over 285 years (three rotation periods in CF and 290 years in CCF).

Figure 18 Total carbon balance over time in (a) clear-cut forestry and in (b) continuous-cover forestry with different substitution levels.

Figure 19 The total carbon balance with 20% and 50% set-aside area for conservation in Sweden. (a) 0.47 Mg CO₂-eqv per cubic meter of biomass (b) 0.72 Mg CO₂-eqv per cubic meter of biomass.
Tables

Table 1 Activities and processes included in the life cycle carbon balance..............27
Table 2 Scenarios studied in this thesis corresponding to appended papers. ..........29
Table 3 Changes in average annual soil carbon stock during each 10-year period (Tg C year⁻¹) for Jämtland and Västernorrland. .................................................................40
**Abbreviations and definitions**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>°C</td>
<td>Degree centigrade</td>
</tr>
<tr>
<td>BIOMASS</td>
<td>BIOMASS is a process-based model to calculate biomass production in the plant during physiological processes</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CCF</td>
<td>Continuous-cover forest</td>
</tr>
<tr>
<td>CF</td>
<td>Clear-cut forest</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CORRIM</td>
<td>Consortium for Research on Renewable Industrial Materials</td>
</tr>
<tr>
<td>eqv</td>
<td>Equivalent</td>
</tr>
<tr>
<td>ESRL</td>
<td>Earth System Research Laboratory</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EUROSTAT</td>
<td>Eurostat is a Directorate-General of the European Commission with a main responsibility to provide statistical information</td>
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<tr>
<td>g</td>
<td>gram</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GJ</td>
<td>Gigajoule (10⁹ joules)</td>
</tr>
<tr>
<td>GJe</td>
<td>Gigajoule of electricity</td>
</tr>
<tr>
<td>GPP</td>
<td>Gross Primary Production</td>
</tr>
<tr>
<td>Gt</td>
<td>Gigatonne (10⁹ tonnes)</td>
</tr>
<tr>
<td>ha⁻¹</td>
<td>Per hectare</td>
</tr>
<tr>
<td>Heureka</td>
<td>Heureka is a model system to describe a long-term planning and decision-making for a forest at a stand level or at a regional level</td>
</tr>
<tr>
<td>HUGIN</td>
<td>HUGIN is an empirical model to project forest growth and harvest of a forest stand</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IFIAS</td>
<td>International Federation of Institutes for Advanced Study</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>m²</td>
<td>Square meter</td>
</tr>
<tr>
<td>m³</td>
<td>Cubic meter</td>
</tr>
<tr>
<td>Mg</td>
<td>Megagram (10⁶ grams, or 1 tonne)</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
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</tbody>
</table>
NAS  National Academy of Sciences
NFI  National Forest Inventory
NOAA  National Oceanic and Atmospheric Administration
NORDEL  Nordic Electricity grid
NPK  Nitrogen Phosphorus and Potassium
NPP  Net Primary Production
OECD  Organization for Co-operation and Development
ppm  Parts per million
Q model  Q model is soil carbon model that describes soil carbon in the presence of litters and decomposition process
SIMBOX  SIMBOX is a software system to estimate carbon stock changes in wood products based on wood flows
SLU  Sveriges lantbruksuniversitet (Swedish University of Agricultural Sciences)
SMHI  Swedish Meteorological and Hydrological Institute
SOM  Soil Organic Matter
SOU  Swedish Government’s Official Reports
SRES  Special Report on Emissions Scenarios
SUBSTITUTION  SUBSTITUTION is a spreadsheet model to calculate the carbon benefit of wood and residues use in place of non-wood products
SW  Stem-wood
Tg  Teragram (10^{12} grams, or 10^{6} tonnes)
TWh  Terawatt-hour
UCTE  Union for the Coordination of Transmission of Electricity, European electricity supply grid
UNFCCC  United Nations Framework Convention on Climate Change
US  United States
WBGU  Wissenschaftlicher Beirat der Bundesregierung Globale (German Advisory Council on Global Change)
WT  Whole-tree
year^-1  Per year
1. Introduction

This introductory chapter presents background information and motivation for this thesis on carbon balance implications of forest biomass production. The objectives and scope of the thesis, and research questions and their relation to objectives are described. The outline and the structure of the thesis are presented.

1.1 Background

Warming of the Earth’s climate system is one of the most widely recognised environmental issues today. A consensus in the climate science research community has emerged that the increase in the atmospheric concentration of carbon dioxide (CO$_2$) is the largest contributor to a positive radiative forcing, leading to the warming of the Earth’s surface (IPCC, 2013). Furthermore, the global mean temperature change appears to be proportional to the cumulative CO$_2$ emissions (Zickfeld et al., 2009). Hence, continued CO$_2$ emissions into the atmosphere are likely to cause further warming of the Earth’s mean surface temperature and changes in all components of the climate system (IPCC, 2013).

The primary source of CO$_2$ is the combustion of fossil fuels (IPCC, 2007), while other reasons could be land use change, when it involves deforestation and decay of biomass, and a decline in the efficiency of CO$_2$ sinks (Canadell et al., 2007a; Canadell et al., 2007b). The global CO$_2$ emissions from combustion of fossil fuels have significantly increased in the last 100 years. Figure 1 shows the trend in world CO$_2$ emissions by fossil fuel use for 1971–2010. In the year 2010, CO$_2$ emissions from coal, oil and natural gas were respectively 43%, 36%, and 20% of total fossil fuel emission, and this trend is expected to continue (OECD/IEA, 2012a).

![Figure 1 World CO$_2$ emissions by fossil fuel use 1971–2010 [Source: (OECD/IEA, 2012a)]](image-url)
Currently, fossil fuels provide over 80% of the world’s primary energy of which 27% is coal (OECD/IEA, 2012b). During the last decade, annual CO₂ emissions from fossil fuel combustion and cement production were 54% above the level of the year 1990 (IPCC, 2013). In recent years, the global annual CO₂ emissions from such activities were about 36 billion tonnes (Quéré et al., 2013; Science Daily, 2013). Considering the trend, it is very clear that substantial reduction in fossil fuel use and cement production is required to avoid CO₂ emissions. It is also likely to avoid 50% of chance of temperature increase above 2 °C, if we substantially reduce the CO₂ emissions (European Union, 2008). However, the target of reducing greenhouse gas (GHG) emission is unlikely to be met unless strong and timely actions are taken (NOAA/ESRL, 2012; IPCC, 2013).

Forests are vital in reducing atmospheric CO₂ as they sequester and store carbon in the biosphere – in principle and in perpetuity; store carbon in the forest products; produce biofuels as an alternative to fossil fuels; and provide wood products that can often be used in place of other products, which require more fossil fuel for their production. Forests constitute approximately 30% of the world’s land surface and store approximately 1,200 billion tonnes of carbon (Freer-Smith et al., 2009). The global forests contribute to turn over about 8% of the total atmospheric CO₂, annually (Malhi et al., 2002; Canadell and Raupach, 2008). A study by Pan et al. (2011) showed that the global forest contributed a net carbon sink of 4.0 ± 2.9 billion tonnes of CO₂ year⁻¹ during the years 1990 to 2007.

The potential of a managed forest for CO₂ emission reduction might depend on management objective and product use strategies. Thus, it is crucial to consider the role of forest management and product use strategies in the context of climate change mitigation. A forest’s carbon sequestration capacity is a function of a particular site’s productivity and the size of carbon pools to retain carbon, including litter, soil, woody materials in the forest floor, standing dead trees and fallen dead wood, live stems, branches, and foliage (Chapin et al., 2002; Malmsheimer et al., 2008). The carbon accumulation in biomass is higher when a tree is in its fast growing stage, and as the tree reaches maturity (>80 years in boreal forests) it becomes almost carbon neutral and eventually become a carbon source if it dies and decays (Gower et al., 2001; Nabuurs et al., 2003).

Not all managed forests are equally capable to turn atmospheric carbon into forest biomass. A forest that has a large biomass production rate and a capacity to retain a large amount of ecosystem carbon will ensure a continued uptake of carbon and creates an opportunity to harvest large amount of biomass. By doing so, biomass can be used for construction materials and bioenergy production to
reduce carbon emission by replacing carbon-intensive materials and fossil fuels (Gustavsson et al., 1995; Marland and Schlamadinger, 1997; Schlamadinger et al., 1997). The burning of biomass, for bioenergy production, grown in a managed forest is part of a cyclical flow with the assumption that carbon emitted during combustion will be absorbed by re-growth in a planted forest. Using wood products from a managed forest in place of non-wood construction materials can reduce net CO$_2$ emission, as less energy is required to manufacture wood materials compared to non-wood materials. Substitution of carbon-intensive materials avoids process emission during the manufacture of non-wood products, such as cement and steel. The use of wood products would delay an emission of biogenic carbon by allowing wood to stay without decay for a longer time. Furthermore, biomass by-products from product-chains can be used for bioenergy, as can wood from construction work at the end of its useful life (Gustavsson et al., 2006b; Sathre et al., 2010). Nonetheless, the net carbon benefits also depend on substitution efficiency, e.g. how and where the products are used and which products are substituted (Schlamadinger et al., 1996; Sathre and O’Connor, 2010).

Hence, the greater the biomass production, the greater the carbon sink and potential harvest will be; the earlier the biomass harvest, the earlier the fossil fuels and carbon-intensive materials can be replaced (Malmsheimer et al., 2008). A forest management strategy aimed at increasing biomass production and its use could thus be effective in reducing carbon emissions leading to climate benefit (Easterling et al., 2007). The climate benefit, generally expressed in this thesis as carbon balance of forestry systems, thus depends on annual carbon stock change in the ecosystem, carbon benefit as a result of non-wood products substitution, and avoided emission as a result of increasing wood products in the technosphere.

The global society’s attempt to mitigate climate change focuses on reduction of atmospheric GHG concentration by reducing CO$_2$ emissions and increasing carbon sinks. The IPCC assessment report (2007) suggested that minimising net emission to the atmosphere requires maximising carbon stocks in the ecosystem and increase substitution of fossil fuel and other carbon-intensive products by using biofuel and wood products (Figure 2).
Recently, concerns about current challenges to reduce carbon emissions into the atmosphere have encouraged the creation of carbon sinks, to ensure the permanency of carbon stock and to reduce carbon-intensive product use (Canadell and Raupach, 2008). In the European context, initiatives have been taken in pursuit of reducing CO₂ emissions such as the EU’s ambitious renewables directive targets reaching a 20% share of energy from renewable sources by 2020 (European-Commission, 2009). This directive has also set targets for different countries, where Sweden is required to meet a target of 49% by the year 2020, but Sweden has increased this target to at least 50% of its final energy use from renewable sources (Swedish Energy Agency, 2012).

1.2 Motivation for the study

Sweden has a long tradition of forest management. Out of the total 28.3 million hectares of forest in Sweden, about 22 million hectares is actively managed for multiple use with timber production being a priority (SLU, 2013a). As a result of active management, forest standing stock in Swedish forests has nearly doubled over the last century. As an effect of improved silviculture and increased standing volume, growth and potential harvest have also increased.

Sweden is located in the northern hemisphere in the range of latitude from 55° N to 69° N. As a result of latitudinal variation, forest biomass growth decreases towards the north mainly because of a shorter growing season and low summer temperatures compared to the southern part of Sweden. A large share of managed forests are dominated by pure coniferous forest, mostly pine and spruce, while remaining forests are mixed coniferous and deciduous. Currently, the average growth rate of Swedish forests is 5.1 cubic meters ha⁻¹ year⁻¹ (SLU, 2013a).
The large area of production forests in Sweden is a rich store of biomass carbon. Considering forest as Sweden’s main land use practice and forest’s role in global carbon balance, managed forests in Sweden might have even larger potential to administer the challenging goal of carbon emission reduction. At present, the Swedish forestry dominates by clear-cut silvicultural system and it has been so for many decades. The clear-cut silvicultural system is set to obtain a long-term sustainable flow of timber from the forest with an even age-class distribution on regional and national level. All forest owners, including the larger forest owners such as forest companies, who regulate forest in the clear-cut silviculture, are obliged to reforest the clear-cut area with the aim of sustained wood production. In addition, Swedish forestry gives importance for preserving biodiversity and public interests while managing forest for timber production in providing economic, environmental and societal benefits (Swedish Forest Agency, 2013).

In Sweden, the effects of different silvicultural methods have been studied for native tree species growth in the long-term experiments in combination with National Forest Inventories (NFI). This has made possible to understand forest growth patterns within the clear-cut silviculture that have been regularly performed since 1923 (SLU, 2013b). As a result, Sweden has a unique set of long-term data describing forest resources on regional as well as national basis. Because of a long set of data and a long tradition of analysing consequences of different management practices (Swedish Forest Agency, 2000, 2004), Sweden is well suited for studies in the current context of carbon emission reduction and climate benefits of forestry.

A number of studies have suggested that future forest growth might be increasing as a result of potential temperature increase, and longer growing seasons at higher latitudes, implying that more sunlight will be used for photosynthesis, which could stimulate biomass production of boreal forests (Bergh et al., 2003; Rosenzweig et al., 2008; Raupach and Canadell, 2010). In addition, results have shown that biomass production can be further increased by various forest management practices (Rosvall, 2007; Nilsson et al., 2011).

Forest biomass production is the primary element in the building up of the carbon pools. Changes in forest biomass production can bring changes in different carbon pools, both in the ecosystem and the technosphere. The carbon pools that might be influenced are standing forest biomass carbon and soil/litter carbon in the ecosystem and carbon emission reduction due to the use of wood products in place of other carbon-intensive products in the technosphere.
There are many studies available in the literature focusing on different carbon pools related to forest management. Studies focusing on biomass production in boreal forests are abundantly available. Similarly, the forest biomass harvest and its use for substitution of carbon-intensive materials are also available for different parts of the world.

1.3 Previous studies

The sub-sections below explore relevant studies in the past in the area of forest biomass production and harvest, soil carbon stock and substitution of fossil fuels and carbon-intensive materials.

1.3.1 Forest biomass production and harvest

In the past, forest biomass production regarding carbon balances largely focused on ecosystem production (Houghton, 2005, 2007). But recent studies have included harvest potential to discuss its implications for total carbon balance. Studies to assess the effects of increased temperatures and CO₂ concentrations on plant photosynthesis and biomass production began early in the 1980s. Solomon (1986) and Pastor and Post (1988) found that forest biomass carbon was increasing because of increased CO₂ concentrations. However, an experimental study from Swedish forest did not find a significant effect of elevated CO₂ concentration on growth (Slaney et al., 2007). Instead, other studies showed that Swedish forest production in response to climate change will likely increase as an effect of increased atmospheric temperatures (Bergh et al., 1998; Bergh and Linder, 1999; Bergh et al., 1999), and several studies suggested that forest biomass production might increase in northern Europe (Kirilenko and Sedjo, 2007; Bergh et al., 2010). Swedish Forest Agency (2008) predicted a 25% increase in annual stem-wood production in Swedish forests due to the direct effects of climate change over the next 100 years. In the past, total annual harvest has always been less, except for a few years, compared to an annual increment in Sweden (Swedish Forest Agency, 2012). The residues and stumps harvesting practice has already started in Sweden, but has not been implemented to any larger extent. For example, in 2012, Sweden gave permission to harvest forest residues from 106 thousand hectares and stumps from 3.36 thousand hectares of forest (Swedish Forest Agency, 2012).
1.3.2 Soil carbon stock

Various studies have explored the effects on forest soil carbon stock due to changes in land use, forest management and climate. Liski et al. (2002) found that the soil carbon stock in Western Europe is increasing because of increased litter fall from living trees. Earlier studies reported that increased temperatures do not necessarily increase the nutrient cycling and oxidation of soil organic matter (SOM) and consequently the decomposition (Lloyd and Taylor, 1994). However, later studies suggested that a warmer climate may play a major role in the decomposition of SOM leading to an increase in CO$_2$ release to the atmosphere and a decrease in soil carbon content (Jones et al., 2005; Davidson and Janssens, 2006; Friedlingstein et al., 2006). Studies have claimed that, because of the release of soil carbon, positive feedback leading to an additional climate warming of 0.1 – 1.5 °C may take place in the future (Knorr et al., 2005; Friedlingstein et al., 2006; Luo, 2007). A significant loss of terrestrial carbon stock in the higher latitude is also possible because of the temperature-dependent net primary production system in boreal forests compared to other parts of the world (Canadell et al., 2007a; Canadell and Raupach, 2008). However, Hyvönen et al. (2007) suggested that, as long as forest biomass production and litter input in a forest floor is increasing, the soil carbon loss will not be significant. Egnell (2011) also suggested that the effect of litter harvest in soil carbon and nutrients are only temporary. It has been evident that the soil carbon stock in Swedish managed forest landscape has been steadily increasing over the years and it is assumed to increase further in the future (Ågren et al., 2007). Therefore, increasing the productivity of forests is a key factor to increase production. Moreover, reducing disturbances in the forests may help retain soil carbon for a longer period of time (Karhu et al., 2010; O’Donnell et al., 2010). Davidson and Janssens (2006) suggested that decomposition of a significant part of unstable organic matter is sensitive to temperature. Karhu et al. (2010) studied the temperature sensitivity of soil carbon and found that 30–45% more soil carbon will be lost in a warmer climate over the next few decades, assuming that there will be no change in carbon input. To compensate for this loss, forest biomass productivity would need to increase by 100–120% (Karhu et al., 2010). O’Donnell et al. (2010) performed an analysis on sensitivity of soil to climate change and found severe losses of organic carbon from soil. Climate changes, particularly temperature increases, have effects on terrestrial ecosystems and have potential to act as positive feedback in the climate system (Friedlingstein et al., 2006; O’Donnell et al., 2010). Although there are uncertainties regarding litter production, their input to the forest floor, variability in climate and forest sites (Ortiz et al., 2013), litter and
soil carbon stock are a major fraction to be considered while managing forests for carbon emission reduction.

1.3.3 Substitution of fossil fuels and carbon-intensive materials

In the past, forest biomass was used mostly for wood products and pulp and paper. During the last decade, the concept of whole-tree use has emerged, focusing on overall carbon benefits of forest management and product use. Recovered forest residues, tree-stumps, wood-chips, sawdust, and bark are important sources for bioenergy. In addition, wood is widely used for building construction, and its use is likely to grow in the future (Ministry of Industry, 2004).

   The use of forest biomass as a source of energy was considered during the global oil supply crisis in the 1970s. It was also in the 1970s that wood products were more explicitly thought of as a sustainable source of materials for construction in place of energy-intensive materials such as cement and steel (Boyd et al., 1976). A methodology for conducting energy analysis was developed in 1974 to provide consistency and comparability among studies (IFIAS, 1974). The Consortium for Research on Renewable Industrial Materials (CORRIM) was established by the National Academy of Sciences (NAS) of United States to study the potential effects of developing and using renewable construction materials (Lippke et al., 2004). Later, CORRIM developed a comprehensive life cycle inventory of forest products by including the processes of product manufacture, use of wood products in buildings and their maintenance, and disposal (Malmsheimer et al., 2008). The analysis focused on energy impacts associated with various wood-based building materials and showed that wood-based materials are less carbon-intensive than other structural materials that perform the same function (Lippke et al., 2004). Methodologies for the analysis of forest biomass as an input in the energy system and for comparisons with carbon-intensive materials for carbon balance were developed in the US, New Zealand, Australia and in Europe. Some noted developments have been highlighted in several reports (Fossdal, 1995; Gustavsson et al., 1995; Schlamadinger and Marland, 1996; Börjesson et al., 1997; Eriksson et al., 2007). Schlamadinger et al. (1997) and Marland and Schlamadinger (1997) developed methodologies to assess forest biomass use for fossil fuel substitution. Börjesson and Gustavsson (2000) calculated GHG emission from the life cycles of multi-story building construction. Pingoud and Lehtilä (2002) studied energy efficiencies of different types of wood products. Lippke et al. (2004) compared energy consumption of energy-intensive materials to CORRIM’s life cycle assessment of wood-based building construction. Werner et
al. (2005) explored GHG emission reduction as a result of the use of wood materials in construction and interior finishing. Gustavsson et al. (2006a) explored the possibility of wood recovery in different stages of a wood chain and its role in GHG emission reductions. Eriksson et al. (2007) considered different scenarios for forest production and biomass use and found that forest fertilisation, residue and stump harvesting, and the use of wood as a construction material, resulted in large reductions of CO$_2$ emission. Further studies have shown that the use of wood products and biomass residues significantly reduces net CO$_2$ emissions; provided that the wood material come from managed forests, where forest lands are regenerated after clear-cut, and emission from the use of biomass are to be removed by replanted forests (Salazar and Meil, 2009; Sathre and O’Connor, 2010).

1.3.4 Carbon accounting of transfer of forest biomass
Carbon accounting methods that include import and export of forest products were proposed as early as in the 1990s. This approach was suggested in the IPCC guidelines for National Greenhouse Gas Inventory (Houghton et al., 1997) to estimate carbon flow because of wood use in countries other than its origin. Winjum et al. (1998) suggested to account carbon flow into the atmosphere because of combustion, use, and decay in the consuming country. Lim et al. (1999) suggested that this approach should be encouraged in countries where the goal is to reduce carbon emission into the atmosphere and increase carbon sink in the forests. Such methodology was further used in different studies by Pingoud et al. (2003), Werner et al. (2005), Werner et al., (2010) and Lun et al. (2012). The complete carbon accounting of Swedish forestry and forest industry sector is also highly relevant to Sweden considering the country’s goal to reach GHG emission reduction.

1.4 The research context
The advancements of modern technique in managing forests have brought a new dimension of thinking in the context of environmental systems. For instance, forestry, as an important component of environmental systems, is seen as an opportunity to address global problems such as climate change mitigation. In this context, one of the contributions recently discussed is the carbon balance of forestry systems. Understanding forestry for its capacity to contribute to climate change mitigation requires an assessment from a system perspective. This means that the system to be studied should start from forest regeneration to the end-use
of the products. However, it has to be understood that forest biomass production is a primary part of the system which influences carbon stock development in forest soils, tree biomass in harvested wood products, use of biomass to replace carbon-intensive materials and reducing carbon emissions.

Despite a number of studies, there are still knowledge gaps regarding how climate change and level of biomass production affects the overall carbon balance of a forestry system. What is most effective in order to achieve a good carbon balance? To store carbon in the forest? To use forest products? And how do different forest management systems respond to carbon stock change rate in the ecosystem and in the technosphere? In this context, studies about biomass production potential in Swedish forests are relevant regarding potential temperature change as an effect of the climate change and increased forest product use on the total carbon balance. In addition to climate change effect, modern silvicultural methods, available today to increase growth, can increase both carbon stock in the forest and the potential to use more forest products for substitution. Production forestry may raise a doubt about addressing the conservation goals. Thus, increasing set-aside area for conservation purposes could address the conservation goals but could be subject to trade-offs for biomass production, which will also influence the overall carbon balance.

A national level study can be a reference to describe the total account of that country’s forestry sector’s total carbon balance. Forest products produced in one country are very often exported to other countries and transfers carbon emissions and substitution benefits, which is subject to account in a total carbon accounting system. A complex system analysis, however, would need to explain such accounting so that different forest management practices with different production and harvest levels are included; different forest product use strategies are considered; exports and imports of products are accounted; and carbon balances within and beyond the country are explained. Forest product use in a general consumer cycle of a country may not necessarily focus on reducing carbon emissions, but is rather directed towards fulfilling the forest product demands of its citizens. For example, forest products might be used for sawn wood, furniture, pulp and paper production, and for other different domestic purposes. At the same time, a country is involved with export and import of forest products. Accounting of such general consumer cycle and product trade and their use abroad is necessary to explain an actual carbon balance of a country’s forestry sector, and to explain its role in mitigating climate change.
Assessments of carbon balance of forestry systems on a stand level management unit and on a landscape level management unit can explain and represent potential contribution from different levels of land use, while a national level study would have implications for future policy. Recently, continuous-cover forestry has been a subject for discussion in the forestry research community because of its potential for the societal and environmental services in addition to timber benefits. In Sweden, the contributions of continuous-cover forestry in biomass production are explained in a fairly small number of studies (Chrimes and Lundqvist, 2004). Comparisons of carbon balance between clear-cut forestry and continuous-cover forestry, however, are unknown. Thus, it is important to exploring methods and contributions of continuous-cover forestry in total carbon balance to further deepen our understanding. Hence, this thesis is a continuation of the progress of carbon balance studies, but adopts a comprehensive systems analysis method to quantify carbon benefit of full chain of forest product use in the stand level, landscape level and national level study in Sweden.

The relevance to study the future forest management scenarios is increasing because of global and country policies aiming to reduce carbon emissions. The reasons to find better future forest management scenarios include enhancing forest productivity, increasing harvest and use of forest products in place of carbon-intensive products, while at the same time ensuring both economic and social well-being of the country population, and contributing to address the global agenda on climate change. When looking at the national context, Swedish GHG emissions in the year 2011 accounted 61 Tg of CO₂-eqv (Swedish Environmental Protection Agency, 2013). Out of 61 Tg, about 45 Tg of emission came from the energy sector (OECD/IEA, 2013). The International Energy Agency (IEA) has examined global energy scenarios for future energy supply and has indicated that fossil fuel use is likely to be continued as a primary source of energy until the year 2035, if the current energy policies are not changed (OECD/IEA, 2012b). This may explain the severity of fossil fuel use in the future, which may result in increasing total anthropogenic GHG emissions. Furthermore, Sweden aims to by 2020, reduce 40% of carbon emissions to the level of 1990 and has as a goal to become a zero carbon emission country by 2050. These goals are very ambitious as the net carbon uptake of land-use, land-use change and forestry in the year 2011 was 35 Tg CO₂-eqv (Swedish Environmental Protection Agency, 2013).

In summary, this thesis addresses a number of research questions that is relevant to the present and future context of carbon emission reduction and mitigating climate change. It explores potentials to reduce CO₂ emissions in the
Swedish forestry sector to address the government’s target to become a zero net GHG emission country.

1.5 Objective and scope of this thesis

The main objective of this thesis is to analyse total carbon balance implications of forest biomass production in different forest management scenarios, at stand level, at landscape level, and at national level in Sweden. This includes calculation of ecosystem carbon stock and carbon benefit of an entire chain of forest product use focusing on forest management at stand level.

The effects of climate change on biomass production and total carbon balance is examined in Paper I. Paper II explores the carbon balance of different forest management alternatives regarding production or set-aside land. Paper III examines the total carbon balance of Swedish production forestry, including forest product use within and outside of Sweden. The first two papers (Papers I and II) estimate carbon balance with higher potential substitution effect, while Paper III considers an actual use of forest products and substitution effect for the landscape-level total carbon balance. Paper III also explores how forest product trade can influence carbon balance. The analyses in Papers I and II represent the regional scale and Paper III represents the national scale. Paper IV compares two different silvicultural systems, i.e. clear-cut forestry and continuous-cover forestry, in terms of total carbon balance.

The research questions in each paper and their relation to the objectives above are described as below:

**Paper I:** Recent projections of forest biomass growth due to climate change in Europe encouraged formulating this research because of large forest area and forest biomass production potential in Sweden. This study analyses the effects of climate change on future forest production in north-central Sweden and explores potential feedback effects of increased forest product use on total carbon emission reduction with its potential role on climate change mitigation.

**Paper II:** Forest productivity can be increased by using silviculture methods such as fertilisation, genetically improved material and choice of tree species. Increased biomass can reduce fossil fuel use, carbon-intensive material use, and avoid industrial processes of non-wood materials. It is important to assess the effect of intensive forestry practice in ecosystem carbon stock change and substitution carbon benefits. In addition, the
effect of increased set-aside area in carbon balance is also presented. This study examines potential effects of intensive forestry practices and increased set-aside area on forest production in north-central Sweden and their effect on total carbon balance.

Paper III: Carbon balance accounting of the forestry sector of a country helps to explore its potential in reducing carbon emissions in the future. As forest industries use forest products in construction material production, pulp and paper production, and energy production, it is essential to estimate an actual amount of wood product consumption in the future and their potential effects on obtaining substitution carbon benefits. Sweden not only uses forest products within the country, but also exports considerable amounts of wood products abroad, which could have an important role in the total carbon balance in the global carbon cycle. This study analyses the effects of forest management scenarios and wood use strategies in the total carbon balance within and outside the country due to export and import of wood products and their substitution effects.

Paper IV: Carbon benefits from a planted forest ecosystem and a natural forest ecosystem differs in many ways. The carbon dynamics, particularly in standing forest biomass and in litters, is important to examine considering their carbon stocks and biomass production. There are not many natural continuous-cover forest stands left in Sweden because of active forest management, thus an argument for increasing such forestry might increase in the future. This study compares the total carbon balances in clear-cut forestry and continuous-cover forestry.

1.6 Outline of the thesis

This thesis is based on the four appended papers and is divided into two parts. The first part includes the introductory remarks contextualizing the research, a presentation of concepts and state-of-the-art and methods used in appended papers, synthesis of the results presented in the papers, discussion and challenges for the implementation of this research and conclusions. The second part includes appended papers. The workflow of the thesis is presented in Figure 3.

The first part comprises of 7 chapters. The first chapter begins with introduction, background, motivation for the studies within Swedish forestry systems, review of previous studies, main objectives, and scope of thesis and
research questions. Chapter 2 presents concepts and state-of-the-art in forest biomass production, harvest and use. Chapter 3 includes the methodological framework for the assessment of forest biomass production and its implications together with methods and approaches used in the studies. Chapter 4 provides information about modelling work and a summary of the results from appended papers for forest biomass production, product harvest, standing biomass carbon and litter and soil carbon stock changes. Chapter 5 describes how forest products are used to substitute carbon-intensive materials and fossil fuels, and presents total carbon balance with result summaries. Chapter 6 presents a general discussion and challenges for implementation of production forestry. Chapter 7 presents conclusions of the thesis and outlines suggestions for future research.

Figure 3 The outline and the workflow of the thesis, arrows denote the work flow.
The studies performed in appended papers have fundamental relations to each other regarding different forest management practices. Figure 4 presents the appended papers corresponding to the objectives of thesis and their relation to different forest management scenarios. Traditional forest management is considered in all appended papers (Papers I–IV). Intensive forestry practices are considered in Papers II and III. Climate change effect is considered in Papers I and II. The study uses a systems analysis approach to estimate carbon stock changes in standing biomass, in forest litter and soil, and in harvested and used products, and substitution of carbon-intensive materials and fossil fuels in different forest management and product use scenarios (Figure 4).

Figure 4 The relations of appended papers corresponding to the objectives as a schematic diagram (Papers I–IV).
2. Concept and state-of-the-art in forest biomass production, harvest and utilization

This chapter presents the basic concepts and state-of-the-art in forest biomass production, forest management, biomass harvest and use for carbon benefit. At first, concepts of forest biomass production and the role of climate change in biomass production are presented. Next, state-of-the-art in forest management, biomass harvest, and use are explained.

2.1 Forest biomass production and carbon

Biomass production in a plant involves physiological processes. The process occurs in a plant with an interception of solar radiation and in the presence of CO$_2$, temperature, and nitrogen (Chapin et al., 2002). The process produces carbon-containing organic matter and then transfers into different components of trees and into soil (Chapin et al., 2002). The biomass carbon stored in trees can be classified, in broad terms, into aboveground and belowground biomass carbon. The aboveground biomass carbon includes the amount of carbon content in stemwood, stem-bark, branches, foliage and shoots. The belowground biomass carbon includes stumps, coarse roots and fine roots. The amount of aboveground biomass may differ according to tree species and their crown characteristics, while belowground biomass carbon may depend on stump and root characteristics of tree species. Other important components of forest biomass carbon are litter and soil carbon. Tree branches and needles falling from standing trees and tree stem mortality are the main source of litter on the forest floor. This litter organic matter will gradually turn into organic soil carbon through decomposition in the presence of temperature and moisture. According to Chapin et al. (2002, pp. 151) the decomposition is “The process of leaching, fragmentation, and chemical alteration of dead organic matter by decomposition produces CO$_2$ and mineral nutrients and a remnant pool of complex organic compounds that are resistant to further microbial breakdown”. Thus, litter and organic soil carbon build-up in a forest depends on litter availability, temperature, soil moisture and decomposition rates.

In principle, potential carbon stock change in a forest ecosystem is limited. Phenomena such as plant respiration, soil decomposition processes, plant mortality, fire, and soil disturbance release carbon into the atmosphere. It is estimated that less than 1% of the carbon, that is taken up by terrestrial ecosystems, remain as a long-term terrestrial carbon (Bolin and Sukumar, 2000). Nonetheless,
increasing forest biomass production would contribute to increase the carbon sequestration rate and thereby subsequent carbon stock increase.

2.2 Climate change and forest biomass production
The future projections for the changes in global mean surface temperature at equilibrium have recently been updated by IPCC, and the likely sensitivity has been presented in the range of 1.5 °C to 4.5 °C (IPCC, 2013). Process based models for terrestrial Net Primary Production (NPP) have produced results showing continuing changes in the global climate change pattern, in particular a likely temperature increase and longer growing season would stimulate forest biomass production in the boreal region as a result of favourable conditions for photosynthesis processes (Melillo et al., 1993; Bergh et al., 2003; Bergh et al., 2010). Increased temperature could lead to increased soil biological activities implying increased mineralization and nitrogen availability in forest soil (Strömgren and Linder, 2002; Rasmussen et al., 2006). The climate change effects in terms of temperature change are very important for studies that involve process-based models. The direct implication of increased temperature in models could relate to tree biomass growth, soil respiration and litter decomposition process, thus it is important to include in future projections of biomass carbon accounting studies.

2.3 Forest management and silviculture
Forest management involves “an integration of silvicultural practices and economic alternatives in such a way as to best achieve a landowner’s objectives” (Bettinger et al., 2009). A recognised plan satisfies the best production and ecological objectives and product demand through a series of silvicultural operations (Buongiorno and Gilless, 2003; Bettinger et al., 2009).

Silviculture as a component of forest management is, in general, referred to as “the theory and practice of controlling establishment, age, composition, growth and quality of forest stands to achieve an objective of multiple goods and services” (Lapedes, 1978; Bell et al., 2000). Silvicultural activities included in this thesis are related to forest biomass production and carbon stocks changes in a forest, litter, soil and products. These include soil scarification, forest regeneration, fertilisation, pre-commercial thinning, thinning, final felling, and extraction of products.

Different silvicultural systems have been developed and practiced aiming to improve timber quality, optimise benefits, shorten investment period, minimise investment and maintain ecosystem health and productivity (Nyland, 1996).
Silviculture of forest stands may depend on the objective of the forest owner, thus the characteristics of a forest can differ, mostly due to the interest of the forest owner (Nyland, 1996). Differences in characteristics have direct implications on forest biomass related carbon pools. The important characteristics, such as density of trees, age structure of a stand, rotation length, thinning intensities, litter fall, and dead wood amount on forest floor might differ in different silvicultural systems. For example, a clear-cut silvicultural system, that has an even-aged stand structure that follows a cyclic harvest-and-regeneration pattern and rotation period, is normally set to optimize average forest production. The aim of developing clear-cut systems is to obtain a higher economic benefit by a resulting sustainable flow of timber (Puettmann et al., 2009). The carbon dynamics of a clear-cut system include a rapid net carbon gain in young stands and a net carbon gain at a lesser rate after canopy closure in more mature stands and significant net biomass carbon removal at final harvest (Hyvönen et al., 2007; Diochon et al., 2009). In general, a reduced amount of dead wood biomass carbon may occur in a clear-cut system. Silvicultural systems with an uneven-aged forest stand, in this thesis expressed as continuous-cover forestry, has an uneven-aged forest stand structure and a continuously maintained forest cover that does not follow a cyclic harvest-and-regeneration pattern as it occurs in clear-cut system (Troup, 1928; Gadow, 2001). The carbon dynamics of an uneven-age forest stand include a slow and steady carbon gain in living stand and a net biomass removal at a certain period in time with selection cutting. Despite uncertainties, a large number of standing trees existing for a longer time period in continuous-cover stands could provide larger amount of litter falls compared to clear-cut forest stands.

Figure 5 Schematic carbon stock development of aboveground biomass under clear-cut and continuous-cover systems [Source: (Böttcher, 2007), from (WBGU, 1998)].
Figure 5 presents the aboveground carbon dynamics of a clear-cut and continuous-cover system over time. Biomass carbon gain in clear-cut systems is greater in the young age and slows down with the maturity of the forest stand (Figure 5a), while carbon gain in a continuous-cover system is slow and steady with larger stock in standing trees (Figure 5b) (see Chapter 3.3).

2.4 Forest biomass harvest and use
Harvested biomass can be classified into various categories. The stem includes stem-wood and stem-bark. In general, stem-wood is divided into large diameter stem-wood and small diameter stem-wood. Large diameter stem-wood could be as small as 20 cm in diameter over bark. The remaining parts i.e. tops and branches are classified as residues. In a mechanised forestry, where harvesters are used, logs are measured simultaneously. In general, large diameter stem-wood go either to sawmills or to pulp and paper mills. The residue either goes to energy production or remains on the forest floor. Harvested stump biomass and coarse and fine roots follow the same procedure as residues or the forest biomass use strategy. However, there are no cases where all biomass is removed from the forest for energy production, as some parts of residues are recommended to be left in the forest (Swedish Forest Agency, 2008, 2009). Forest biomass harvest plans depend on management strategies, the forest’s growth level, financial returns, and forest product utilization strategies. The higher biomass growth will provide the opportunity for the larger biomass removal, shorter rotation length, higher frequency and intensity of thinning and their influence on biomass stock in the following generation (Liski et al., 2001; Kaipainen et al., 2004).

In the past, stem-wood was removed to be used as sawn wood. However, the use pattern has changed because of time, land-use practice, and export use of products (Burton et al., 2003). For example, bioenergy production from forest biomass was discussed during the 1970s and was subsequently in action during the 1980s (Pimentel et al., 1981). Using forest residues as energy influenced decisions about forest residues removals in practice. The methods of forest biomass use in energy production and building construction have been developed and they are generally based on life cycle assessment (LCA) (IFIAS, 1974; Fossdal, 1995; Gustavsson et al., 1995; Schlamadinger and Marland, 1996; Börjesson et al., 1997; Lippke et al., 2004; Eriksson et al., 2007; Malmsheimer et al., 2008). Noticeable methodological studies in forest biomass use for energy and building construction have also focused on accounting GHG emissions, and been compared to the
conventional materials such as fossil fuels and non-wood construction materials (Marland and Schlamadinger, 1997; Schlamadinger et al., 1997; Werner et al., 2005; Gustavsson et al., 2006a; Eriksson et al., 2007; Salazar and Meil, 2009; Sathre and O’Connor, 2010).
3. Methodological framework

This chapter presents the methodological frameworks used in this thesis in order to analyse carbon balance implications of forest biomass production potential. The chosen methods in the studies are discussed for biomass production, forest management, and material life cycle and energy systems. The activities included in the analysis, study area, scenarios and assumptions for studies, are explained.

3.1 The systems concept

This thesis understands forestry as a system and considers all activities, from forest regeneration to the end use of forest products, as entities of this system. A system is defined as a set of objects, together with relationships between the objects, and their attributes connected to each other and to their environment in such a way as to form an entity or a whole (Hall and Fagen, 1968; Schoderbek et al., 1975). It is a complex whole that functions based on its parts and the interaction between them, and response of the complex interaction is seldom simple (Jackson, 2003; Meadows, 2008). In this thesis, systems thinking is understood as an approach to address a problem in a complex whole. The systems thinking approach brings diverse disciplines in one place to define a problem, and shows a possibility to solve them (Meadows, 2008; Asterios G. and “Stell” Kefalas, 2011).

A comprehensive analysis of carbon balance implications of forest biomass production requires a systems thinking approach because of the complexity in forestry systems. This thesis puts together a set of different disciplines into one framework. The methodological tools used in this thesis, such as the life cycle of forest product use, have been developed and used in the past (Schlamadinger et al., 1997). However, forest management practices and their role in forest biomass production, harvest and the use today is facing an increased complexity because of the importance of forest products in several sectors. Thus, a complex set of subject matters from forest ecology such as physiological processes in trees, annual changes in standing biomass, forest litters and soil carbon stock; from silvicultural systems such as regeneration, thinning and final felling; from product utilization systems such as wood, bioenergy, pulp and paper and end-of-life management of materials are considered in the thesis.
**Life Cycle Assessment:** The material flow analysis of a product, such as production, processing, use and end-of-life management, requires an evaluation from a life cycle perspective. A product system, where unit processes are involved in the life cycle of a product, can be analyzed for that system’s environmental impacts using the LCA method (Guinee, 2002). ISO 14040 defines LCA as "the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). The LCA method uses all processes of a product system, from its manufacture to end generally referred to as ‘cradle-to-grave’, to assess every impact associated with that product (Baumann and Tillman, 2004; ISO, 2006). The LCA method can include large systems, and interaction between subsystems and can thus be considered as a systems analysis method (Tillman, 2000; Baumann and Tillman, 2004). A comprehensive analysis of forest product use in place of non-wood materials while determining carbon balances requires a systems analysis from a life cycle perspective. The LCA method in this thesis includes all carbon emissions associated with raw material extraction, production, use, maintenance and disposal of a product.

### 3.2 Methodological framework

This thesis uses a methodology that integrates knowledge from different sectors such as, forest ecology, forest management, forest product utilization, wood product engineering and bioenergy production. It considers different models for carbon accounting such as, process based model, empirical model, litter and soil carbon model and substitution model (see Chapter 4). In appended Papers I and II, where climate change effects on biomass production is accounted, a process-based model for forest biomass production projection is included. In other studies (Papers III and IV), an empirical forest biomass growth model is used to estimate standing biomass stock and harvest levels in forests based on Swedish NFI data. Analysis of forest product use includes wood as building material, bioenergy, pulp and paper, and estimation of substitution carbon benefits due to avoidance of carbon-intensive materials. It also estimates litter and soil carbon changes under different types of forest management practices.

The carbon flow chart (Figure 6) shows how carbon flow is estimated in appended studies. A balance between NPP and biomass loss during ecological processes determines an annual change in plant biomass stock (Chapin et al., 2002). At the same time, changes in plant biomass will have influence on changes in below-ground biomass. Forest biomass production estimation begins with a
calculation of NPP, which is fed into an empirical forest growth model and an annual forest growth in Swedish NFI data is incorporated to calculate annual biomass harvest (Papers I, II, and III). Biomass production in Paper IV is estimated in an empirical model based on other experimental studies and Swedish NFI data. Model outputs, in the form of different assortments of forest products (stem-wood, stem-bark, foliage, tops, branches, stumps), are used for different purposes. For example, stem-wood is used for construction material and pulp and paper production, and tree residues and processing residues are used for bioenergy production. The system boundary for biomass input in energy production, building construction, and pulp and paper production is described schematically in Paper III (see Figure 2, Paper III). Carbon emission reduction due to substitution of fossil fuels and carbon-intensive materials is estimated. Carbon stocks in standing biomass, in harvested wood products that are used for domestic purposes, construction materials, and in forest soils are estimated. Fossil carbon emission from forest operations (CO₂ emission during regeneration, pre-commercial thinning, commercial thinning, fertilisation, and final felling) and wood waste material operations are included in the analysis.

Figure 6 Schematic diagram of carbon flow during forest production and biomass utilization.
3.3 Forest management, product harvest and conversion

In this thesis, two forest management systems: clear-cut forestry (Papers I, II, III and IV) and continuous-cover forestry (Paper IV) are studied. Clear-cut forestry assumes a pre-commercial thinning and two to three commercial thinnings before final harvest (Papers I, II and III). Continuous-cover forestry assumes regular biomass removals during selection cuttings in a certain period of time (Paper IV). Pre-commercial thinning is not included in stand base analysis (Paper IV) because of the potential higher cost and lower economic value of recoverable biomass. Details of how forest is assumed to be regenerated and established are discussed in Section 2 of Paper I and Section 2 of Paper IV. Forest biomass is assumed to be recovered and used as wood materials and biofuels to replace carbon–intensive construction materials and fossil fuels. The forest product chain starts with harvest operation either during thinning or final harvest. The product recovery chain includes thinning, selective cutting, final felling, harvest residues recovery from final felling, stumps recovery during final felling, residues recovery from wood processing and building construction activities, and wood from demolished buildings at the end of its life cycle (see Figure 7).

Harvested biomass is assumed to be used as stem-wood and whole-tree. The stem-wood biomass consists of stem up to 20 cm diameter of a log and bark, which is also known as the merchantable diameter. Bark will eventually go to processing residues after a debarking process in the sawmill. Stem-wood is assumed to be used for construction material (Papers I, II and IV). In Paper III, stem-wood is assumed to be used for construction material and pulp and paper production. Harvesting residues, stumps, small-diameter stem-wood, and all biomass recovered from building demolition are used for energy production.

Although, timber harvesting has been a common practice in Swedish forests, residues harvests are seen as a valuable source for bioenergy production, including stumps. However, residue recovery is subject to ecological constraints involving nutrient cycling and organic matter (Börjesson et al., 1997; Sathre, 2007). The Swedish Forest Agency recommends that at least 20% of logging residues and 15–20% of stumps should be left at the site of final felling (Swedish Forest Agency, 2008, 2009). Although biomass harvest potential is high, concerns about logistical capability to efficient collection and transportation of residues are raised (Sathre, 2007). A study by Gustavsson et al. (2011) has shown that forest biomass can be harvested and transported abroad with minor impact on carbon emissions.
In general, tree logs are converted into different wood products in a sawmill. This process creates by-products such as bark, slabs and sawdust. Today, the by-products are used for energy recovery in sawmills and in many cases brought to district heating plants to use for heat and power generation. Some products, such as sawdust and small pieces of wood, are used for particle board and composite board production. The processing residue from sawmill, to be used in other products, was assumed to be 22% of total processing residue (Sathre, 2007). Remaining processing residue is considered to be used as biofuel to produce bioenergy. Other wood waste generated during building construction and demolitions are considered to be used for bioenergy production.

### 3.4 The material life cycle and energy systems

The wood products used in buildings are referenced to the Wälludden building constructed in Växjö, Sweden, which is functionally equivalent to a concrete frame building (Papers I, II, and IV). The Wälludden building is described in detail by Dodoo (2011), Sathre and Gustavsson (2007), Sathre (2007), Gustavsson et al. (2006b), and Gustavsson and Sathre (2006). All steps in the building life cycle starting from material acquisition to construction, operation, demolition and disposal phases are included in the analysis. The national level study (Paper III) includes all processes in a building e.g. raw material extraction, production, use, maintenance and disposal of a product from a different reference building. The reference building materials in Paper III were taken from a Swiss catalogue of building elements (Werner et al., 2005, 2006), but conditions were adapted to the Swedish wood flow (Paper III). The total amount of fossil fuels used for material extraction, processing, transportation, conversion and distribution are included in this study. Accounting of fossil fuel use includes the amount of material to be used and end-use energy required for the processing of such material.

This thesis follows a standard methodology developed for comparing carbon balances of fossil fuel and biofuel energy systems (Schlamadinger et al., 1997). It is assumed that harvest residue, wood processing residue and building demolition residue are used to substitute fossil fuels. Total avoided fossil fuel use and respective carbon emissions, due to the use of bioenergy production, are accounted. Values of specific carbon emission from fossil fuels such as atomic carbon are assumed to be 30 kg GJ\(^{-1}\) for coal, 22 kg GJ\(^{-1}\) for oil, and 18 kg GJ\(^{-1}\) for natural gas, and include emissions during the entire fuel-cycle from the natural resource to the delivered energy service (Gustavsson et al., 1995). Energy used for
recovery and transport of biofuels is assumed to be diesel fuel, calculated as a percentage of the heat energy content of the biofuel. The share of energy use in percentage is 10% for stumps, 5% for slash and small diameter stem-wood, and 1% for processing residues (Eriksson et al., 2007). Emissions from forest management activities are based on Berg and Lindholm (Berg and Lindholm, 2005).

This thesis uses the concept of reference fossil fuel to be replaced by energy produced from forest biomass. The reference fuel can be varied in an analysis to determine the significance of carbon emission intensity (Sathre, 2007). Coal and natural gas are two reference fuels used and replaced, which represent high and low intensity of carbon emission respectively (OECD/IEA, 2012b).

The life cycle of a building and a forest product use chain requires electricity for various processes. Since there are various types of electricity production systems available, the choice of particular electricity production system could influence the primary energy use and CO₂ emissions. The average values are not suggested to use for primary energy efficiency and related CO₂ emissions, because the changes in electricity supply do not occur at average level, but at marginal level (Sathre, 2007; Hawkes, 2010). The changes in electricity use in one place forces a change in electricity production in a marginal source. Introduction of electricity supply due to biomass residue use in a power plant would replace marginal energy production.

Total electricity production in Sweden in 2011 was 45% from hydropower, 40% from nuclear power, 11% from biofuel and fossil fuel-based production and 4% from wind power (Swedish Energy Agency, 2012). In combustion-based electricity production, 32% of the fuel input was based on fossil fuels in the year 2011. Apart from this, the Swedish electricity supply grid forms part of the Nordic Electricity grid (NORDEL) including Finland, Denmark and Norway, and this grid is connected to the European electricity supply grid, Union for the Coordination of Transmission of Electricity (UCTE). In 2012, the European Union (EU-27 countries) produced 52% electricity from conventional thermal power plants using fossil fuels (EUROSTAT, 2014). Since Sweden uses electricity from NORDEL and UCTE, the majority of marginal electricity production in these grids is still based on fossil fuels. OECD/IEA (2012b) has put forward that the global energy supply is still largely dependent on fossil fuels and this trend will continue in the near future.

For all these reasons, this study considers coal-fired or natural gas-fired condensing plants as realistic Swedish marginal electricity production. The conversion efficiencies of coal-fired and natural gas-fired condensing plants are assumed to be 40% and 50%, respectively (Sathre, 2007). Bioenergy produced from
forest biomass is considered to substitute the energy produced in coal and natural gas-fired plant (Papers I, II and IV). A marginal energy mix of fossil fuels used for thermal energy generation in Sweden and the UCTE mix have been used for all processes occurring abroad (Paper III).

3.5 Activities included in the analysis
Various activities and processes shown in Table 1 are included in the analysis. The activities and processes are defined according to their life cycle. All energy used during activities and processes and carbon emissions are accounted.

Table 1 Activities and processes included in the life cycle carbon balance.

<table>
<thead>
<tr>
<th>Description</th>
<th>Activities and processes included</th>
<th>Carbon implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production of materials (forest biomass and non-wood e.g. cement and steel)</td>
<td>Forest operation activities (regeneration, pre-commercial thinning, thinning, harvesting, fertilisation); Wood processing, extraction of process residues and transportation; Non-wood material extraction, processing, and transportation.</td>
<td>Carbon stock change in forest and building materials; Carbon stock changes in forest soil; Fossil fuel use for forest operation, non-wood material production; Cement processes.</td>
</tr>
<tr>
<td>Use of materials</td>
<td>Forest biofuel and wood processing residues use in power plants; Forest biomass use in pulp and paper production; Wood material use in buildings.</td>
<td>Forest residues and wood-process residues replaces fossil fuel; Carbon emissions during pulp and paper production; Wood materials replace non-wood materials.</td>
</tr>
</tbody>
</table>

3.6 Study area
All forest management scenarios considered in this thesis are assumed to be implemented in Sweden (Figure 7). Papers I and II are based on a landscape of Jämtland and Västernorrland counties i.e., north-central Sweden (Figure 7b). Paper III uses the whole of Sweden as study area (Figure 7a). Paper IV assumes a forest stand from central Sweden near to 60°N latitude in the figures.
3.7 Scenarios and assumptions

Different forest management scenarios (Table 2) are formulated to describe potential variability of climate and forest management practices along with forest biomass use strategy.
Table 2: Scenarios studied in this thesis corresponding to appended papers.

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>Forest management</th>
<th>Biomass harvest</th>
<th>Biomass use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Current management</td>
<td>Stem-wood and bark (95%) and residues (75%), stumps (50%)</td>
<td>Building construction, bioenergy production</td>
</tr>
<tr>
<td>Climate</td>
<td>Current management plus climate change effect (4 °C temperature increase in next 100 years)</td>
<td>Stem-wood and bark (95%) and residues (75%), stumps (50%)</td>
<td>Building construction, bioenergy production</td>
</tr>
<tr>
<td>Reference</td>
<td>Current management plus climate change effect (4 °C temperature increase in next 100 years)</td>
<td>Stem-wood and bark (95%) and residues (75%), stumps (50%)</td>
<td>Building construction, bioenergy production</td>
</tr>
<tr>
<td>Environment</td>
<td>Current management, set aside land is increased to 8% compared to 4% in Reference scenario, special environmental care area is increased to 14% compared to 8% in Reference scenario</td>
<td>Stem-wood and bark (95%) and residues (75%), stumps (50%), (set-aside area and special environmental care area is excluded)</td>
<td>Building construction, bioenergy production</td>
</tr>
<tr>
<td>Production</td>
<td>Silvicultural actions taken to increase production, e.g. soil scarification, fertilisation</td>
<td>Stem-wood and bark (95%) and residues (75%), stumps (50%)</td>
<td>Building construction, bioenergy production</td>
</tr>
<tr>
<td>Maximum</td>
<td>Silvicultural actions taken to maximise production, e.g. balance fertiliser supply, species selection/change</td>
<td>Stem-wood and bark (95%) and residues (75%), stumps (50%)</td>
<td>Building construction, bioenergy production</td>
</tr>
<tr>
<td>Baseline</td>
<td>No climate change effect, current forestry conducted as today</td>
<td>Stem-wood and bark, and residues 15%</td>
<td>Construction, interior, industrial wood use</td>
</tr>
<tr>
<td>Baseline</td>
<td>No climate change effect, current management, more tree biomass is used compared to today</td>
<td>Stem-wood and bark, residues 35%, and stump 20%</td>
<td>As for Baseline, increased use of forest residues</td>
</tr>
<tr>
<td>Increased</td>
<td>No climate change effect, forest growth increases substantially, sustainable felling level increased by 50%</td>
<td>Stem-wood and bark, residues 35%, and stump 20%</td>
<td>As for Baseline, Increased Harvest, additional wood use</td>
</tr>
<tr>
<td>CF+</td>
<td>No climate change effect, production of 7.01 m$^3$ ha$^{-1}$, thinning at 45, 65 years, final harvest at 95 years</td>
<td>Stem-wood and bark 95%, residues 80%, stumps 80%</td>
<td>Building construction, bioenergy</td>
</tr>
<tr>
<td>CF</td>
<td>No climate change effect, production of 7.01 m$^3$ ha$^{-1}$, thinning at 45, 65 years, final harvest at 95 years</td>
<td>Stem-wood and bark 95%</td>
<td>Building construction, bioenergy</td>
</tr>
<tr>
<td>CCF100</td>
<td>No climate change effect, production of 7.01 m$^3$ ha$^{-1}$, selection cutting every 10 years</td>
<td>Stem-wood and bark 95%</td>
<td>Building construction, bioenergy</td>
</tr>
<tr>
<td>CCF80 (20% less production than CF and CCF100)</td>
<td>No climate change effect, Production of 5.61 m$^3$ ha$^{-1}$, Selection cutting every 10 years</td>
<td>Stem-wood and bark 95%</td>
<td>Building construction, bioenergy production</td>
</tr>
</tbody>
</table>
The *Reference* scenario in Paper I assumes an unchanged climate, while the *Climate* scenario (Paper I) assumes climate change. Assumed climate change is based on the IPCC Special Report on Emissions Scenarios (SRES) B2 climate change scenario (Nakicenovic and Swart, 2000) that corresponds to a steady emission of GHGs that leads to a 621 ppm of atmospheric CO₂ concentration by the year 2100 (Levy et al., 2004). Details on considered climate change effects are given in Papers I and II. Scenarios in Paper I assume current forest management practices. Paper II includes four scenarios, with the *Climate* scenario in Paper I serving as a *Reference* scenario in Paper II. Remaining scenarios in Paper II assume different forest management practices to meet different objectives. The *Environment* scenario assumes to increase the setting aside of forest lands for preservation with no claim on production. The *Production* and *Maximum* scenarios aim to meet higher production goals, with intensive forestry practices adopted to increase forest production. The *Production* scenario assumes to include improved genetic material in seedling plantations, soil scarification, selection of suitable high productive tree species. In addition, pre-commercial thinning and traditional fertilisation area is increased in the *Production* scenario compared to that of the *Reference* scenario. Balanced fertilisation (a fertiliser mix of Nitrogen, Phosphorus and Potassium, generally referred as NPK) in young stands of Norway spruce and forest establishment in former agricultural land, are also included in the *Production* scenario. The *Maximum* scenario includes all those activities in the *Production* scenario. In addition, it assumes to replace Scots pine with Lodgepole pine, and increase the area of balanced fertilisation in young stands of both Lodgepole pine and Norway spruce up to maximum extent (see Table 2, Paper II). Harvested biomass is used as “stem-wood” and “whole-tree” (see Table 2).

Paper III considers three different forest management scenarios to represent different forest land use strategies. The *Baseline* scenario describes forest management with current silvicultural practices in Swedish forestry. In the *Baseline Increased Harvest* scenario, forest management resembles the *Baseline* scenario but forest residues and stumps are harvested to a much larger extent. In the *Increased Growth* scenario, intensified silviculture is considered to increase forest growth. Paper III assumes three phases in modelling. Phase one (year 1900 to 2005) represents current carbon stock of the Swedish forestry and forest industry sector. The second phase (year 2005 to 2035) assumes changes in consumption and foreign trade. The third phase (year 2035 to 2105) assumes consumption and foreign trade to remain same as in the previous phase. Service life of long living wood products lasts more than 100 years until a new steady state is reached, therefore, substitution
effects and the effects of carbon stock change in the Swedish forest product cycle are calculated up until 2105 (Paper III).

Paper IV assumes that the initial state of existing forest is an unmanaged natural heterogeneous forest before starting management programs. Two silvicultural systems (clear-cut forestry and continuous-cover forestry) are assumed for the management of that unmanaged natural heterogeneous forest stand. For clear-cut forestry, the first clear-cut is made and plantation was carried out, which will reoccur after a fully stocked forest is clear-felled at the end of the 95 years. For continuous-cover forestry it starts with first removal (by selective cutting), which will go through a long term selective cutting program. The selective cutting is carried out every 10 years. It is assumed that the average growth of the initial stand was 5.61 m$^3$ ha$^{-1}$ year$^{-1}$, the average standing volume is 150 m$^3$ ha$^{-1}$ and the initial basal area is 20 m$^2$ ha$^{-1}$. The forest stand is assumed to grow in two different management systems: continuous-cover forest and clear-cut forest. Continuous-cover forest is assumed to have two growth levels, 5.61 m$^3$ ha$^{-1}$ year$^{-1}$ (CCF80) and 7.01 m$^3$ ha$^{-1}$ year$^{-1}$ (CCF100), and clear-cut forest 7.01 m$^3$ ha$^{-1}$ year$^{-1}$.

Continuous-cover forest assumes to harvest stem-wood biomass only. It is because the principle of continuous-cover forestry is to keep forest ecosystem undisturbed in a semi-natural condition, and due to practical difficulties of recovering residues and stumps. Clear-cut forestry is analysed under two different harvest intensities: stem-wood only (CF), and stem-wood and residues and stumps harvest (CF+) (Paper IV).

This thesis uses different units for measuring forest biomass. In general, cubic meter of wood is expressed as green volume of wood including bark; cubic meter of biomass is expressed as green volume of biomass; dry biomass is expressed as a dry weight, which is about half of the green weight of biomass, considering 49 – 50% moisture content in the green weight. Carbon values are expressed as 50% of dry biomass and CO$_2$-eqv values are calculated by multiplying carbon values by 44/12.
4. Forest production, forest biomass pools and harvest

Forest biomass production and harvest are of fundamental significance for the study of carbon balance implications of future forest management scenarios. Forest management scenarios favouring production forestry (Papers I, II, and III), increasing set-aside area to favour environmental protection (Paper II), and favouring to develop continuous-cover forestry (Paper IV), are discussed to compare carbon balances for the next 100 years. The forest management scenarios in this thesis assume to provide products regularly, generation and after generation, thus explaining the renewability of the products. Biomass production in the thesis is related to sustained-yield of biomass, which is fairly a foundation of sustainable forest management (Adamowicz and Burton, 2003).

This chapter provides information on different models and assessments used for the estimation of biomass production and harvest. In addition, assessments on litter and soil carbon stock changes are presented. Finally, summaries of results from different appended studies on biomass production, harvest, changes in forest standing biomass carbon stock, and changes in litter and soil carbon stocks are presented and discussed.

4.1 Forest biomass production modelling with BIOMASS

A process-based growth model, BIOMASS, was used to estimate NPP. BIOMASS is a simple, dynamic, process-based model that considers tree canopy as a homogenous entity for all species (McMurtrie and Landsberg, 1992). It consists of two sub-models, a canopy photosynthesis model and water balance model, and a series of equations based on established theories of physiological plant processes and soil-water dynamics (McMurtrie et al., 1990). A canopy photosynthesis sub-model uses solar radiation interception and estimates photosynthesis based on leaf area index while water balance sub model estimates soil water content in the root zone of plants (McMurtrie et al., 1989).

The data input required for BIOMASS are canopy characteristics, foliage photosynthetic characteristics, and daily meteorological conditions, such as maximum and minimum air temperature, total incoming daily shortwave radiation, humidity and total rainfall. Other canopy characteristics inputs, such as initial foliage mass, leaf area index, specific leaf area, were also needed. Site specific data required were latitude, longitude, stocking, rooting depth, soil type, and physiological characteristics and parameters for tree species (species, diameter
and height). The model required an input of the foliage’s photosynthesis characteristics and maximum photosynthetic rate and stomatal conductance that calculates daily evapotranspiration from the stand. The data output of BIOMASS model is NPP. The calculation of carbon accumulation in foliage, branches, stems, bark, and roots, including below-ground components, are included to obtain NPP.

A detailed description of the BIOMASS model for canopy photosynthesis and water balance was given by McMurtrie et al. (1990) and McMurtrie and Landsberg (1992). BIOMASS uses climatic data from the SRES B2 scenario. These climatic data were taken from transient simulations of 1961–2100 with reference to 1961–1990 climatic data. The simulations were performed for a 30-year cycle to determine the effects of a temperature change on NPP increment at the end of this century, which was found to be 21.6%, 11.0%, and 13.0% greater for Norway spruce, Scots pine, and Silver birch, respectively compared to unchanged climate (Bergh et al., 2010). This NPP increment data from BIOMASS simulations was implemented in the HUGIN model where forest growth function was adjusted at a county level (Papers I and II).

4.2 Forest biomass growth modelling with HUGIN
HUGIN is a model system for long-term projections of timber yields and potential harvest levels that is used for planning at a regional level and for strategic planning for large forestry companies. The model uses data from sample plots from the Swedish NFI to define initial forest conditions. HUGIN describes all stages in plant development from stand establishment through treatments, thinning, and final fellings. The parameters used in HUGIN are validated for Swedish forests, thus the growth simulators can be used for all types of stands in Swedish forest landscapes, and within a wide range of management practices. Details on stand establishment, treatments, thinnings, and final fellings are given in an appended paper (Section 2.4.2, Paper I), and further details are provided by Lundström and Söderberg (1996). HUGIN was used in Papers I, II and III, while ‘Heureka’ was used in Paper IV to model forest growth.

4.3 Forest biomass growth modelling with Heureka
The Heureka model system is used for stand development of clear-cut forestry while comparing to continuous-cover forestry (Paper IV). Heureka is a model system for long-term planning and decision-making at a stand level or at a regional level. The Heureka system has been described in detail in Elfving (2010) and
Wikström et al. (2011) with the procedures used for growth modelling. The system requires input data comprising information on one or more sample plots and all of the relevant factors affecting them. Variables describing the site (latitude, altitude, site index, vegetation type), the stand (stand age, number of stems) and the individual trees (species, diameter and height) are input into the simulator. The system has two growth phases, stand establishment and stand development, to describe the forest stand. The height growth in the stand establishment phase was estimated using functions developed by Elfving (1982). The height-diameter relationship in the establishment phase is described according to Nyström and Söderberg (1987) to calculate tree diameters. Estimates of mortality and damage in the young forest were based on functions developed by Näslund (1986). Basal area growth was calculated at both the tree-level, using functions for single trees, and for the whole stand using a stand-level function (Elfving, 2010). In the combined model, the latter function was used to calibrate the growth level, while the individual tree functions are used to model how the overall growth is distributed between the various trees present. Diameter-height relationships by Söderberg (1992) were used for estimation of heights of individual trees. The mortality was predicted with functions presented by Bengtsson (1978), and functions by Fridman and Ståhl (2001) was used to distribute the mortality along the dimension distribution.

Field data from a young stand of Norway spruce situated on a similar site as the plots used by Chrimes and Lundqvist (2004) was selected as input to Heureka. The stand had 2000 stem ha⁻¹, which corresponds to a typical planting in central Sweden. The simulated treatments also followed conventional forest management with current practices. Two thinnings from below with a thinning grade of 25–30 % of the basal area were carried out during the simulated stand development. Clear cutting was carried out at a total stand age of 95 years. The biomass of whole trees as well as fractions of trees (stem, branches, needles and roots) was calculated according to Marklund (1988).

4.4 Forest biomass growth modelling for continuous-cover forestry
Growth models developed by Lundqvist et al. (2007) and Chrimes and Lundqvist (2004) were used to simulate stand development in a theoretical continuous-cover forest stand. The growth models were based on data from six uneven-aged Norway spruce experimental plots situated in central Sweden (60°53’N, 14°25’E, 300 meters above sea level). The soil moisture was mesic and the field layer was
dominated by bilberry (*Vaccinium myrtillus* L.). The site index, defined as the dominant height at a total age of 100 years for a Norway spruce, was in average 24 m according to Hägglund and Lundmark (1981). Single-tree selection harvests had been applied on the plots and initially the diameter distribution resembled a reverse-J shaped curve on most of the plots. Only trees with a diameter at breast height greater than 8.5 cm were used for the development of the models. The diameter distribution was divided into 2 cm classes, and the tree-wise basal area growth within each class was estimated as a function of diameter, total basal area and basal area of overtopping trees. Functions to estimate mean height and form height for each diameter class was developed. The same mortality rate was assumed as that of clear-cut forestry.

### 4.5 Litter decomposition and soil carbon modelling

The soil carbon stock changes due to different forest management practices, and removal strategies are based on the amount of organic carbon available in the SOM, litter fall from the standing biomass and below-ground carbon stock development, and biomass left in the forest after final harvest and thinning. A fraction of foliage, branches, and fine roots in a standing stand, and a fraction of biomass left at the site during thinning and final harvest contribute to litter and soil carbon stock development. The decomposition of the different litter fractions was calculated using the Q model, which incorporates the invasion rates of different litter types (Papers I and II) (Ågren and Bosatta, 1998; Hyvönen and Ågren, 2001). There is a detailed description of the Q model and soil carbon modelling in an appended paper (see Section 2.5, Paper I).

In Paper I, at first, the soil carbon stock change was calculated for the Reference scenario, then a shift in latitude as a proxy for warmer mean temperatures is used to calculate soil carbon stock in the Climate scenario in comparison to the Reference scenario. The increased average temperature of 4 °C corresponds to a shift of about 4 degrees of latitude towards the equator. Thus, the calculation assumes 58 – 59 °N latitude instead of the actual latitude of 62 – 63 °N. The parameters for temperature change were included in soil carbon modelling in Paper II. Litter decomposition equation was used for the comparison of litter carbon in clear-cut and continuous-cover forestry (Paper IV). The standing biomass and the annual turnover rates for needles and branches from the standing stand were estimated in Heureka (Paper IV). The mass loss function, used to calculate dry mass decomposition in the forest floor, was based on a
negative exponential approach as described by Melin et al. (2009), with a constant
decomposition rate equal to the initial decomposition rate (see Table 2, Paper IV).

4.6 Results

4.6.1 Forest biomass production

Increasing forest biomass growth increases above and below ground carbon stock
following the greater amount of carbon uptake and litter fall in the forest stands
(Häkkinen et al., 2011). The annual biomass production in the Climate scenario was
calculated as the effect of a temperature increase by 4 °C by the end of the study
period and results were compared to the Reference scenario in Paper I (Figure 8).
The biomass production increase in the Climate scenario was 49% for whole-tree
biomass and 40% for stem-wood biomass compared to the base year 2010 (Paper I),
while the increase in the Reference scenario for whole-tree biomass and stem-wood
biomass were 17% and 8% respectively for the same period.

Figure 8 Annual biomass productions at the beginning and end of the study period for Reference and Climate scenarios.

The effect of climate change and intensive forestry practice (Paper II) resulted in
the annual biomass production in the Maximum and Production scenario for year
2109 being 75% and 53% greater compared to biomass production in the base year
2010 (Figure 9). The production increase in the Maximum and Production scenario
was 26% and 4% greater for whole-tree biomass compared to the Reference scenario
respectively (Paper II). The Environment scenario biomass production was 40%
greater compared to the base year 2010, though it appeared to be 9% smaller
compared to the production in the Reference scenario (Figure 9).
The forest biomass production in the Maximum scenario has kept increasing at a higher rate compared to the Reference scenario throughout the study period (see Figure 3, Paper II). It appears that the intensive forestry practices were largely stimulus for biomass increase in the Maximum scenario (see Figure 3, Paper II), while production in the Environment scenario was smaller than in the Reference scenario (see Figure 3, Paper II).

The current average annual forest productivity for Jämtland and Västernorrland is about 2.1 Mg (dry mass) ha$^{-1}$ year$^{-1}$ (Swedish Forest Agency, 2010). In this study, biomass production started at 2.09 Mg (dry mass) ha$^{-1}$ year$^{-1}$ in the year 2010 and reached up to 3.14 Mg (dry mass) ha$^{-1}$ year$^{-1}$ in 2109 due to the effects of climate change (Paper I). Biomass production was larger when the effects of climate change and intensive forestry practices were combined. The largest biomass productions at the end of the study period were 3.3 and 3.74 Mg (dry mass) ha$^{-1}$ year$^{-1}$ in the Production and Maximum scenarios, respectively (Paper II).

In the national level study, forest biomass production was higher in the Increased Growth scenario, where forest management considered intensive practices (Paper III). Forest biomass production in continuous-cover forestry has been a recent concern following the interest in semi-natural forest management. Model results for clear-cut and continuous-cover forestry are presented in Table 3 of Paper IV. As assumed, the reference production is 7.01 m$^3$ ha$^{-1}$ year$^{-1}$ in CF and CCF100 scenario (see Chapter 3.7). At the same time the lower production level in continuous-cover forestry is also assumed in the CCF80 scenario with 5.61 m$^3$ ha$^{-1}$ year$^{-1}$. In the past, a few studies have assessed that the production in continuous-cover forestry would be about 80% compared to that of the clear-cut forestry in
Swedish conditions (Andreassen and Øyen, 2002; Elfving, 2006). Other studies have reported different production levels in continuous-cover forestry such as 52–124% in northern and central Sweden (Lundqvist, 1989) and a 100% production level in the modelling results (Pukkala et al., 2012). In this study, biomass production in continuous-cover is assumed to be both lower (80%) and higher production (100%) compared to clear-cut forestry.

4.6.2 Forest biomass harvest
The harvest determines the amount of biomass to be recovered from the forest. The decision about harvest is also crucial because of the product’s role in the ecosystem. The potential amount of biomass harvested increased considerably with the effect of climate change on biomass production (Figure 5, Paper I). Harvested biomass increased significantly for the Production and the Maximum scenario, while it deceased slightly in the Environment scenario compared to the Reference scenario (Figure 10). Nonetheless, the harvest amounts for all scenarios were increasing over the study period for both whole-tree and stem-wood biomass (Table 1, Paper I and Table 3, Paper II).

![Figure 10](https://via.placeholder.com/150)

Figure 10 The biomass harvests for Reference, Environment, Production and Maximum scenarios (Paper II).
The biomass harvests in the *Baseline Increased Harvest* and *Increased Growth* scenarios were greater compared to the *Baseline scenario* (Paper III). In Paper IV, harvests in the CF+ scenario were greater, the obvious reason being recovering whole-tree biomass (Table 3, Paper IV). The stem-wood biomass recovery in CF was smaller than in CCF100. This was because of omission of last clear-cut in CF and regular selective cuttings in continuous-cover forestry. There was less biomass recovery in CCF80 compared to other scenarios (Paper IV).

### 4.6.3 Standing biomass carbon stock change

The standing biomass stock change is vital considering the future biomass production. The forest biomass growth, harvest and natural disturbances determine the standing biomass change. In Papers I and II, the changes were estimated in the HUGIN after the deduction of harvest, mortality, and disturbances from the total annual biomass production of the forest.

The standing biomass changes were positive in both the *Reference* and *Climate* scenario, but greater in the latter (Table 2, Paper I). Paper II shows that the standing biomass carbon stock changes were positive in all scenarios, but large in the *Maximum* and the *Environment* scenarios (Table 4, Paper II). The stock change for the *Maximum* and the *Environment* scenarios were 56% and 44%, respectively, compared to a 31% in the *Reference* scenario. The greater standing biomass in the *Maximum* scenario is because of increased production, while in the *Environment* scenario it was because of increased set-aside land (Figure 6, Paper II).

These results suggest that standing biomass in the production scenarios will keep increasing in the future. The standing biomass carbon stock change in clear-cut and continuous-cover forest will depend on production level providing a larger positive change with larger growth and *vice versa* (Paper IV). The larger average standing biomass might not necessarily increase the stock change in continuous-cover forest because of higher density and lower ingrowths. Thus, the structure and dynamics of a forest is very important in a continuous-cover system.

### 4.6.4 Litter decomposition and soil carbon

The amount of litter and soil carbon stock in a forest depends on organic matter input from above and below ground. It has been argued that the logging residues and stumps removals could influence soil carbon stock change in the forest. The results in this thesis show that increased biomass production (see Table 2, Paper I) increases soil carbon stock change (Table 3). Soil carbon stock changes were positive in all scenarios, but were greater in the production scenarios, presumably
due to the greater amounts of litter fall in high productive forests (Paper II). Removing slash and stumps causes the soil carbon to increase at a slower rate.

Table 3 Changes in average annual soil carbon stock during each 10-year period (Tg C year\(^{-1}\)) for Jämtland and Västernorrland.

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Paper III assumed that the soil carbon stock change rates in forest management scenarios (Baseline, Baseline Increased Harvest and Increased Growth) were the same despite the changes in silviculture. Paper III aimed to study forestry in a national perspective. Estimating soil carbon stock change in all forests of Sweden requires the inclusion of precise values for related parameters representing geographical distribution, the climate, the soil type and the forest management practices. This work would be too vague in Paper III, thus was beyond the scope of the paper. Instead, Paper III assumes that the soil carbon stock in managed forest has been steadily increasing over the years and will keep increasing at this rate in the future (Ågren et al., 2007). The soil carbon stock increase rate in managed forest landscape was assumed to be 4 g C m\(^{-2}\) year\(^{-1}\) (Paper III).

In Paper IV, soil carbon pool and the litter carbon turnover in the initial stand was assumed to be the same for all scenarios before the start of management. Thereafter, litter carbon turnover and decomposition are explained for all scenarios. The litter carbon development in both continuous-cover and clear-cut forests are presented in Figure 11 (Paper IV, Figure 2). Continuous-cover forestry had larger and positive litter carbon stock change than clear-cut forestry.
The estimated annual litter carbon change for CF+, CF, CCF100 and CCF80 scenarios were 0.01, 0.02, 0.05 and 0.04 Mg C ha\(^{-1}\) year\(^{-1}\) respectively. When residues and stumps were removed during final fellings, the litter carbon increase rates were smaller. The larger changes in CCF scenarios are mostly because of residues left during selection cutting while in CF, residues were left only in the thinnings but not in the final fellings.
5. Forest product use and carbon balance

Forest product use and its implications on carbon benefits were analysed using systematic methods. The spreadsheet model ‘SUBSTITUTION’ is used to estimate substitution carbon benefit as a result of biomass use in bioenergy production thus replacing fossil fuels, and wood use as construction materials thus replacing non-wood carbon-intensive materials (Papers I, II, and IV). A wood flow model is used for Swedish forest industry based on wood use trends in a Swedish consumer product cycle (Paper III). This chapter describes the calculation methods for the use of forest biomass in bioenergy production, pulp and paper production and wood use in buildings. A method for estimating the total carbon balance of the whole system is presented. At the end, the results for the substitution of fossil fuels and total carbon balance accounting are summarised and discussed.

5.1 Biomass use modelling with SUBSTITUTION

SUBSTITUTION is a simple spreadsheet model for estimating carbon emission avoidance as a result of forest biomass use for energy production and wood use as construction material in place of carbon-intensive materials. Forest biomass input were large-diameter stem-wood, small-diameter stem-wood, residues bark and stumps. The material substitution effects were based on a multi-story apartment building (Gustavsson et al., 2006b) (see Chapter 3.4). Large-diameter pine and spruce stem-wood were used for construction materials. Processing residues, small-diameter pine and spruce stem-wood, all deciduous stem-wood and residues from the forest are used for bioenergy as well. The wood materials in the buildings were assumed to be recovered and used as bioenergy at the end of building service life. All biofuels are assumed to substitute either coal or fossil gas in stationary plants with conversion efficiencies of 100% and 96% relative to the conversion efficiencies of the respective fossil fuel-fired plants (Gustavsson et al., 2006b).

5.2 Biomass use modelling with national wood flow model

The wood flow model for the Swedish forest industry is a model adapted for Sweden using an existing model for Switzerland. The wood flow model incorporates all relevant wood use in the Swedish consumer product cycle including the wood sector, building stocks, the paper cycle and the energy produced from forest biomass, wood residues and waste wood stocks, and exported and imported forest products. The product stocks are calculated by
means of dynamic modelling using different lifetimes of the products (Paper III, Table 3). The model calculates wood use starting in the year 1900. The consumption and foreign trade figures from 1900 to 2005 were taken from various statistical sources (Paper III, Table 3). The changes in wood use were assumed to occur between 2005 and 2035 and remain constant thereafter to allow various components of the model to approach a steady state. The steady state is considered because of the long lifetime of many wood products and the long response time in the forest ecosystem in relation to biomass growth and yield. In order to see the long-term effects of current or future wood use, the stock developments are considered over a period of 100 years. The input flows include industrial round wood, fuel wood including residues and stumps, imports by the timber industries including all types of forest products, imports of pulp, recovered paper for paper production, and paper imports for final consumption. The output flows includes the export by the timber industries, export of pulp and paper, export of lignin residues, and paper export.

The material flow in the wood flow model is fed into the software SIMBOX (Taverna et al., 2007). SIMBOX estimates carbon stock changes in wood products based on wood flows (Taverna et al., 2007) and includes carbon flows entering a pool and carbon flows leaving that pool in the same year. The total carbon stock changes in Sweden are estimated by summing up the carbon stock change in buildings, carbon stock change in other wood products (e.g. furniture), and carbon stock change in the pulp and paper cycle. The carbon stock changes within and outside Sweden due to foreign trade are also estimated. The global effects are calculated as the sum of the effects within the country and abroad.

The GHG emission effects due to material substitution on a building element is based on functionality aspects of the buildings and carbon emissions related to final processing ancillary materials and the associated impacts from their transportation, mounting, maintenance and demolition. Substitution effects as a result of the pulp and paper cycle is based on energy recovery and its use to substitute fossil fuels. The GHG emission for the production and processing of all wood and non-wood products is calculated in SimaPro software based on the database Ecoinvent 2.0 using the life cycle assessment method ISO 14040/ISO 14044 (ISO, 1997b, a). Hence, carbon emission for all associated processes such as raw material extraction, production, use, maintenance and disposal of a product are accounted.

The pulp and paper cycle is included when calculating substitution effects and emission (Paper III). The two most important pulp types, mechanical and
chemical, are classified for the analysis. Furthermore, three different types of paper from each fresh fibre (newsprint, wood-free coated, corrugated board) and recycled fibres (with deinking, without deinking, cardboard) are classified. Export of pulp, paper and recovered paper included in substitution effects following the exported products substitute the production of respective pulp types abroad. Similarly, imports of pulp and paper lead to a reduced domestic production. It is assumed that energy lignin (from pulp production), black liquor as well as the waste fibre fraction from the processing of recovered paper are entirely used within the pulp and paper industry. A process resulting in (external) energy substitution effects is the incineration of waste paper. Abroad, no additional substitution effect is assumed due to the use of pulp and paper originating from Sweden for energy purposes. It is assumed that the net consumption of pulp and paper abroad does not change due to different import/export scenarios for Sweden. Bioenergy production in Paper III includes the use of forest residue and processing residue for the generation of heat and power. The overall efficiency of a combined heat and power plant is 75% of the net calorific value of the wood input. The energy produced was classified as 75% heat and 25% electricity. The heat energy replaced the average marginal mix of fossil fuels used for the thermal energy generation in Sweden and the electricity replaced marginal electricity.

5.3 Carbon balance accounting
In this thesis, carbon balance is defined as the reduced net carbon emission into the atmosphere due to forest biomass production and their uses. As used in the appended papers, a positive carbon balance has a net climate benefit, i.e. net removal of CO\textsubscript{2} from the atmosphere (Papers I, II and IV). A negative carbon balance has a net climate impact, i.e. net emission of CO\textsubscript{2} to the atmosphere (Paper III). The activities included in the system analysis (see Chapter 3.5) are categorised so as to represent either carbon emission reductions or carbon emission. The carbon emission reductions are expressed as a total change as a result of changes in standing biomass carbon stock, changes in forest soil carbon stock, changes in wood product carbon stocks in buildings, changes in carbon stock because of the pulp and paper production cycle, substitution carbon benefits achieved due to the replacement of fossil fuels by recovered forest biofuels and wood processing residues, and substitution carbon benefits due to the avoidance of non-wood material production and process emissions. Avoided emissions from production of non-wood materials are included in the calculation of substitution carbon benefits.
The parameters included for material production and process emission include fossil-fuel-cycle carbon emission, end-use fossil fuel carbon emission, emission due to end-use electricity to extract, process, and transport of material, the pulp and paper production cycle, and emission from industrial process reactions.

The total carbon balance is calculated as:

$$CB = \sum [\Delta C_{sb} + \Delta C_{fs} + \Delta C_{wp} + \Delta C_{ppp} + \Delta C_{scb} - (C_f + C_f)]$$

where

- $\Delta C_{sb}$ is the change in standing forest biomass carbon stock;
- $\Delta C_{fs}$ is the change in forest soil carbon stock;
- $\Delta C_{wp}$ is the change in carbon stock in wood products;
- $\Delta C_{ppp}$ is the change in carbon stock as a result of the pulp and paper cycle;
- $\Delta C_{scb}$ is the substitution carbon benefits due to the replacing of fossil fuels with recovered biofuel and avoidance of material production and process emission due to use of wood materials;
- $C_f$ is the carbon emission due to forestry operation activities;
- $C_f$ is the equivalent carbon emission due to fertilisation in the forest.

5.4 Results

5.4.1 Substitution of fossil fuels and carbon-intensive materials

The average annual carbon emission reduction in the Climate scenario was larger compared to the Reference scenario (Paper I, Table 2). The climate change effect on biomass production increased average annual carbon emission reduction (substitution effect) by 14% compared to the Reference scenario when using coal as a reference fuel in the whole-tree use alternative (Paper I). The larger biomass harvested in the Production and Maximum scenarios provided larger carbon emission reduction (Paper II). The carbon benefit for Production and Maximum scenarios were 8% and 12% larger respectively compared to the Reference scenario in Paper II (Figure 12). The carbon emission reduction in the Environment scenario was 7% smaller compared to the Reference scenario.
Substitution carbon benefits were larger with clear-cut forestry with whole-tree use (CF+) and provided a 2.24 Mg C ha\(^{-1}\) year\(^{-1}\) carbon emission reduction. CF, CCF100 and CCF80 scenarios provided a 1.74, 1.88 and 1.68 Mg C ha\(^{-1}\) year\(^{-1}\) substitution benefit respectively. The larger benefit in CCF100 compared to CF is because of a larger amount of stem-wood harvest and use to replace construction materials. This result suggests that forest biomass production and use strategy are major factors in increasing carbon emission reduction because the substitution effect depends on the amount of biomass to be used and types of materials to be substituted. In this thesis, various forest management and biomass use scenarios (see Chapter 3.7) provided varying substitution carbon benefits. The higher values were obtained, when the products were used for construction materials, while the lower values were obtained when pulp and paper production was included (Paper III). The resulting substitution factors ranged from 0.47 to 1.13 Mg CO\(_2\)-eqv for the use of one m\(^3\) of green biomass. The largest factor obtained with only stem-wood use was in the Maximum scenario (Paper II) and the smallest factor, with stem-wood plus 15% residues, use was in the Baseline scenario (Paper III). In clear terms,
the largest factor is the largest potential that can be achieved and the lowest factor is a near-real value that can be achieved with current forest management and product use strategies.

In a scenario where there is no increased demand for biomass for pulp and paper production, a question could be whether all wood materials produced in Sweden can be used in building construction or to replace fossil fuels in the future. Jonsson (2009) claimed that the number of multi-storey wood frame houses may be increasing in the future following the implementation of national timber construction strategy in the year 2004, which aims to increase the use of wood in construction. But, at this point it is not clear how much wood could be used in buildings in the near future. An international trade of woody biofuels could be an alternative strategy, which is feasible and can efficiently be done for long-distances with little loss of net energy (Junginger et al., 2008; Gustavsson et al., 2011).

5.4.2 Wood product carbon stock
Harvested wood products are used as material in the structure store carbon until it is demolished. Wood product carbon stock is one of the major components of total carbon balance analysis in all appended papers. The wood product carbon stock changes were positive for all scenarios. The changes were larger for the scenarios with intensive forestry practices, larger harvest and use compared to scenarios with conventional forestry and product use strategies (Papers I and II). The longer the life time of products, the more delay will occur in carbon emission, thus a product use in long-lasting construction work can help delaying emission. Hence, the product carbon stock depends on different lifetime of the products according to their use in the consumer product cycle (see Table 3, Paper III). Wood product carbon stocks in the stand level study were relatively small compared to landscape level studies (Paper IV). In stand based analysis, carbon stock change in wood products will be the same after certain period of time considering the lifetime of building, its demolition and use of products as bioenergy.

5.4.3 Carbon balance
The potential carbon balance of a forest management system depends on the carbon flows into and out of the system. In landscape-based analysis carbon balance can be accounted simply as the carbon stock changes in the different component of the systems. The net carbon balance estimation in a stand based analysis (for a clear-cut system), however, should treat the final harvest as carbon loss. It is because the biomass will transfer into the litters and products, which is
accounted accordingly in the litter carbon and substitution carbon benefits. The cumulative avoided carbon emission for the *Reference* and the *Climate* scenarios over 100 years are presented in Figure 7, Paper I. The carbon emission difference between the *Reference* and the *Climate* scenario (Paper I) appeared to be greater with whole-tree use and coal fuel substitution, largely due to higher biomass production, harvest and use (Figure 13).

The *Environment* scenario, which has a smaller amount of forest biomass harvest compared to other scenarios, had to a lesser extent avoided carbon emission (Paper II). Figure 14 shows the differences in cumulative carbon emission reduction between the *Reference* scenario and the *Environment*, *Production*, and *Maximum* scenarios for whole-tree biomass use (left) and for stem-wood biomass use (right) with coal and fossil gas as reference fuels (Figure 8, Paper II). The largest difference is observed when the *Maximum* scenario deducted the *Reference* scenario for both whole-tree and stem-wood biomass use. A greater amount of carbon emission was reduced when coal was the reference fuel than when fossil gas was the reference fuel.

![Figure 13 Differences in cumulative total carbon balance (Tg C) between the *Climate* and *Reference* scenarios (Paper I).](image)

![Cumulative differences: Climate change and Reference](image)
The total carbon emission reduction for the whole of Sweden with different forest management scenarios are explained in Paper III. Figure 15 presents all carbon emission reduction effects for the whole of Sweden (Figure 3, Paper III).

Figure 15 The CO₂ reduction effect in the *Baseline* scenario, in-country (a), abroad (b) and global (c), as an effect of Swedish forestry.

The total emission reduction for the *Baseline* scenario within Sweden was estimated to 14 Tg CO₂-eqv year⁻¹ at the end of the study period. The CO₂ reduction effect was
greater abroad, where it reached 46 Tg CO$_2$-eqv year$^{-1}$. In a global perspective, the present Swedish forestry model results in reduced CO$_2$ emission in the order of 60 Tg CO$_2$-eqv year$^{-1}$ according to the assumptions made in this analysis.

The peak in 2005 was caused by a major storm-felling, which resulted in significant biomass loss and was a source of CO$_2$ (Figure 15). It is also noteworthy that the material substitution effects from pulp and paper were net emission because it was assumed that there were no real substitute for pulp and paper. The in-country and abroad, and global effects of the CO$_2$ balance of the three studied forest management scenarios (Baseline, Baseline Increased Harvest and Increased Growth) are presented in Figure 16 (Figure 4, Paper III). The total emission reduction at the end of the study period for Baseline Increased Harvest and Increased Growth scenario were 66 Tg CO$_2$-eqv year$^{-1}$ and 103 Tg CO$_2$-eqv year$^{-1}$ respectively compared to Baseline scenario of 60 Tg CO$_2$-eqv year$^{-1}$. The results showed that a 50% increase in forest growth in Sweden and utilization of forest residues can reduce the total CO$_2$ emission by an additional 43 Tg CO$_2$-eqv year$^{-1}$.

Figure 16 The overall CO$_2$ emission reduction effect for in-country (a), abroad (b) and global (c) for different scenarios; Baseline (solid line), Baseline Increased Harvest (dotted) and Increased Growth (dashed).
In Paper IV the total carbon balance for two different forest management systems, clear-cut and continuous-cover forestry, are compared (Figure 17a and b). It appeared that the cumulative total carbon balance since the beginning of the management program to the end of the study period for CF+, CF, CCF100 and CCF80 were estimated to 784, 642, 597 and 531 Mg C ha⁻¹. With these estimations, the average net annual carbon balance for CF+, CF, CCF100 and CCF80 would be 2.75, 2.25, 2.06 and 1.83 Mg C ha⁻¹. The results showed that the average net annual carbon balance in CF+ were 34 and 50% larger compared to CCF100 and CCF80 whereas, CF results were 9 and 23% larger compared to CCF100 and CCF80 respectively. In stand based analysis, the net annual carbon balance was calculated in a dynamic analysis including cutting and removal of biomass in the intermediate and final fellings. The results showed that the difference in ecosystem carbon stock change in two forest management systems was not significant. But the substitution benefits were major contributor for total carbon balance.
Figure 17 Cumulative total carbon balance in (a) CF and (b) CCF100 scenarios over 285 years (three rotation periods in CF and 290 years in CCF).

As discussed earlier, the substitution factor is the key for obtaining carbon benefit of a forest management system. In Paper IV, carbon balances were compared for higher potential (when coal reference fuel was substituted), with lower potential (the carbon balance when substitution level was 0.47 Mg CO$_2$-eqv for one cubic meter of green biomass use) (see Section 2.4, Paper IV). The latter value is considered to be a lower carbon benefit compared to the higher potential substitution level. The average annual net carbon balance for all scenarios was
highly sensitive to the lower substitution effect level and provided total carbon benefits of 1.81, 1.29, 1.02, and 0.91 Mg ha$^{-1}$ for CF+, CF, CCF100 and CCF80 scenarios respectively. These values were 52, 75, 101 and 102% smaller for CF+, CF, CCF100 and CCF80 scenarios respectively compared to higher substitution effect (Figure 18). Since stem-wood has the potential to replace highly carbon-intensive products, larger amounts of stem-wood production and use can provide an even larger net carbon balance. The net annual carbon balance, achieved with a greater substitution level, is the potentially higher climate benefit, while the benefit can be as low as it is with lower substitution level; hence oscillates within the range of lower and higher values (Figure 18).

Figure 18 Total carbon balance over time in (a) clear-cut forestry and in (b) continuous-cover forestry with different substitution levels.
The results in this study clearly showed that if forest products are used for different purposes (not specific purpose such as in Papers I and II) but in a general consumer’s product cycle, the substitution value and the total carbon balance could be small (Paper III). This result highlights the importance of a forest management system, biomass production level, biomass harvest level, and the substitution factor as key factors for obtaining large carbon benefits. A clear-cut system appeared to be a slightly better option compared to a continuous-cover system even when the production levels in both systems were the same. But, it should be noted that the initial harvest level in a clear-cut system was larger. In a long-run temporal dynamic system, the carbon benefits in continuous-cover and clear-cut forestry may well depend on substitution levels while considering very small differences in the stock changes in living biomass, litter carbon and product carbon in both systems.

The higher substitutability of forest products underlines the value of the forest’s climate benefit. Substituting concrete and coal is promising for climate benefits, however, the use of forest products in pulp and paper production and lack of consistency in residues harvest may well reduce the carbon benefit that could go as low as shown in Figure 18. In the future, the climate benefit value may vary from 0.91 Mg C ha⁻¹ year⁻¹ in CCF80 to 2.75 Mg C ha⁻¹ year⁻¹ in CF+. The variation shown in Figure 18, can serve as a policy guide in selecting different forest management and product utilization alternatives while aiming for climate change mitigation through carbon emission reduction.

Thus, the marginality of total carbon balance of a forest stand will be similar to that in Figure 18, where a decision-maker can choose either a clear-cut system or a continuous-cover system to achieve a carbon balance that distributes from a lower to a higher level depending on production level, harvest level and substitution level. In general, potential use of forest products for different purposes in the stand based analysis may not be representative considering the smaller amount of product harvest and use. However, these stands are part of a landscape, thus the carbon balance results in this study represent a unit of a forest landscape. If it is assumed that a forest landscape has as many units of CF+, CF, CCF100 and CCF80 stands as their rotation period, then the total annual carbon balance of a landscape will be equivalent to the cumulative total carbon balance for a rotation period of a forest stand.
6. Discussion and challenges for implementation

One of the objectives of this thesis was to explore the implications of different types of forest biomass production strategies to reduce carbon emissions. Results in this study have shown that the steps for accumulating a large amount of carbon emission reduction would be to increase biomass production, harvest and product use. Swedish forest policy aims at a sustainable timber production in managed forest landscape, while at the same time giving the environmental goals such as biodiversity conservation, public recreational needs, and protection of waters and soils an equal importance. With an intensive forestry practice the potential for Swedish forest biomass production is high. However, a number of trade-offs can impede implementing such intensive forestry programmes.

The goal of biodiversity often conflicts with the goal of production forestry. Inclusion of provisions for the protection of waters and soils would compel decision-makers to think about the precautionous actions before, during and after the mechanical work in the forest. Thus, addressing challenges of managing forest for mitigating climate change requires a comprehensive planning process. It is clearly a challenge for decision-makers to tackle issues related to forest management, harvest, and product use systems.

6.1 Trade-offs

The most important forest-based strategy to reduce long-term carbon emission is to use biomass to substitute fossil fuels and carbon-intensive materials. Harvest of stem-wood, harvest residues, and stumps and roots would increase the potential of substitution benefit and so the total carbon emission reduction. However, an alternative is to increase biomass stock in the forest by leaving a forest uncut or less-cut and leave all harvest residues in the forest. If we continuously increase biomass stock in the forest without harvest, the biomass will accumulate in the trees until a part of the tree or the whole tree dies. This alternative is likely to be very beneficial in a short-term perspective, however, a standing forest will risk a higher rate of mortality if the stand is dense. Harvest residues left in the forest would also decompose during respiration and release back carbon into the atmosphere in the long run. Furthermore, the natural disturbances release carbon into the atmosphere (Kurz et al., 2008c).
The significance of utilizing forest biomass to reduce carbon emission also depends on the fossil fuel substituted. Melin et al. (2010) suggested that if a stump is harvested and used in a power plant and substitutes coal reference fuel then it will have larger carbon benefit, than it would have had being left in the forest for a long period of time. However, decision-makers have to make sure that the carbon emitted during the bioenergy production would be sequestrated as soon as possible. If a forest landscape is managed in such a way, that at least a similar amount of forest area is harvested and planted every year, it will compensate and regulate the emission and sequestration. The use of forest products as bioenergy, can be regarded as an opportunity considering the use of biomass in pulp and paper production.

The Swedish target is to reduce GHG emission by 40% by the year 2020 compared to the 1990 level, and to envision a zero net emission of GHG into the atmosphere by 2050. This target might impose an increased demand on forest products in Sweden and thus interests in producing large amounts of biomass in Swedish forests. However, it is the forest owners who make the decisions. A study has shown that the majority of private forest owners are against exotic species, while their desire remains to increase forest growth (Hemström et al., 2013). Another study found that the motive of Swedish society on intensive forestry practice varies and the resistance to such practice largely seems to remain in favour of novel land use and novel tree species (Lindkvist et al., 2012).

6.2 Factors influencing carbon balance
Biomass production in different forest management system urges some changes in land use. The forest management scenarios in this thesis assume different land use options such as traditional practice (Paper I, III), preferred environmental care (doubling set-aside area of production forest compared to today, Paper II), intensive forestry practice (Paper II), increased production (Paper III), and continuous-cover forestry (Paper IV). The differences in land use practice would also affect the carbon balance of the existing forest.

Carbon balance of a forest management system might also depend on spatial and temporal differences. Papers I and II are based on landscape level analysis, and Paper III focuses on the entire country. Paper IV explains carbon balance on a stand level forest management with two different forest management systems. Forest management is a very time-consuming practice and thus it takes time to see the effects in the ecosystem and in the economy. This thesis considers a period of
time of about 60-300 years, and similar land use practices are assumed to be continued for successive rotation periods in all Papers. Any changes in the spatial boundaries and temporal variation could result in different carbon balances of the system.

In this thesis, carbon balance results depend on the availability of biomass to be used for building construction materials, pulp and paper production and energy production. The amount of biomass production and harvest depend on silviculture, policy goals and forest land owners. Substitution carbon benefit depends on non-renewable materials that are substituted by the use of forest biomass. The amount of harvest and export of materials in one country could pose an indirect land use change in another country. Although this thesis has not included such an analysis, it cannot be denied that such indirect land use change occur as a result of Swedish forestry.

It has been argued that conserving large stocks of boreal forest biomass will safeguard a major global carbon sink (Angelstam and Andersson, 2001; Keith et al., 2009). The studies in this thesis compared 4% setting aside area to 8% setting aside area of production forest (Paper II) to examine the effect on total carbon balance. The result showed that the ecosystem carbon stock was larger in the 8% setting aside scenario, but total carbon benefit was larger in the 4% setting aside scenario (Paper II). This result gives rise to yet another question: How would an increased conservation area affect the ecosystem carbon stock and the total carbon balance?

In a study by Poudel et al. (2014), a forest management strategy was assumed to manage only 80% and 50% of production forest area and the remaining 20% and 50% were set aside for the conservation purposes. The preliminary results in Poudel et al. (2014) showed that withdrawing management activities in the current forest stand would increase the ecosystem carbon stock in the near future (Figure 19). This result is in line with other studies that claim the occurrence of larger ecosystem carbon stock in conservation forests compared to the managed forests (Keith et al., 2009; Hoover et al., 2012). When the net carbon balance change was calculated for the 20% and 50% setting aside scenarios with lower substitution level (i.e. 0.47 Mg CO₂-eqv per cubic meter of biomass), the net change was a large sink in the beginning but became a carbon source after 100 years (Figure 19a). When a larger substitution value (0.72 Mg CO₂-eqv per cubic meter of biomass) was considered, the carbon balance change became a source after just 75 years (Figure 19b). It shows that the carbon balance still depends on the substitution level. It means that if the foregone substitution level in the conservation scenarios was small, then conserving forest is better for carbon stock, at least for short period
of time. If the forgone substitution level was large, then the potential carbon benefit in the conservation scenarios would be smaller and the conservation scenarios will become a carbon source after a certain period of time.

Figure 19 The total carbon balance with 20% and 50% set-aside area for conservation in Sweden. (a) 0.47 Mg CO$_2$-eqv per cubic meter of biomass (b) 0.72 Mg CO$_2$-eqv per cubic meter of biomass.

This claim draws the attention to whether we can afford to lose the whole Swedish total carbon benefit from the forestry sector after 75 years. In addition, setting aside larger forest land would considerably reduce Swedish forest product export and increase import (Poudel et al., 2014). This will eventually affect a policy to increase GHG emission reduction, while at the same time maintaining economic benefit from the forestry sector. It is uncertain, if any disturbances will occur in the forests in the future and thus, if it would cost a large amount of stored carbon in the forest (Kurz et al., 2008b; Lindner et al., 2010).

6.3 Carbon balance and climate change mitigation

The overall carbon balance depends on the intensity of biomass production, what reference system is selected for biomass utilisation, which reference fuel and materials are substituted and compared. In Sweden, forest residue is mainly used within the forest industry to process heat, for district heating, and in the residential sector. District heating plants used forest biofuels for the production of 20 TWh of energy out of the total 36 TWh of energy supplied by bioenergy in 2006 (Swedish Energy Agency, 2009). The share of biofuel used in total energy production in Sweden increased from 10% in 1980 to 22% in 2009, and an increase is expected in the future due to higher demands for biofuels in heating systems (Swedish Energy Agency, 2010). The increasing use of wood as a construction material is an important option to reduce net CO$_2$ emission because of low energy requirements
for processing, potential to increase wood product stock in the buildings, and increased availability of biofuel as by-products (Gustavsson and Sathre, 2006).

The calculated carbon emission reductions in the Production scenarios are large enough to contribute to the carbon emission reduction target in Sweden. In the year 2011, the total amount of CO₂ emission in Sweden was 61 Tg (Swedish Energy Agency, 2010). Based on the calculations performed in this study, forest management in the counties of Jämtland and Västernorrland, based on the Maximum scenario, would reduce annual average CO₂ emission corresponding to 14% and 11% of Sweden’s total carbon emission in 2011, if the biomass is used to replace coal fuel and fossil gas fuel respectively (Paper II). The CO₂ emission reduction due to forest management based on the Production scenario corresponds to a 13% and 10% reduction of Sweden’s total carbon emission in 2011, if the biomass is used to replace coal and fossil gas respectively (Paper II). The net carbon balance in clear-cut forestry was larger compared to continuous-cover forestry (Paper IV). However, if the biomass growth in continuous-cover forestry was smaller than in clear-cut forestry, the net total carbon balance will be large in clear-cut forestry. The result of Paper III suggested that a 50% increase in forest growth and higher utilization of forest residues can reduce the total CO₂-emission by an additional 43 Tg CO₂-eqv year⁻¹ (from 60 to 103 Tg CO₂-eqv year⁻¹).

6.4 Modelling limitations

It is important to remember that the models used in this thesis are simplified representations of complex processes, and do not include all aspects of the Swedish forestry system. The results obtained must be interpreted with care, since most of the results would imply only the ideal conditions assumed in this study. The process-based model BIOMASS was originally developed based on Pinus radiata forest growth. However, the model has been used in Swedish studies in the past with adaptive calibrations in the parameters. BIOMASS does not include feedback of soil nutrient dynamics to the canopy development (Bergh et al., 1998). This could be a limitation, since in a long-term study there could be a change in soil nutrient, and its effect on photosynthetic carbon assimilation could differ. The HUGIN system does not have functions for trees older than 100 years. It limits the scope of old tree growth but calculates the biomass of old trees similar to nearly 100 years old trees. This could overestimate biomass carbon in old tree stands. Furthermore, HUGIN’s functions are limited in the calculation of regular tree mortality. It does not estimate or project any kind of mass mortality (e.g. wind
The stump biomass might have been overestimated because the HUGIN model uses spruce stumps as a proxy for the calculation of deciduous and pine tree stumps. Furthermore, because of little demand in the past, forest management practices in the past did not consider promoting deciduous trees. But today, the number of deciduous trees in forests has increased, which might result in an overestimation of deciduous tree biomass production. It could also be because the model considers deciduous trees to live longer than coniferous trees, so the model could have considered larger deciduous tree sizes compared to coniferous trees.

Mortality in clear-cut and continuous-cover forest is assumed to be similar, but in reality they could differ (Paper IV). The Q model uses certain invasion rates for litter decomposition; this could differ depending on the climate. The substitution model uses a reference building to describe wood material use in buildings (see Chapter 3.4). It may not be an ideal building to estimate substitution carbon benefit in the future. There could be differences in carbon emission reduction values, if other reference buildings were considered in the study. The wood flow model uses historical data from the Swedish forest product use cycle. This model assumes three phases in wood use: the current carbon stock phase (1900–2005), the carbon stock change phase (2005–2035), and the consumption and foreign trade steady phase (2035–2105). Any changes in the carbon stock change rate after 2035 would have affected the results (Paper III). Furthermore, a wood flow model for the Swedish forest industry was developed through the adaptation of an existing model for Switzerland (Paper III) and fed into the software SIMBOX. Although the factors were adapted to Swedish conditions, any changes that do not correspond to the Swedish system might have affected the results. SIMBOX uses total country population as reference for forest product demand change in the future (Taverna et al., 2007). The population change rate projected today may not correspond to the rate in the future, which would influence the results.

6.5 Uncertainties

The integrated analysis method used in this thesis contains inherent uncertainties because of the large number of factors to be considered and assumptions to be made. One of the basic assumptions of this study was the temperature change due to the climate change effect. As discussed by the IPCC, climate change and subsequent temperature changes may depend on changes in global population, energy demand, and climate change mitigation activities that are implemented. This thesis uses the SRES B2 scenario of climate change, which assumes an increase
of temperature by 4 °C, but the actual temperature increase in the future is uncertain. The sources of uncertainties related to environmental factors controlling the forest productivity could be such as differences in solar radiation values, precipitation and soil water availability, plant numbers and their competition in the forest stand, the photosynthetic performance of a single plant/tree, age and the health of trees. According to previous studies an elevated temperature may encourage an earlier onset of bud-burst in the spring and increase the risk of frost injury, which could affect the forest growth (Cannell and Smith, 1986; Hänninen, 1991; Kramer, 1994; Krasowski et al., 1995).

The increased biomass production, as an effect of climate change, implies an increased demand for nutrients which must be met by increased mineralisation, nutrient availability, and uptake by roots; otherwise, the growth response will stagnate at a lower level (Bonan and Cleve, 1992; Houghton et al., 1998; McMurtrie et al., 2001). Any error in BIOMASS would be multiplied in HUGIN and in the other models as well (Papers I and II). BIOMASS, however, is a suitable model for predicting NPP as forest productivity in boreal and cold-temperate environments because low-temperature effects have been included, and the response to elevated temperature is predicted in in the model. HUGIN uses Swedish NFI data for harvest projections. Any error in NFI data would yield different values for the production and harvest of products. The Q model, used for soil carbon estimation uses slightly different forest growth functions than HUGIN, so the soil carbon numbers might be slightly different than they would have been if they were calculated with a function similar to that used by HUGIN. The substitution modelling is based on a case study of a multi-story building (Papers I, II and IV) and wood use in the Swedish consumer product cycle (Paper III). In General, climate benefits of wood substitution are quite robust (Sathre and O'Connor, 2010).

Climate change may result in increased wind damages, fire risk, pathogens, and insect outbreaks, which may affect forest growth, vitality and increase mortality (Battles et al., 2008; Kurz et al., 2008a; Blennow et al., 2010; Lindner et al., 2010). Such risks have not been considered in this study but could be substantial in Sweden. A Swedish governmental survey (SOU, 2007) noted these uncertainties and risks as possible threats to future forestry in Sweden. In Paper IV, biomass production in continuous-cover forestry is based on functions developed in an experimental plot. Because of unavailability of large-scale data on continuous-cover forestry, this study relies on the small-scale experiment and its results, which could differ with any other growth rate that may occur in continuous-cover forestry. Other uncertainties may include differences in physical properties of raw
materials such as round wood sizes, moisture content, specific heat values; processes of material production, such as harvest and transportation machine use, types of fossil fuel used, and the amount of wood to be utilised in the buildings.
7. Conclusions

This chapter summarises the conclusions of the studies for the carbon balance implications of forest biomass production. Future research is suggested in the following section.

7.1 Conclusions

Various forest management strategies have been studied to examine their implications on total carbon balance. It has been found that the future climate change effect and intensive forestry practice could considerably increase the forest biomass production in the counties of Jämtland and Västernorrland i.e. the north-central landscape of Sweden. Increased forest biomass production increases the potential harvest of biomass. Increase in biomass production will have a positive effect on the carbon stock change in standing biomass, forest soil, wood products and substitution carbon benefit, all contributing to reduce carbon emission. The harvest and use of residues and stumps can increase carbon benefit through the substitution of carbon-intensive fossil fuels. Carbon emission reductions as a result of forest biomass use can be achieved at each harvest occasion, and the reductions would be cumulative in the long run. An implementation of a large set-aside area could increase ecosystem carbon stock, but the total carbon benefit would be small. Annual carbon stock change would be smaller in set-aside scenario.

The results of substitution carbon benefit differed with respective materials as the highest potential substitution carbon benefits were estimated with stem-wood only use and values became smaller with the inclusion of residues and stumps in use. This was because the stem-wood has the potential to substitute more carbon-intensive materials compared to residues and stumps use for bioenergy production. The higher carbon benefits estimated in this thesis are all potential benefits, while use of biomass in pulp and paper production has reduced the carbon benefits. Use of forest products in a daily Swedish consumer cycle provided a very small carbon benefit compared to the potential carbon benefits. But, at the same time, if an extra amount of biomass production can be achieved, it would help to achieve a larger potential carbon emission reduction.

The conclusions from the national level study that can be drawn are: (i) current forestry practices in Sweden and use of forest products within country and abroad, causes a reduction in CO\textsubscript{2} emission (ii) CO\textsubscript{2} emission reduction is almost equal to total emission of GHG in Sweden, (iii) the benefits of CO\textsubscript{2} reduction
occurred mainly abroad and not within-country as a result of the high share of exported wood products from Sweden and higher substitution effect abroad, (iv) more intensive silvicultural methods can increase forest production and is an effective way to further reduce emission of CO₂.

The results from stand based analysis on two silvicultural systems, continuous-cover forestry and clear-cut forestry revealed that the net carbon balance does not differ due to two silvicultural systems. The net annual carbon stock changes in the standing biomass, litters, and wood products were nominal, and the majority of the carbon emission reduction effect came from substitution benefits. Yet again, the biomass production level was found to be crucial to determine the total net annual carbon balance. In a dynamic analysis the carbon stocks in living tree biomass, litter and soil, and wood products will change every year. However, substitution benefits occur due to product use, and occur simultaneously when wood products and biofuels are used in place of non-wood carbon intensive products and are permanent. This explains that the net annual climate benefit of forest management depends on the result of substitution benefit of study. A strategy aimed at larger production, harvest, and use of a large amount of stem-wood can provide larger emission reductions and vice versa. Therefore, when selecting a strategy to achieve larger carbon emission reductions, it is important for decision makers at different levels to recognize that specific forest management systems are less important than the biomass growth, yield levels, and product use strategies.

Based on the results from this study, it is evident that the effects of forest production and trade of wood products are important considerations in determining CO₂ emission reductions as the total climate benefit. To optimize the domestic Swedish CO₂ balance, wood should be used in place of carbon intensive non-wood products and residues for energy generation. In the long term, the energy and material substitution effects are much more important than the stock change effects in the forests. The substitution effects, which depend on continuing harvests from sustainably managed forests, create a durable and sustainable mitigation of CO₂ emission. It is crucial to understand the likely effects of forest management policies and practices in reducing GHG emission from forestry and forest industry sector. This study provides vital knowledge to policy makers, forest managers and forest owners about how different silvicultural strategies, use and trade of forest products influence the overall carbon balance.
7.2 Suggestions for future research

Previous studies, where the climate change implications were associated with forest production, have generally focused on ecosystem carbon budgets, bioenergy use and material substitution. It would be useful to design complete carbon balance analysis models that include parameters such as forest production, utilisation, carbon emission, and radiative forcing effects from different types of forest management practices. Carbon balance differences due to changes in shorter and longer rotations should be a topic of future research. Generally, carbon balance studies do not include economic valuations of the forest production and carbon benefits. Adding economic analyses to carbon balance studies would provide a clearer picture of the economic costs and benefits.

Sweden has made commitments to reduce GHG emission by 40% of the 1990 level by the year 2020 and envisions becoming a country of net zero GHG emission by the year 2050. It would be interesting to study carbon storage in forest ecosystems and wood products for these different time perspective. It is also necessary to examine the current physical quantities of forest products and their use so that future plans can be developed for the energy and construction sectors. Studies on wood consumption in the building sector would provide information about the potential demand for wood in this sector in the future. Sweden produces large amounts of forest biomass, but still imports biofuels from other countries. Studies on trade-offs between production, harvest, export and import of biomass and ecosystem services would provide a picture of impacts on ecosystem and society.

This study provides a brief assessment of comparison between continuous-cover and clear-cut forestry in selected forest stands of a landscape. Extending comparison of these two management systems to a landscape level might explore future policy implementation alternatives. The comparison of continuous-cover forestry in other boreal landscapes to the Swedish landscapes would provide information for the potential development and benefits in Swedish forests. In such studies, the specific quantity of biomass use in the energy sector, the specific quantity of wood use in the building sector, and the amounts of energy recovery can be analysed to provide more precise results for the carbon balance.

Environmental problems such as heavy metals leaking into the groundwater and freshwater, runoff increase in the mountainous forest land and water quality problems downstream, in relation to the intensive forest management practices have been pointed out. Studies on potential impacts of intensive forestry
practices are suggested to find out the possible solutions for future management planning.

It may be of interest to the Swedish government and to forest owners to plan their forest management, harvest and product business, both in a national and an international context. Future studies should also focus on estimating the value of the substitution effect that is lost if nothing is harvested from the forest. A study on the history of carbon storage and the substitution effect, when the forest biomass stock was smaller than it is today, would provide a reference for forest product use, in the future.
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