Forest Biomass Production Potential and its Implications for Carbon Balance

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Abstract

An integrated methodological approach is used to analyse the forest biomass production potential in the Middle Norrland region of Sweden, and its use to reduce carbon emissions. Forest biomass production, forest management, biomass harvest, and forest product use are analyzed in a system perspective considering the entire resource flow chains. The system-wide carbon flows as well as avoided carbon emissions are quantified for the activities of forest biomass production, harvest, use and substitution of non-biomass materials and fossil fuels. Five different forest management scenarios and two biomass use alternatives are developed and used in the analysis. The analysis is divided into four main parts. In the first part, plant biomass production is estimated using principles of plant-physiological processes and soil-water dynamics. Biomass production is compared under different forest management scenarios, some of which include the expected effects of climate change based on IPCC B2 scenario. In the second part, forest harvest potentials are estimated based on plant biomass production data and Swedish national forest inventory data for different forest management alternatives. In the third part, soil carbon stock changes are estimated for different litter input levels from standing biomass and forest residues left in the forest during the harvest operations. The fourth and final part is the estimation of carbon emissions reduction due to the substitution of fossil fuels and carbon-intensive materials by the use of forest biomass. Forest operational activities such as regeneration, pre-commercial thinning, commercial thinning, fertilisation, and harvesting are included in the analysis. The total carbon balance is calculated by summing up the carbon stock changes in the standing biomass, carbon stock changes in the forest soil, forest product carbon stock changes, and the substitution effects. Fossil carbon emissions from forest operational activities are calculated and deducted to calculate the net total carbon balance.

The results show that the climate change effect most likely will increase forest biomass production over the next 100 years compared to a situation with unchanged climate. As an effect of increased biomass production, there is a possibility to increase the harvest of usable biomass. The annual forest biomass production and harvest can be further increased by the application of more intensive forestry practices compared to practices currently in use. Deciduous trees are likely to increase their biomass production because of climate change effects whereas spruce biomass is likely to increase because of implementation of intensive forestry practices.
Intensive forestry practices such as application of pre-commercial thinning, balanced fertilisation, and introduction of fast growing species to replace slow growing pine stands can increase the standing biomass carbon stock. Soil carbon stock increase is higher when only stem-wood biomass is used, compared to whole-tree biomass use. The increase of carbon stocks in wood products depends largely on the magnitude of harvest and the use of the harvested biomass. The biomass substitution benefits are the largest contributor to the total carbon balance, particularly for the intensive forest management scenario when whole-tree biomass is used and substitutes coal fuel and non-wood construction materials. The results show that the climate change effect could provide up to 104 Tg carbon emissions reduction, and intensive forestry practices may further provide up to 132 Tg carbon emissions reduction during the next 100 years in the area studied.

This study shows that production forestry can be managed to balance biomass growth and harvest in the long run, so that the forest will maintain its capacity to increase standing biomass carbon and provide continuous harvests. Increasing standing biomass in Swedish managed forest may not be the most effective strategy to mitigate climate change. Storing wood products in building materials delays the carbon emissions into the atmosphere, and the wood material in the buildings can be used as biofuel at the end of a building life-cycle to substitute fossil fuels.

These findings show that the forest biomass production potential in the studied area increases with climate change and with the application of intensive forestry practices. Intensive forestry practice has the potential for continuous increased biomass production which, if used to substitute fossil fuels and materials, could contribute significantly to net carbon emissions reductions and help mitigate climate change.
Sammanfattning


Resultaten visar att effekter av klimatförändring sannolikt kommer att öka produktionen av skogsbiomassa under de närmaste 100 åren jämfört med en situation med oförändrat klimat. Som en effekt av ökad produktion av biomassa är det möjligt att även öka skördens av användbar biomassa. Årlig produktion och skörd av skogsbiomassa kan ökas ytterligare genom användning av intensivare skogsbruksmetoder än nuvarande. Lövträd kommer sannolikt att öka sin produktion av biomassa till följd av klimatförändringens effekter, medan granbiomassan sannolikt kommer att öka till följd av intensivare skogsbruksmetoder.
Intensivare skogsskötselmetoder såsom röjning, balanserad gödsling och introduktion av snabbväxande arter för att ersätta långsamt växande tallbestånd bidrar till att öka kolförrådet i trädbiomassan. Ökningen av kolförrådet i marken är högre när endast stambiomassa skördas jämfört med när hela trädet tas ut. Ökningen av kolförrådet i träprodukter beror till stor del på avverkningsnivåerna och vad den skörda biomassan används till. Substitution av fossila bränslen och råvaror mot biomassa ger det största bidraget till den totala kolbalansen, särskilt när hela trädbiomassan används och när den ersätter fossil kol som bränsle och icke träbaserade byggnadsmaterial. Resultaten visar att effekten av klimatförändringar kan ge upp till 104 Tg minskade koldioxidutsläpp, och att intensivare skogsbruk därutöver kan ge upp till 132 Tg minskning under de närmaste hundra åren i det studerade området.

Denna studie visar att ett productionsskogsbruk kan skötas så att tillväxt och skörd av biomassa balanseras långsiktigt, så att skogen kommer att bibehålla sin förmåga att öka kolförrådet i trädbiomassan och ge kontinuerliga skördar. Ökad trädbiomassa i Sveriges skogar är kanske inte den mest effektiva strategin för att motverka klimatförändringarna. Lagring av trä i byggnadsmaterial fördjprar koldioxidutsläppen till atmosfären, och vid slutet av byggnadens livscykel kan träprodukterna användas som biobränsle och då ersätta fossila bränslen.

Resultaten visar att potentialen för skogens produktion av biomassa i det studerade området ökar med klimatförändringarna och med ett intensivare skogsbruk. Intensivare skogsbruk har potential att kontinuerligt öka produktionen av biomassa som, om den används till att ersätta fossila bränslen och material, kan bidra till betydande nettoutsläppsminskningar och till att minska klimatförändringarna.
Preface

This work was performed as a doctoral research project in the Ecotechnology Research Group at Mid Sweden University in Östersund, Sweden. It is a part of an interdisciplinary programme to study “Forest as a resource in sustainable societal development”. The financial support of the European Union, Jämtland County Council, Sveaskog AB, and Swedish Energy Agency is gratefully acknowledged.

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Bishnu Chandra Poudel
Östersund, 2012
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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>C</td>
<td>Carbon</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>CPF</td>
<td>Collaborative Partnership in Forests</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</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 tonne)</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>Mg</td>
<td>Megagram (10⁶ grams, or 1 tonne)</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>NEP</td>
<td>Net Ecosystem Productivity</td>
</tr>
<tr>
<td>NFI</td>
<td>Swedish National Forest Inventory</td>
</tr>
<tr>
<td>NPK</td>
<td>Nitrogen Phosphorus and Potassium</td>
</tr>
<tr>
<td>NPP</td>
<td>Net Primary Production</td>
</tr>
<tr>
<td>OECD</td>
<td>Organization for Co-operation and Development</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>SMHI</td>
<td>Swedish Meteorological and Hydrological Institute</td>
</tr>
<tr>
<td>SOM</td>
<td>Soil Organic Matter</td>
</tr>
<tr>
<td>SOU</td>
<td>Swedish Government’s Official Reports</td>
</tr>
<tr>
<td>Tg</td>
<td>Teragram (10¹² grams, or 10⁶ tonne)</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
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<td>US</td>
<td>United States</td>
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1 Introduction

1.1 Climate change and forests

Climate change is one of the most widely recognised environmental issues today. A consensus in the climate science research community has emerged that emissions of anthropogenic greenhouse gases (GHGs) into the atmosphere are altering the global climate system (2007c). Emissions of GHGs into the atmosphere are likely to increase the earth’s mean surface temperature, thereby affecting physical and biological systems (Rosenzweig et al., 2008; Trenberth et al., 2009; UNFCCC, 2011). Many effects of temperature increase have been observed, including threats to natural phenomena, societal disturbances, and threats to economic growth (IPCC, 2007a; UNFCCC, 2011).

The atmospheric concentration of the most significant GHG, carbon dioxide (CO₂), has increased substantially during the last 20 decades, primarily as a result of fossil fuel combustion (IPCC, 2007c). Currently, fossil fuels provide over 80% of the world’s primary energy and are responsible for over 50% of all anthropogenic GHG emissions (OECD/IEA, 2010). The global energy supply is largely dependent on fossil fuels of which 27% of the total primary energy is dependent on coal (OECD/IEA, 2010). The International Energy Agency (IEA) has examined the global energy scenarios for future energy supply and has indicated that coal fuel use is likely to increase until the year 2035 if the current energy policies are not changed (OECD/IEA, 2010). These findings may explain the severity of fossil fuel use in the future which may result in increasing total anthropogenic GHG emissions in the future (OECD/IEA, 2010).

The likely increase of global mean surface temperature (Nakicenovic and Swart, 2000) is expected to be greater at higher latitudes (IPCC, 2001), which may result in a temperature increase of up to 1-2 °C in summer and 2-3 °C in winter in northern Europe in the next 50 years (Carter et al., 2005). The European Union (EU) suggests that limiting temperature increase to 2 °C, relative to pre-industrial levels, may avoid the risks of climate change (European-Commission, 2007). The projection of CO₂ emissions reduction that is required to avoid climate change is difficult to predict because of the complexity of the global system. However, stabilising atmospheric GHG concentration levels below 450 ppm CO₂-eq is likely to avoid a 50% chance of increasing temperature above 2 °C (EU, 2008). This stabilisation target is unlikely to be met unless strong and timely actions are taken.
to reduce CO\textsubscript{2} emissions, considering the current atmospheric CO\textsubscript{2} concentration level of 394 ppm CO\textsubscript{2}-eq (NOAA/ESRL, 2012).

The Intergovernmental Panel on Climate Change (IPCC) has presented several strategies that may help mitigate climate change (IPCC, 2007b). Various initiatives have been taken to reduce the atmospheric CO\textsubscript{2} concentration such as the Kyoto protocol requiring industrial countries to reduce GHG emissions below 1990 levels by the year 2012. The EU has set an ambitious target of reaching a 20% share of energy from renewable sources by 2020 (European-Commission, 2009) in the pursuit of reducing CO\textsubscript{2} emissions. Sweden, an EU member state, already obtains more than 20% of its energy from renewable sources (Swedish Forest Agency, 2011) and has a target of extending this share to 49% by the year 2020 (Swedish Energy Agency, 2008).

The global society’s attempt to mitigate climate change may include reducing carbon emissions and increasing carbon sinks. Strategies to reduce CO\textsubscript{2} emissions by reducing fossil fuel use and by increasing carbon sinks through a sustainable production forestry may be one of the practical solutions. A Sustainable production forestry in this context may be considered as a practice that maintains indefinitely the natural productive capacity of forest ecosystems, while providing an opportunity for harvesting and using at least a certain amount of forest product at regular intervals. Thus, such practice will ensure the continued existence of forest ecosystems and the availability of forest biomass for use in future. By doing so, forest biomass use for bioenergy may play a vital role in replacing fossil fuels and reaching the aim of increasing renewable energy use. Forest biomass can also replace carbon-intensive construction materials. Hence, the greater the forest biomass production, the greater the amount of harvest that is possible, and the earlier the biomass is harvested, the earlier the fossil fuels and carbon-intensive materials can be replaced (Malmsheimer et al., 2008). A strategy aimed to increase forest biomass production and use could thus be effective in mitigating climate change (Easterling et al., 2007).

1.2 Forest management and carbon balance

The role of a sustainable forest management in reducing atmospheric carbon emissions is very important. The IPCC suggests that the conservation of biological carbon in the forest ecosystem, the storage of carbon in wood products, and the use of forest biomass to replace fossil fuels and carbon-intensive materials would help to mitigate climate change (IPCC, 1996). The strategies of a forest
management for increasing carbon benefit needs to increase the carbon sink into the forest biomass by increasing biomass production, increase soil carbon stock, and increase the potential biomass harvest to contribute in obtaining higher carbon benefits.

Forests constitute approximately 30% of the world’s land surface and contribute to the global net removal of three gigatonnes (Gt) of anthropogenic carbon per year (Canadell and Raupach, 2008). Forest ecosystems, including forest soil, store approximately 1200 Gt of carbon, which is considerably more than the 762 Gt of carbon present in the atmosphere (Freer-Smith et al., 2009). Annually, global forests turn over approximately one twelfth of the atmospheric stock of CO$_2$ through gross primary production (GPP$^1$), accounting for 50% of all terrestrial GPP (Malhi et al., 2002). It is estimated that, in 2005, forests contained 572 Gt of standing biomass (equivalent to 280 Gt of carbon) (IPCC, 2007b; CPF, 2008).

The carbon stock increase 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 remains as a long-term terrestrial carbon sink (IPCC, 2000). Several studies suggested that increasing atmospheric CO$_2$ and nitrogen (N) deposition rates are likely to increase the forest biomass in the future (Norby et al., 1999; Norby et al., 2005; Canadell et al., 2007a; IPCC, 2007c; Galloway et al., 2008; Malmheimer et al., 2008; Dupre et al., 2010). Luo (2007) observed that elevated atmospheric CO$_2$ concentrations result in enhanced biomass production and subsequently increased carbon pools in living biomass, litter, and soil. Although uncertain, climate change projections predict temperature increases and longer growing seasons at higher latitudes, implying that more sunlight will be utilised for photosynthesis, thereby stimulating the biomass production of boreal forests (Bergh et al., 2003; Rosenzweig et al., 2008; Raupach and Canadell, 2010). In addition, biomass production can be further increased by various forest management practices (Bergh et al., 2005; Houghton, 2007; Skogsforsyrelsen, 2008).

Forest management involves the integration of silvicultural practices and economic alternatives (Bettinger et al., 2009) to achieve production and ecological objectives through a series of silvicultural operations, such as regeneration, fertilisation, tending operations (commercial and pre-commercial thinning),

---

$^1$ Gross primary production is the sum of the photosynthesis by all leaves measured at the ecosystem scale, represented as biomass (Chapin et al. 2002).
harvesting, and reforestation (Buongiorno and Gilless, 2003; Bettinger et al., 2009). The scope of this thesis limits the definition of silvicultural activities to those that are relevant to forest production and management for CO$_2$ emission reduction. Forest management strategies are associated with forest production and harvest goals, with defined goals for carbon sequestration and accumulation as above-and below-ground biomass, litter that falls to the ground, dead wood, soil organic matter, and harvested products and their utilisation. A harvest goal that has higher frequency and intensity of thinning and shorter rotation length may influence the biomass stock in the following generation (Liski et al., 2001; Kaipainen et al., 2004). The influence can be related to the types of forest products harvested. For instance, the removal of stem-wood-only biomass adds all litters to the soil, while whole-tree removal adds a part of litter to the soil.

A forest sequesters carbon by removing carbon from the atmosphere through the photosynthesis process and storing the carbon in living biomass. A forest’s capacity for sequestrating carbon is a function of the productivity of the site and the potential sizes of the various carbon pools, including soil, litter, subterraneous woody materials, standing and fallen dead wood, live stems, branches, and foliage (Chapin et al., 2002; Malmsheimer et al., 2008). The carbon accumulation in biomass is typically higher when the tree is in its fast growing stage, and as the tree reaches maturity (older than 80 years in boreal forests) it becomes almost carbon neutral and may eventually become a carbon source if dies and decays (Gower et al., 1996; Gower et al., 2001; Nabuurs et al., 2003). Shortening rotation periods would encourage the growth of young stand forests in the long run and thus may result in the sequestering of carbon at higher rates.

Soil type, texture, structure, and air and water availability inside the soil pores govern the soil carbon development process. The rates of accumulation and magnitudes of soil carbon stocks depend on the litter input into the soil and in part on nutrient management (Lal, 2004). Fertilisation may help to increase nutrient level in the soil thus may help to build up carbon stocks (Johnson, 1992). Changes in tree phenology, species composition, soil temperature, and water balance can change soil respiration and decomposition rates (Davidson et al., 2000; Luo, 2007). When the litter is fresh, nutrient cycling and oxidation stimulate its decomposition; however, later, as litter quality decreases, higher temperatures might increase decomposition and carbon cycling rates (Kirschbaum, 2004). Hyvönen et al. (2008) explained that elevated CO$_2$ would encourage carbon sequestration by activating the carbon cycling process by adding litter to the soil, which can later assimilate with soil organic material (SOM), thereby increasing soil carbon stock. Ågren et al.
suggested that the soil carbon stocks in Swedish forests will increase but that the rate of increase will quickly slow down when the input is stopped. Ågren et al. (2007) warned that reducing litter input by harvesting more forest biomass would lead to a decline in soil carbon stocks. Nevertheless, increasing forest biomass production to allow more litterfall and input may reverse the positive feedback.

Nitrogen is one of the limiting factors in boreal forest production (Pastor and Post, 1988; Tamm, 1991). If nutrients are a limiting factor, balanced fertilisation, which includes three major nutrients Nitrogen, Phosphorus and Potassium (NPK), may allow for increased productivity especially at nutrient-poor sites (Oren et al., 2001; Malmsheimer et al., 2008). Bergh et al. (2005) suggested that the forest production in northern Sweden could be increased by 300% if an additional nitrogen fertiliser is applied to address the nutrient deficiency. Providing a balanced nutrient supply to reduce the nitrogen deficiency, particularly in the young stands, could increase the production. Forest biomass production can be increased by improving site conditions for plantations and by selecting improved genetic plant materials and productive tree species suitable to local site conditions and microclimates. Density regulation through pre-commercial thinning reduces the competition between trees and shortens rotation periods, and shortened periods between two rotations will allow more time for biomass production.

Forest biomass can be used to substitute fossil fuels to reduce GHG emissions (Zebre, 1983; Gustavsson et al., 1995; Bergman and Zebre, 2004). The IPCC (2007b) suggests that material substitution is an important part of climate change mitigation strategy through the production of forest biomass. Eriksson et al. (2007) claimed that there could be significant reductions in CO₂ emissions if forest biomass from sustainably managed forests replaced fossil fuels. The burning of biomass grown in sustainably managed forests is part of a cyclical flow, as carbon emitted during combustion will be absorbed by re-growth of the harvested forest stand. Using wood products from sustainably managed forests can reduce net CO₂ emissions, as less energy is used to manufacture such materials compared to carbon-intensive materials. Substitution of carbon-intensive materials also avoids non-energy process emissions during the manufacture of non-wood-based products, such as cement and steel. The use of wood products may also delay the emission of biogenic carbon into the atmosphere by allowing the wood to be used for a longer period of time. Furthermore, biomass by-products of wood production chains and wood from construction work at the end of its useful life
can be used (Sirkin and Houten, 1994; Gustavsson et al., 2006b; Gustavsson and Sathre, 2006; Sathre et al., 2010). The wood product life cycle optimised for mitigating climate change would entail the use and possible reuse of wood products (Sathre, 2007). Nevertheless, the net carbon benefits depend on substitution efficiency, i.e., on how and where the wood products are used and on which products are substituted (Schlamadinger and Marland, 1996; Schlamadinger et al., 1996; Gustavsson et al., 2006a; Sathre and O’Connor, 2010).

1.3 Review of previous studies

Several studies have discussed potential forest biomass production and harvest over the past decades. Carbon balance studies in the past were largely focused on ecosystem production (Houghton, 2005, 2007) but recent studies have included the forest biomass use as material and bioenergy and their implications for carbon emissions reduction.

1.3.1 Forest biomass production and harvest

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) performed studies on the effect of increased atmospheric CO₂ concentrations on forest growth and composition in North America. They found that the forest biomass carbon in the boreal forests would be increasing because of increased CO₂ concentrations. Kauppi et al. (1992) explored the increasing forest biomass and carbon budget for most of western Europe. Prentice et al. (1993) developed a model to describe the transient effects of climate change-induced temperature and precipitation change on the dynamics of forest landscapes, growth processes, and species compositions. Swedish forest production in response to climate change was explored in several studies (Bergh et al., 1998; Bergh and Linder, 1999; Bergh et al., 1999). Furthermore, several studies explored forest productivities in boreal forests (Pussinen et al., 2002; Bergh et al., 2005; Briceño-Elizondo et al., 2006; Kirilenko and Sedjo, 2007; Eggers et al., 2008). Several studies suggested that forest biomass production might increase in northern Europe with increased atmospheric temperatures and CO₂ concentrations. 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. A larger amount of biomass production may
correspond to a larger biomass removal. Currently in Sweden, residues and stumps harvesting is in practice. In the year 2010, Sweden gave permission to harvest forest residues from 155 thousand hectares and stumps from 7.5 thousand hectares of forest (Swedish Forest Agency, 2011).

1.3.2 Soil carbon stock

The influence of increased harvest level on soil carbon stock and nutrients have been discussed in the recent literature (Liski et al., 2001; Egnell and Valinger, 2003; Kaipainen et al., 2004; Egnell, 2011). The studies found that the effect of increased harvest level in soil carbon and nutrients are only temporary. Various studies have analysed the effects on forest soil carbon stock due to land use changes, forest management, climate change and other disturbances. Liski et al. (2002) found that the soil carbon stock in western Europe is increasing because of increased litter fall from living trees. Early studies reported that increased temperatures do not necessarily increase the nutrient cycling and oxidation of SOM and therefore decomposition (Lloyd and Taylor, 1994). However, later studies suggested that a warmer climate may govern a major role in the decomposition of SOM leading to an increase in CO2 release to the atmosphere and a decrease in soil carbon content (Davidson et al., 2000; Jones et al., 2005; Davidson and Janssens, 2006; Friedlingstein et al., 2006). Because of the release of soil carbon, positive feedback leading to additional climate warming of 0.1-1.5 °C may take place (Kirschbaum, 2000, 2004; Knorr et al., 2005; Friedlingstein et al., 2006; Luo, 2007; Piao et al., 2008). A significant loss of terrestrial carbon stock in the higher latitude is also possible because of the temperature-dependent net primary production system in the boreal forests compared to other parts of the world (Canadell et al., 2007b; Canadell and Raupach, 2008). However, Hyvönen et al. (2007) suggested that, as long as forest input is increasing, soil carbon loss will not be significant. Therefore, increasing the productivity of forests is a key factor. Moreover, reducing disturbances in 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 a significant fraction of relatively unstable SOM is clearly subject to temperature-sensitive decomposition. 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 the 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 the potential to act as positive feedback in the climate change system (Friedlingstein et al., 2006; O’Donnell et al., 2010).

1.3.3 Substitution of fossil fuels and carbon-intensive products

In the past, forest production has been used mostly for wood products and pulp and paper. Recently, the concept of whole-tree utilisation has emerged, which focuses on the 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 material is widely used for building construction, and its use will be growing in the future (Ministry of Industry, 2004).

Schulz (1993) speculated that dependency on wood would increase with increased interest in renewable resources to replace conventional materials and energy for environmental reasons. The use of forest biomass as a source of energy was considered during the global energy crisis in the 1970s. It was also in the 1970s when wood products were thought of as a sustainable source of materials for construction in place of energy-intensive products 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 of United States (US) to study the effects of producing and using renewable materials (Lippke et al., 2004). CORRIM developed a comprehensive life cycle inventory of environmental inputs and outputs from forest regeneration through product manufacturing, building construction, use of wood in buildings and their maintenance, and disposal (Malmheimer et al., 2008). The analysis focused on the 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 (Boustead and Hancock, 1979; Buchanan and Honey, 1994; Fossdal, 1995; Gustavsson et al., 1995; Schlamadinger and Marland, 1996; Börjesson et al.,
1997; Schlamadinger et al., 1997; Gustavsson and Karlsson, 2006; 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 emissions from the life cycles of multi-story building construction. Pingoud and Lehtilä (2002) studied the 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 the wood chain and its role in GHG emission mitigation. Eriksson et al. (2007) considered different scenarios for forest production and biomass use and found that forest stand fertilisation, residue and stump harvesting, and the use of wood as a construction material provided high reductions in CO₂ emissions. Further studies have shown that the use of wood products and biomass residues significantly reduces net CO₂ emissions, provided that the wood material used comes from sustainably managed forests and that biomass residues are used responsibly (Salazar and Meil, 2009; Gustavsson et al., 2010; Sathre and O'Connor, 2010).

1.4 Knowledge gaps

Previous studies have made significant contributions to assessing forest biomass production, soil carbon stock change, and substitution benefits for carbon emissions reductions. Nonetheless, biomass production projections in north-central Sweden due to the regional climate change effect have not been carried out before. Biomass growth projections in most cases include only the forest growth data (from inventory) instead of physiological processes of plant biomass production with the interaction to the environment. Studies of soil carbon stock changes may require a comprehensive approach such as input of organic materials, decomposition processes, and the climate change temperature increase effect to explain. Forest biomass production and product use were considered most often at the stand level. When this study began, there were no comprehensive studies that quantified the full chain of forest biomass production, harvest, effects in soil carbon stocks, and biomass use implications for carbon balances on a landscape level including climate change effects. In general, little work has been done using
an integrated methodological approach with a system perspective to draw a complete picture of carbon balance from forest biomass production and utilization.

1.5 Study objectives

This study explores carbon balances using an integrated analytical framework for the entire forest product chain, including forest management on a landscape level. The aims of the study are as follows:

- To quantify the potential biomass production due to climate change in the Middle Norrland region of Sweden and the total carbon balance effects of biomass production and substitution of carbon-intensive materials.
- To quantify the potential biomass production due to intensive forestry practices and the total carbon balance effects of biomass production and substitution of carbon intensive materials.

1.6 Thesis organisation

This thesis is based on three original papers and is divided into two parts. The first part includes an introduction, a discussion of methodology, a synthesis of the results presented in the papers, and a discussion and conclusion. The second part contains the three original papers. Paper I analyses the effects of climate change on forest biomass production and subsequent effects on carbon stock changes in standing biomass, soil carbon, and carbon emission reduction as a result of fossil fuel and building material substitution. Paper II analyses the effects of intensive forestry on biomass production, the carbon stock changes in forest biomass and forest soil, and carbon emission reduction as a result of fossil fuel and building material substitution. Paper III provides integrated results of total carbon balances in standing biomass, forest soil, and wood products as well as substitution effects. The major portions of the results and discussion sections are based on Paper I and II.
2 Methods

2.1 Integrated approach

An integrated carbon analysis includes modelling of forest generation, growth and harvest, the use of products, and the end-of-life management of products. The integrated approach used in this thesis consists of four different sub-models (BIOMASS, HUGIN, Q model, and SUBSTITUTION). A process-based model for forest biomass growth (see Paper I, II and III) provides biomass production values. These values serve as input for the empirical model HUGIN to estimate the harvest levels in the forests. The use of forest products as bioenergy and wood and its potential carbon reduction are calculated in a system analysis-based model (SUBSTITUTION). Soil carbon developments under different types of forest management practices are modelled using the Q model. The analysis is made for a 100-year period, starting from the year 2010 and ending at the year 2109.

The flow chart used in this study is presented in Figure 1. The balance between net primary production (NPP\(^2\)) and biomass loss during ecological processes determines the annual change in plant biomass (Chapin et al., 2002). At the same time, the changes in plant biomass have influence on changes in below-ground nutrient content. The analysis begins with a calculation of NPP in the BIOMASS model to provide NPP data, which is fed into the HUGIN system. The annual change in tree biomass based on all silvicultural activities, from regeneration to the final felling, is incorporated into HUGIN to calculate the amount of harvestable biomass. There are several possibilities for the utilisation of tree biomass after harvesting. For example, stem-wood may be utilised as construction materials, and tree residues may be utilised for bioenergy. The model outputs, in the form of different assortments of forest products from a landscape, are used in the SUBSTITUTION model to conduct a system analysis of forest biomass utilisation based on a life cycle perspective. Fossil carbon emissions from forest operations (CO\(_2\) emissions during regeneration, pre-commercial thinning, commercial thinning, fertilisation, and final felling) are included. Finally, carbon balances in standing biomass, harvested wood products, and forest soil are

\(^2\) NPP is the balance of carbon gained by GPP and the carbon lost by respiration of all plant parts (Chapin et al. 2002).
The carbon reduction associated with the use of harvested biomass to replace fossil fuel and carbon-intensive construction materials is also calculated.

Figure 1 Schematic diagram of carbon balances during forest production and biomass utilization

2.2 Functional unit

In this study, the carbon balance associated with forest production and the utilisation of wood and non-wood products is analysed. A “functional unit” is a key element for defining the function(s) to enable the objective comparison of different systems. This analysis focuses on the potential climate change mitigation effects of forest management and use. Hence, the overall net carbon emissions reduction in grams of carbon per unit of forest land is considered as a functional unit in this study.

2.3 Reference system

Forest management in this study is based on clear-cut forestry with one pre-commercial thinning and two to three commercial thinnings before the final harvest. The harvested biomass is assumed to be used as “stem-wood” and
“whole-tree”. It is assumed that stem-wood is used as construction material to replace carbon-intensive materials, while the remaining processing residues, small-diameter pine and spruce stem-wood, and all deciduous stem-wood are used as biofuels. The Wälludden building constructed in Växjö, Sweden, which is functionally equivalent to a concrete frame building, is used as a reference building for wood use. 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). Coal and fossil gas are considered as substituted reference fossil fuels, which currently covers 80% of the world’s primary energy (OECD/IEA, 2010).

2.4 Activities included in system analysis

Various activities and processes included in the study show the life cycle carbon balance (Table 1). The activities are defined to include the life cycle of forest biomass and in case of non-wood building materials, the analysis includes carbon emissions during the material production and its processes to be substituted by forest biomass. All energy inputs are accounted in the analysis.

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)</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 process.</td>
</tr>
<tr>
<td>Use of materials</td>
<td>Forest biofuel and Wood processing residues use in power plant; Wood materials use in buildings.</td>
<td>Forest residues and wood-process residues replaces fossil fuel; Wood materials replace non-wood materials.</td>
</tr>
<tr>
<td>End use of materials</td>
<td>Building demolition, Recovery of wood materials.</td>
<td>Wood use as biofuel replaces fossil fuel.</td>
</tr>
</tbody>
</table>

2.5 Study area
The study area (Paper I, Figure 1) encompasses the counties of Jämtland and Västernorrland in north-central Sweden, from 61° 33' to 65° 07' N latitude and from 12° 09' to 19° 18' E longitude. The elevation ranges from sea level to 1500 m in altitude. The annual precipitation ranges from 600-700 mm in the eastern part to 1500 mm in the western part (SMHI, 2009), and the duration of the growing season (mean temperature above +5 °C) is approximately 120-160 days per year (Sveriges-Nationalatlas, 1995). The average monthly temperatures during 1961-1990 varied in January between +1 °C to -12 °C and in July between 10 °C to 14 °C. The forest land areas of the counties of Jämtland and Västernorrland are 3.5 and 1.9 million hectare, respectively. The dominant tree species are Norway spruce (Picea abies (L.) Karst.), Scots pine (Pinus sylvestris L.) and birch (Betula spp.) (Swedish Forest Agency, 2010). The study area accounts for approximately 10% of the total forest land of Sweden. Detailed descriptions of the study area are given in Papers I and II.

2.6 Scenarios

Five different forest management scenarios are formulated (Table 2) to describe the potential variability of climate and forest management practices through 2109.

Table 2 Overview of scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climate</th>
<th>Forest management goals</th>
<th>Biomass use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>No change</td>
<td>Reference (current management)</td>
<td>Stem wood or whole tree</td>
</tr>
<tr>
<td>Climate</td>
<td>Change</td>
<td>Current management</td>
<td>Stem wood or whole tree</td>
</tr>
<tr>
<td>Environment</td>
<td>Change</td>
<td>Fulfil environmental goals</td>
<td>Stem wood or whole tree</td>
</tr>
<tr>
<td>Production</td>
<td>Change</td>
<td>Increase biomass production</td>
<td>Stem wood or whole tree</td>
</tr>
<tr>
<td>Maximum</td>
<td>Change</td>
<td>Maximize biomass production</td>
<td>Stem wood or whole tree</td>
</tr>
</tbody>
</table>

The Reference scenario in Paper I assumes an unchanged climate, and the Climate scenario assumes climate change as described in Section 2.7 below. These two scenarios 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. The remaining scenarios assume different forest management practices to meet different objectives. The Environment scenario satisfies Swedish environmental goals by increasing the forest area allocated to natural set aside area. 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 tree species suitable for particular site
conditions, and shorter time between clear-cut and re-planting. In addition, pre-commercial thinning and traditional fertilization area is increased. Balanced nutrient supply in young stands of Norway spruce and in former agricultural land forest are also included. The Maximum scenario includes all those activities, and also assumes to replace Scots pine with Lodgepole pine, and balanced nutrient supply in young stands of Lodgepole pine and Norway spruce forest land. Harvested biomass is used as “stem-wood” and “whole-tree”. Stem-wood harvest assumes the extraction of 95% of tree stems of >20 cm diameter with the rest of the biomass left on the forest floor. Whole-tree harvest assumes a harvest of 95% of the felled stem-wood, 75% of needles, branches and tops (referred to as “residue”), and 50% of stumps and coarse roots.

2.7 Climate change

This study considers climate change based on the IPCC SRES B2 climate change scenario (Nakicenovic and Swart, 2000). This scenario corresponds to moderate emissions of greenhouse gases leading to an atmospheric CO₂ concentration of 621 ppm by the year 2100 (Levy et al., 2004). The simulations of temperature change were conducted using the Rossby Centre’s regional atmospheric model based on IPCC global scenarios with the downscaled climate model RCA3 with a grid of approximately 50 km x 50 km (SMHI, 2009). In the calculations, RCA3 uses global driving variables from the general circulation model ECHAM4/OPYC3 (Kjellström et al., 2006). Climate projections for north-central Sweden are for an increase in average regional annual temperatures of more than 4 °C by 2100 for SRES B2 (see Figure 3 in Paper I). Soil carbon modelling was performed with the assumption of a shift in latitude to 58-59 °N instead of the actual latitude of 62-63 °N because the temperature change due to climate change is expected to make the climatic conditions at 62-63 °N similar to those at 58-59 °N.

2.8 Forest biomass production modelling with BIOMASS

The process-based growth model BIOMASS was used to estimate NPP. BIOMASS uses canopy characteristics, foliage photosynthetic characteristics, and daily meteorological conditions as inputs and calculates daily evapotranspiration from the stand. Later, foliage, stem and branch respiration values are subtracted from the total CO₂ uptake by the canopy to obtain daily NPP values. Both litterfall and stand water balances are incorporated into the model. BIOMASS consists of a
series of equations based on established theories of physiological plant processes and soil-water dynamics. This is summarized by the simple equation

\[ NPP = GPP - R_{\text{plant}} \]

where GPP is the gross primary production, and \( R_{\text{plant}} \) is respiration by tree components.

All sub-models for the calculation of carbon accumulation in foliage, branches, stems, bark, and roots, including below-ground components, were formulated, and respiration in each component was subtracted from the total accumulation 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 temperature change on NPP increment 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. The NPP output data were first estimated and then assimilated with the HUGIN model to determine the forest growth function at a county level.

2.9 Forest biomass harvest modelling with HUGIN

HUGIN is a model system for long-term forecasts 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 National Forest Inventory (NFI) to define initial forest conditions. HUGIN describes all stages in plant development from stand establishment through treatments, thinning, and final fellings. The growth simulators in HUGIN are valid for all forest land in Sweden, for all types of stands, and within a wide range of management practices. The details on stand establishment, treatments, thinnings, and final fellings are given in Paper I (Section 2.4.2), and further details are provided by Lundström and Söderberg (1996).
2.10 The use of forest biomass as bioenergy and construction materials

Forest biomass harvested in the whole-tree scenario is classified as large diameter stem-wood and residues. Large-diameter stem-wood is defined as stems with a minimum diameter of 20 cm and is assumed to be used to produce wood construction materials to substitute conventional reinforced concrete. The material substitution effects are based on a multi-story apartment building. The details of wood use for material substitution in building construction are given by Gustavsson et al. (2006b).

Large-diameter pine and spruce stem-wood is used for the production of wood construction materials, while the processing residues (bark, sawdust, chips) are used for bioenergy. In the whole-tree scenario, tops, branches, needles, and stumps including coarse roots are also used for bioenergy. Small-diameter pine and spruce stem-wood, and all deciduous stem-wood are used for bioenergy. In this study, small-diameter stem-wood is not used for pulp and paper production because we have not analysed whether the demand for additional pulpwood in the pulp industry in Sweden would increase. The wood materials in the buildings are assumed to be recovered and used for energy purposes as biofuels at the end of the 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). Fossil energy inputs for the recovery and transport of biofuels and forest management practices are analysed according to Eriksson et al. (2007) and Berg and Lindholm (2005).

2.11 Carbon balance
2.11.1 Total carbon balance

In this study, total carbon balance is defined as the reduced net carbon emission into the atmosphere due to forest biomass production and their uses. Hence, a positive carbon balance refers to a net carbon benefit, and a negative carbon balance refers to net carbon emission. The activities included in the system analysis (Section 2.5) are categorised so as to represent either carbon emissions reductions or carbon emissions. The carbon emissions reductions are expressed as a positive change as a result of increased standing biomass carbon stock, changes in forest soil carbon stock, changes in wood product carbon stocks in the buildings, 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. The carbon emissions are expressed as the fossil fuel emissions during forest operation activities including fertilisation. 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 emissions include fossil-fuel-cycle carbon emission, end-use fossil fuel carbon emission, emissions due to end-use electricity to extract, process, and transport the materials, and emissions from industrial process reactions such as the calcination reaction during manufacture of the cement.

The total carbon balance for the Jämtland and Västernorrland forest landscape is calculated as:

\[
CB = \sum \left( \Delta C_{sb} + \Delta C_{fs} + \Delta C_{wp} + C_{sb} - (C_{fo} + C_f) \right)
\]

where

- \(CB\) is the total carbon balance (gram C);
- \(\Delta C_{sb}\) is the change in standing forest biomass carbon stock (gram C);
- \(\Delta C_{fs}\) is the change in forest soil carbon stock (gram C);
- \(\Delta C_{wp}\) is the change in carbon stock in wood products (gram C);
- \(C_{sb}\) is the substitution carbon benefits due to the replacing of fossil fuel with recovered biofuel (gram C) and avoidance of material production and process emissions (gram C) due to use of wood materials;
- \(C_{fo}\) is the carbon emissions due to forestry operation activities (gram C);
- \(C_f\) is the equivalent carbon emissions due to fertilization in the forest (gram C);

Emissions of nitrous oxide and methane also occur during fertilization. Global Warming Potentials of nitrous oxide (298) and methane (25) are used to convert them into equivalent CO\(_2\) emissions based on their relative radiative efficiencies and atmospheric residence times compared to CO\(_2\) (IPCC, 2007c).

A positive carbon balance signifies reduction in carbon emission to the atmosphere, while a negative carbon balance signifies increase in carbon emission to the atmosphere.

### 2.11.2 Standing biomass carbon stock

In this study, the annual increase in standing biomass carbon stock is estimated after the deduction of harvest, mortality, and disturbances from the total
annual biomass production of the forest. On average, approximately 95% of the annual production of forest biomass is felled. HUGIN calculates the standing biomass carbon stock based on an evaluation of forest production, disturbances, harvests, and retained standing biomass in the forest. HUGIN uses spruce stumps as a proxy for the calculation of deciduous and pine tree stumps.

2.11.3 Soil carbon stock

In this study, soil carbon stock changes due to different forest management practices and removal strategies are estimated. The estimates are based on the amount of organic carbon available in the SOM, soil carbon development due to litterfall from the canopy of the standing biomass and below ground carbon stock development, and carbon development due to biomass residues left in the forest after harvest and thinning. A fraction of leaves/needles, branches, and fine roots die and fall in a standing stand, and a fraction of stems and parts of stumps and coarse roots are left at the site during harvest and thinning, contributing to soil carbon stock development. The decomposition of the different litter fractions is calculated using the Q model, which incorporates the invasion rates of different litter types (Ågren, 1983; Ågren and Bosatta, 1998; Hyvönen and Ågren, 2001). This study excluded the soil carbon stock available in mineral soil because the land use history of the landscape was unknown. The details of soil carbon modelling are given in Paper I (Section 2.5).

2.11.4 Wood product carbon stock

Wood products stored in the buildings are considered for wood product carbon stock estimation. Increasing the total amount of wood product stock allows for the storage of more carbon in the products. The carbon content in wood was assumed to be 49% of the dry weight of the wood (Swedish Forest Agency, 2010). Wooden buildings store carbon for the lifetime of the buildings but not beyond that time. Therefore, it was assumed that when the building is demolished, 100% of the used wood is recovered and used as biofuel to replace fossil fuels. The carbon in the wood products returns to the atmosphere as CO₂ when the wood is used as biofuel.
2.11.5 Substitution of fossil fuels and carbon-intensive products

Carbon emissions reduction due to substitution of fossil fuels and carbon-intensive products by the use of forest biomass is estimated. This substitution is calculated by estimating fossil fuel emissions during material production and during process reactions (e.g., cement calcination) of material production. These emissions are compared with emissions from wood construction material production and processes. Fossil fuel substitution by the use of biomass residues as bioenergy is estimated separately. A full fuel-cycle emission is considered to estimate carbon emissions reduction. This study assumes that the biomass considered in this study is harvested from sustainably managed forests thus the combustion of biofuel is assumed to contribute a net emission of zero. However, emissions from fossil fuels used to produce, transport, and process the biofuels contribute net emissions. Detailed methods and processes for bioenergy use, conversion, and co-generation opportunities are discussed elsewhere (Schlamadinger and Marland, 1996; Schlamadinger et al., 1997). This study assumes that construction of the reference building is substituted by a wood-framed building that is replaced with another wood-framed building using similar wood products indefinitely.

2.11.6 Forestry operations and carbon emission

Emissions from fossil fuels used for forest operations (stand establishment, thinnings, final harvest of roundwood, and forwarding and transport of roundwood to mills and fertilisation) are calculated based on Berg and Lindholm (2005). Energy use data for forestry operations for northern Sweden are used to calculate carbon emissions. The details of management activities and fertilisation and carbon emissions are described in Paper II (Section 3.6).

2.12 Data quality

Many factors can affect the data used in carbon balance calculations. Different values of solar radiation, water amount in the soil, plant numbers and their competition in the forest stand, the photosynthesis capability of a single plant, and growing capacity in terms of carbon content storage capacity may result in different values in biomass production, thereby affecting the final result. Forest
inventory data collected by the Swedish Forest Agency has been used to model forest growth and harvest by HUGIN. Any error in the data bank may also affect the final results of this study. This study assumes the existence of only three tree species; therefore, the existence of any other species in the forest stand would change the values and results. Forest product removals may not match current practices, and there will be different results based on different systems of harvest, removal, and use. Furthermore, the differences in physical properties of raw materials, processes of material production, types of fossil fuel use, and the amount of wood to be utilised in the buildings may lead to different results.
3 Results

3.1 Forest biomass production and harvest

Figure 2 shows the annual forest biomass production and harvest at the year 2010 and year 2109 for the five scenarios for both whole-tree and stem-wood use. The annual biomass in the Reference scenario increased by ~17% in the year 2109 for whole-tree biomass and by ~8% for stem-wood biomass compared to the base year 2010 (Paper I). More biomass was produced in the other scenarios compared to the Reference scenario, with values increasing up to ~75% for whole-tree biomass and ~65% for stem-wood biomass in the Maximum scenario during the study period from 2010 to 2109 (Paper III).

The potential amount of biomass harvested during the study period increased significantly when taking into account the effect of climate change and intensive forestry practices. However, the harvest was only slightly larger in the Environment scenario compared to the Reference scenario. The Climate, Production and Maximum scenarios all resulted in larger biomass harvests than the Reference scenario (Figure 2). Harvests were greater in the Climate, Environment, Production, and Maximum scenarios than in the Reference scenario (Table 1 in Paper I and Table 3 in Paper II).

The differences in forest production and harvest between the different scenarios and the Reference scenario for both whole-tree biomass and stem-wood biomass represent a net increase during the study period (Table 3). The differences
gradually increased throughout the entire study period (Paper I, Table 1 and Paper II, Table 3).

Table 3 Differences in forest biomass production and harvest between the Reference scenario and other scenarios (Tg dry biomass)

<table>
<thead>
<tr>
<th></th>
<th>2010-2019</th>
<th>2020-2029</th>
<th>2030-2039</th>
<th>2040-2049</th>
<th>2050-2059</th>
<th>2060-2069</th>
<th>2070-2079</th>
<th>2080-2089</th>
<th>2090-2099</th>
<th>2100-2109</th>
<th>Cumulative (Tg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Differences between the Climate and Reference scenarios</strong></td>
<td></td>
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<tr>
<td><strong>Biomass production</strong></td>
<td></td>
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Paper I and II discuss differences in biomass production and harvest in different tree species (Norway spruce, Scots pine and birch) due to climate change and intensive forestry practices. The production and harvest of biomass are classified into different types of forest products. Stem-wood and stump biomass yield a greater amount of biomass than other biomass components. However, the stump biomass may be overestimated because the HUGIN model uses spruce stumps as a proxy for the calculation of deciduous and pine tree stumps. Furthermore, because of very few deciduous trees in the past, forest management practices in the past did not consider promoting their production. But today, the number of deciduous trees in forests has increased more than the model expected, which may result in an overestimation of deciduous tree biomass production. It
may be also because the model considers deciduous trees to live longer than coniferous trees, so the model could have considered the larger deciduous tree sizes compared to coniferous trees.

3.2 Standing biomass carbon stock

The average annual carbon stock in the tree biomass for all scenarios increased continuously during the study period (Table 4). Overall, the Maximum and Environment scenarios had higher rates of carbon stock increase than the Reference and Production scenarios.

Table 4 Average annual tree biomass carbon stock changes during each 10-year period (Tg carbon year⁻¹) for Jämtland and Västernorrland (Paper I and II)

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The total standing biomass at the beginning and end of the study period for each scenario was calculated (Figure 3). All scenarios had larger standing biomasses at the end of the study period than at the beginning. The stock increases for the Maximum and Environment scenarios were 56% and 44%, respectively, compared to a 21% increase in the Reference scenario. The production increase in the Reference scenario is because the large areas with low productive forests are replaced with new planted forests with improved genetic material. The greater standing biomass in the Production and Maximum scenario may be explained as increased production due to climate change and intensive forestry practices, while it may be explained in the Environment scenario as a result of an increase in the amount of land set aside and a lower harvest intensity.
Figure 3 Standing forest biomass carbon stock at the beginning (2010) and end (2109) of the study period in the different scenarios (Paper II, Figure 6).

3.3 Soil carbon stock

Soil carbon changes due to different types of forest management and residues harvest were analysed. The results for soil carbon changes are presented in Table 2 of Paper I and Table 5 of Paper II, and the total soil carbon stock are presented in Figure 3 of Paper III. Figure 4 shows that the soil carbon changes occurred throughout the entire study period. The soil carbon stock increased more following stem-wood biomass harvest than following whole-tree biomass harvest. Total soil carbon stock was the highest for Maximum scenario and the lowest for Climate scenario compared to all other scenarios.
3.4 Substitution of fossil fuels and carbon-intensive products

The average annual carbon emissions reductions due to the use of forest biomass in place of fossil fuel and materials during each 10-year period are given in Table 5. Carbon emission reduction amounts were smaller when only biofuel substitution or non-wood construction material substitution was considered. The carbon emission reductions were smaller when biofuel only considered for fossil fuel substitution compared to both biofuel and construction material considered for fossil fuel substitution.
Table 5 Average annual carbon emissions reductions (Tg C year$^{-1}$) due to fossil fuel and carbon-intensive material substitution by the use of stem-wood and whole-tree biomass during each 10-year period (emissions reduction is shown with coal as a reference fuel, with values in parentheses representing substitutions using fossil gas as a reference fuel) (Paper I and II)

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Production increase associated with climate change (see Paper I) could increase carbon reduction by 10% using coal as a reference fuel and by 8% using fossil gas as a reference fuel compared to the Reference scenario. With intensive forestry practices, the Maximum scenario yielded a larger carbon emission reduction. The average annual carbon emission reductions as a result of whole-tree and stem-wood biomass use to replace fossil fuels and non-wood construction materials are shown in Figure 5. For all scenarios, the substitution of coal fuel with whole-tree biomass provided the greatest carbon emission reduction.
Climate change and intensive forestry significantly increased carbon emission reductions. Carbon emission reductions due to whole-tree use were compared to reductions due to the use of stem-wood. The greater carbon emission reduction occurred with whole-tree use. The \textit{Production} and \textit{Maximum} scenarios yielded the largest carbon reductions due to the greater amounts of biomass production and harvest in these scenarios compared to other scenarios. Overall carbon emission reductions due to substitution were greater compared to reductions due to standing biomass increases. Forest operation emissions were negligible compared to the carbon emission reductions.

3.5 Wood product carbon stock

Harvested wood products used as construction materials in buildings store carbon until the building is demolished. The carbon stocks calculated to be in the buildings are shown in Figure 6. The carbon stocks increased in all scenarios throughout the study period. A larger increase was observed in the \textit{Maximum} and \textit{Production} scenarios than in the other scenarios.
Figure 6 Wood product carbon stock (Tg carbon) due to non-wood material substitution (Paper III).

3.6 Carbon emissions from forest operations

Intensive forestry requires additional operational activities in the forest. In addition, a larger biomass production requires additional work for e.g., thinning and harvest of the biomass. This study includes the calculation of carbon emissions during forest operational activities from forest regeneration to the final harvest. The Maximum, Production, and Climate scenarios yielded greater carbon emissions than the Reference scenario. The greater emissions in these scenarios are due in part to the fertiliser production and application, and greater amounts of biomass to be harvested and hauled to the road head (Figure 7). The largest percentage of the emissions comes from round wood harvest during thinning and final felling. Stump harvest and haulage result in carbon emissions comparable to those associated with residue collection and haulage.
Figure 7 Carbon emissions due to forest operations and fertilisation for all scenarios for whole-tree biomass (Mg carbon year\(^{-1}\)).

3.7 Total carbon balance

Table 6 shows the total carbon balance, which is reduced net carbon emissions into the atmosphere due to forest biomass production and their uses. The calculation of carbon emissions reductions takes into account the carbon stock increases in living biomass, in forest soil, in wood products, and substitution carbon benefit due to the substitution of non-wood materials and fossil fuels by the use of forest biomass. Forest operation emissions were deducted from the carbon emissions reductions due to substitution effects to obtain net substitution values. Thus, the total carbon balance is the net carbon emission reduction resulting from forest production and product use. The carbon balance is increasing every year because of carbon stock increases in trees, soil, and products, as well as increasing substitution effects.

Table 6 The total carbon balance including forest production, forest biomass harvest, soil carbon stock change, and stem-wood and whole-tree biomass use to replace of fossil fuels and carbon-intensive materials (Tg carbon year\(^{-1}\)) during each 10-year period in Jämtland and Västernorrland. The total carbon balance is for coal as a reference fuel, with values in parentheses representing fossil gas as a reference fuel (Paper I and II).

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Whole-tree   6.3(4.8)  6.2(4.8)  5.5(4.0)  5.9(4.3)  5.9(4.3)  6.0(4.4)  6.1(4.5)  6.4(4.8)  6.4(4.8)  6.5(4.8)  
Climate scenario
Stem-wood    5.5(4.5)  5.5(4.6)  4.9(3.8)  5.4(4.3)  5.7(4.5)  5.8(4.5)  6.1(4.8)  6.3(5.0)  7.1(5.8)  7.5(6.0)  
Whole-tree    6.4(4.9)  6.5(5.1)  6.0(4.4)  6.6(4.9)  6.9(5.1)  7.1(5.2)  7.4(5.5)  7.6(5.7)  8.5(6.5)  9.0(6.8)  
Environmental scenario
Stem-wood    5.5(4.5)  5.7(4.7)  5.0(4.0)  5.4(4.4)  5.6(4.5)  5.7(4.5)  6.1(5.0)  6.4(5.2)  6.5(5.2)  7.0(5.7)  
Whole-tree    6.3(4.9)  6.6(5.2)  6.1(4.6)  6.6(5.0)  6.8(5.2)  6.9(5.2)  7.3(5.6)  7.6(5.8)  7.8(5.9)  8.4(6.4)  
Production scenario
Stem-wood    5.6(4.6)  5.8(4.8)  5.5(4.4)  6.2(5.0)  6.6(5.3)  6.5(5.1)  6.8(5.4)  7.1(5.6)  7.6(6.1)  8.1(6.5)  
Whole-tree    6.5(5.0)  6.8(5.3)  6.7(5.0)  7.4(5.7)  7.9(6.0)  7.9(5.9)  8.3(6.2)  8.5(6.4)  9.1(6.0)  9.7(7.3)  
Maximum Scenario
Stem-wood    5.6(4.6)  5.8(4.8)  5.6(4.4)  6.6(5.4)  7.0(5.7)  7.0(5.6)  7.7(6.2)  8.2(6.7)  8.8(7.3)  9.4(7.7)  
Whole-tree    6.5(5.0)  6.8(5.3)  6.8(5.1)  7.9(6.1)  8.4(6.5)  8.5(6.4)  9.2(7.0)  9.7(7.5)  10.4(8.2) 11.2(8.7)  

Figure 8 shows the average annual carbon emission reductions (Tg carbon year$^{-1}$) over the 100-year period for all scenarios for whole-tree biomass use to replace coal and fossil gas. The largest carbon emission reduction was achieved in the Maximum scenario (8.53 Tg carbon year$^{-1}$) when compared to the Reference scenario (6.07 Tg carbon year$^{-1}$) while replacing coal fuel. The average annual carbon emission reductions were smaller when fossil gas was replaced.

Figure 8 The average annual carbon emissions reduction (Tg carbon year$^{-1}$) for different scenarios when whole-tree biomass was used to replace coal and fossil gas.

The total carbon balance is highly influenced by substitution effect. The carbon balance increased for both stem-wood and whole-tree biomass during the study period, with the greatest increase occurring when whole-tree biomass was used as an alternative to fossil fuel. The use of whole-tree biomass resulted in lower soil carbon stock increases than the use of stem-wood biomass, though the increased substitution benefits more than compensated.

Figure 9 shows the average annual carbon emission reductions per hectare of forest (Mg ha$^{-1}$ year$^{-1}$) for all scenarios for whole-tree biomass use during the study period. The reduction was greatest in the Maximum scenario. When coal was
replaced with biofuel instead of fossil gas, the overall carbon emission reduction increased by ~30-35% for whole-tree biomass. Forest carbon stock increases were greater for the Environment and Maximum scenarios than for the other scenarios. The increase in the amount of set aside areas and lower harvest levels in the Environment scenario led to an increase in the forest carbon stock. Greater carbon emissions reductions in the Maximum scenario compared to other scenarios were due to forest management practices that promoted biomass production.

Figure 9 The average annual carbon emissions reductions per hectare of forest land (Mg carbon ha\(^{-1}\) year\(^{-1}\)) due to the benefits associated with the use of whole-tree (WT) and stem-wood (SW) biomass to replace fossil gas and coal.

The carbon emissions reductions were greatest in the Maximum scenario. The cumulative carbon emissions reductions in different scenarios of whole-tree biomass use with coal as a reference fuel are presented in Paper I and II. The largest carbon reduction was found in the Maximum scenario, and the lowest reduction occurred in the Reference scenario. Figure 10a and 10b shows the differences in cumulative carbon emission reduction between the Reference scenario and the Climate, Environment, Production, and Maximum scenarios for whole-tree biomass use (Figure 10a) and for stem-wood biomass use (Figure 10b) with coal and fossil gas as reference fuels. The difference is largest between the Maximum and Reference scenarios for both whole-tree and stem-wood biomass use with coal as a reference fuel. A greater amount of carbon emissions was reduced when coal was used as a reference fuel than when fossil gas was used as a reference fuel.
Figure 10 Differences in cumulative carbon emission reduction (Tg carbon) between the Climate, Environment, Production and Maximum scenarios and the Reference scenario for each 10-year period.
4 Discussions

4.1 Forest production and harvest

The current average annual forest productivity for the Jämtland and Västernorrland forests is about 2.1 Mg (dry mass) ha\(^{-1}\) year\(^{-1}\) (Swedish Forest Agency, 2010). In this study, the forest 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. Levels of biomass production were larger when the effects of climate change and intensive forestry were included compared to results from a Reference scenario that did not include these effects. 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, which included both climate change and intensive forestry effects. Increasing forest production increases the potential harvest, substitution potential, standing biomass and soil carbon.

The harvesting of forest residues from forest land during final felling is a common practice in Sweden, while stump harvesting is not. The Swedish forest agency recommends that at least 20% of logging residues and 15-20% of stumps should be left at the site of the final felling (Swedish Forest Agency, 2008, 2009). The practice of whole-tree harvest is debated because harvesting residues and stumps may reduce forest productivity in the following generation because of tree litters removals. This issue has been discussed in earlier studies (Jacobson et al., 2000; Egnell and Valinger, 2003; Smolander et al., 2010; Egnell, 2011). However, results from other studies, such as that performed by Egnell (2011), show that these effects are only temporary and can be compensated for by fertilisation. Nutrient deficiencies are assumed to be satisfied because this study includes balanced fertilisation (except for the Reference scenario).

The forest management practices considered in this study assume that the biomass production and harvest is continuous without losing the forest’s capacity to produce and deliver at least the same amount of product every growth cycle. This study also follows criteria for increased environmental ambitions, for example increased set-aside areas for special environmental care proposed by the Swedish Environmental Agency. All scenarios follow, at a minimum, the specified environmental goals set by current Swedish forest and environmental policy.
4.2 Carbon-intensive products substitution

Substituting fossil fuels with forest biomass has a significant impact on the life cycle carbon balance. Biomass residues left in the forest after harvest release carbon into the atmosphere for some period of time as they decay; however, recovering residues to replace fossil fuels reduces net carbon emissions due to avoided fossil emissions and forest regrowth. Carbon emissions resulting from forest operations are less for stem-wood harvest than for whole-tree harvest because of the smaller amount of biomass to be harvested compared to whole-tree biomass. Although carbon emissions resulting from forest operations are greater for whole-tree harvest, the overall carbon emission reduction is greater with whole-tree biomass harvest compared to stem-wood biomass harvest, because of the increased substitution benefits.

Substituting coal provides greater carbon emission reductions than substituting fossil gas, because coal emits more CO₂ per unit of energy than does fossil gas. The production of non-wood construction materials such as cement and steel uses a greater amount of fossil energy compared to the amount needed to produce wood products. Therefore, replacement of carbon-intensive fuels and materials with wood products will generally reduce carbon emissions. However, there may be a question as to whether all of the wood material produced can be used in building construction or to replace fossil fuels. Jonsson (2009) claimed that about 30% of multi-storey houses constructed in Sweden by 2015 will be wood-framed buildings. When the total number of wood-framed buildings increases, the carbon benefit will increase (Gustavsson et al., 2006b). Wood products can also be exported to substitute for non-wood products in other countries. The use of bioenergy is also increasing, and international trade in bioenergy is made feasible by efficient long-distance transport methods (Junginger et al., 2008). Gustavsson et al. (2011) calculated that woody biofuels can be economically transported internationally with little loss of net energy. If additional wood biomass is exported and used in place of non-wood building materials in other countries, high emission reductions per unit of biomass could be obtained using a large amount of the forest biomass, thus resulting in a greater overall emission reduction globally.

4.3 Carbon balance

This study considers carbon reduction benefits in different stages of forest production and utilisation. The overall carbon balance depends on the intensity of
forest management practices, what reference system is selected for biomass utilisation, which reference fuel is considered to be replaced during substitution, and which materials are compared. Sweden has adopted advanced forest management practices for decades. Continuously increasing the carbon stock in living forest biomass is not a viable long-term option for the mitigation of climate change because the carbon stock starts to be released into the atmosphere after its equilibrium level is reached, thereby limiting total carbon sequestration (Schlamadinger and Marland, 1996). Furthermore, the dead biomass left in the forest eventually decomposes and most of its stored carbon is released into the atmosphere.

The calculated carbon emission reductions are large enough to contribute significantly to the carbon emission reduction target in Sweden. In the year 2008, the total amount of CO₂ emissions in Sweden was 50 million tonnes (Swedish Energy Agency, 2010). Based on the calculations performed in this study to determine the additional potential contribution of forest production and product use to the reduction of carbon emissions, forest management in Jamtland and Västernorrland counties based on the Maximum scenario would reduce annual average CO₂ emissions corresponding to 18% and 15% of the total 2008 carbon emissions of Sweden if the biomass is used to replace coal fuel and fossil gas fuel respectively. The CO₂ emissions reduction due to forest management based on the Production scenario corresponds to a 13% and 11% reduction in the total 2008 carbon emissions of Sweden if the biomass is used to replace coal and fossil gas respectively. In this study, it was not possible to calculate the total carbon benefit for all of Sweden due to the differences in forest growth, soil carbon, and standing biomass in the different parts of the country. However, extending this study to all of Sweden may provide a more comprehensive picture of possible carbon emission reductions.

In Sweden, forest residue is mainly used within the forest industry for 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). Biofuel not utilised in Sweden can be transported and used in other countries in Europe. The increasing use of wood as a construction material is an important option for reducing net CO₂ emissions because of the low energy requirements for
processing, the increased wood product stock, and the increased availability of biofuel as by-products (Gustavsson and Sathre, 2006). The soil carbon stock was found to increase, but the increase occurred at a slower rate in the later stages of the study period, assuming whole-tree harvest. The reduction in soil nutrients and forest soil carbon due to residue harvest may be only temporary if the forest is enriched by fertilisation (Paper I and II) (Egnell, 2011).

4.4 Uncertainties and limitations

The integrated analysis method used in this study contains inherent uncertainties because of the large number of factors to be considered and assumptions to be made. In addition, the carbon balance analysis is carried out over long time periods, resulting in a greater number of factors to be considered and inherent uncertainty about future events. One of the basic assumptions of this study was the temperature change due to climate change effect. As discussed by the IPCC, climate change and subsequent temperature changes will depend on changes in global population, energy demand, climate change mitigation activities that are implemented, and the additional need for resources, leading to changes in land use patterns and an increase in the number of methods developed to improve industrial efficiency to reduce CO₂ emissions. This thesis uses the SRES B2 scenario of climate change, which assumes an increase of temperature of 4 °C, but the actual future increase is uncertain. A number of factors in plant growth and nutrient cycling could not be taken into account and might result in different NPP results. The elevated temperature may encourage the earlier onset of bud-burst in the spring, which may increase the risk of frost injury during the early growth stage of planted seedlings (Cannell and Smith, 1986; Hänninen, 1991; Kramer, 1994; Krasowski et al., 1995). Potential injuries and shoot mortality due to frost were not included in this study.

The increased demand for nutrients and increased biomass production 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, 1991; Houghton et al., 1998; McMurtrie et al., 2001). In the Reference and Environment scenarios, traditional fertilisation was assumed to supply additional nutrients in some part of forest land, whereas in the other two scenarios, balanced fertilisation was provided to assist soil nutrient dynamics in increased forest area. Changes in the amount of fertilisation and the availability of water resources during growth periods might result in slightly different values of NPP. In this
landscape study, the site fertility was not known in detail, and the decision to fertilise forest stands may yield different results in a site-specific analysis. Increased mineralisation and nutrient availability as effects of increased soil temperatures have been observed in earlier studies (Jarvis and Linder, 2000). In a soil-warming experiment in northern Sweden, stem-wood production was greater for heated plots compared to unheated plots (Strömgren and Linder, 2002). In this study, a residue harvest of 75% and a 50% stump harvest in the whole-tree harvest scenario did not affect plant growth in the subsequent years. The amount of soil nitrogen and plant growth might be affected to some degree in these scenarios, which could affect biomass production.

Any error in BIOMASS would be multiplied in HUGIN and in the other models as well. 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 of elevated temperature is predicted in a realistic way.

HUGIN uses national forest inventory 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 have been slightly different than they would have been had they been calculated with a function similar to that used by HUGIN. Substitution modelling is based on a case study of a single building, and may give slightly different results if the architectural or engineering designs of the building were different. However, climate benefits of wood substitution in general are quite robust (Sathre and O’Connor, 2010).

Climate change may result in wind damages, fire risk, pathogens, and insect outbreaks, which may affect forest growth and mortality (Battles et al., 2008; Kurz et al., 2008; 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. The carbon balance analysis is based on both the forest products derived from a sustainably managed forest and the Swedish forest production and utilisation recommendations and guidelines. The risks and advantages of intensive fertilisation in the forest and the use of whole-tree biomass need to be compared.
5 Conclusions

Climate change could significantly increase the forest biomass production in Jämtland and Västernorrland. Forest productivity could further be increased by applying intensive forestry practices. Intensive forestry practices are possible for all of the forest types in Jämtland and Västernorrland and in some cases can be applied on a large scale, such as soil scarification during regeneration, increased pre-commercial thinning, and fertilisation. Increased forest biomass production increases the potential harvest of biomass. The harvest of residues and stumps could increase the carbon benefit through the substitution of carbon-intensive fossil fuels and materials. The harvesting of residues and stumps does not significantly reduce soil carbon, but available biomass could be used to achieve a greater reduction in carbon emissions. Carbon emission reductions as a result of forest biomass use can be achieved during each rotation period, and the reductions would be cumulative in the long run. Carbon emission reduction benefits would be lower if the forest is not managed to increase biomass production and harvest. The carbon emission reduction benefits may be greater if the biomass harvest is larger. In such cases, forests can only sequester carbon until the natural equilibrium of biomass stock is reached and it then either remains near constant or is reduced due to mortality. Leaving residues and stumps in the forest during harvest operations would help increase soil carbon by a small amount compared to the carbon emission reductions achieved by the use of residues and stumps to substitute fossil fuels. Forest management strategies that promote an increase in sustainable biomass production and use would provide a reduced net carbon emission.
6 Future research

Previous studies of the climate implications 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 emissions, and radiative forcing effects from different types of forest management practices. The concept of forest conversion into continuous cover forestry has emerged, and studies on the standing biomass carbon stock and soil carbon stock in continuous cover forestry would allow for a comparison of the carbon balance benefits between continuous cover forestry and clear-cut forestry. 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 carbon emissions by 2020. It would be interesting to study carbon storage in forest ecosystems and wood products for this very short 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 the building sector in the future. Sweden produces large amounts of forest biomass (a recent annual harvest is 90 million m³), but it still imports biofuels from other countries. The tradeoffs between the production, harvest, export and import of biomass could be useful.

This study provides a brief assessment of forest production and utilisation at the landscape level in only part of Sweden. Extending this study over all of Sweden may provide a clearer picture of the potential effects of forest production and product use for the entire country. 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 for the entire country. This may be of interest to the Swedish government and to forest owners for planning their forest management, harvest and product business both in the national and international contexts. 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 what it is today would provide a reference for forest product use in the future.

7 References


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