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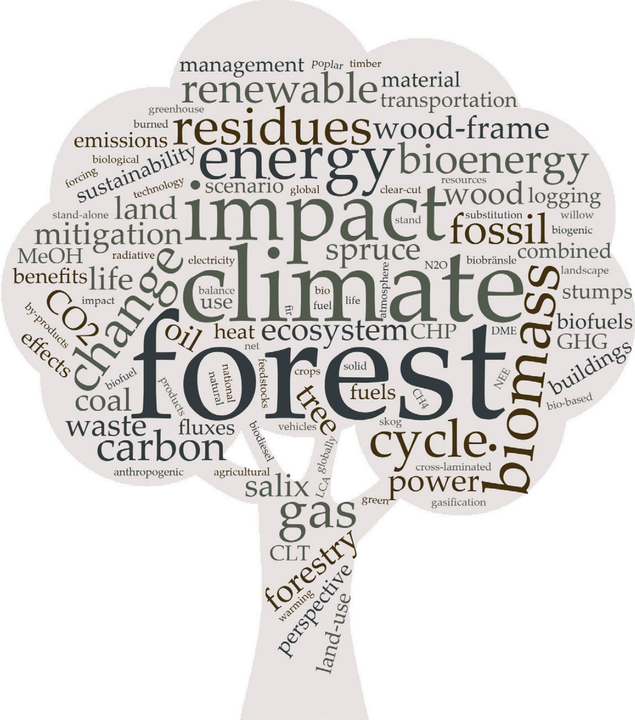
– a life cycle perspective



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CLIMATE IMPACT OF THE SUSTAINABLE USE OF FOREST BIOMASS IN ENERGY AND MATERIAL SYSTEM

– *a life cycle perspective*

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Climate impact of the sustainable use of forest biomass in energy and material system - a life cycle perspective
Doctoral Dissertation, Department of Built Environment and Energy Technology, Linnaeus University, Växjö, 2018

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Abstract

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Human society releases greenhouse gas emissions to the atmosphere while providing housing, heat, mobility and industrial production. Man-made greenhouse gas emissions are the main causes of climate change, coming mainly from burning fossil fuels and land-use changes. Sustainably managed forests play an important role in climate change mitigation with the prospect of sustainably providing essential materials and services as part of a low-carbon economy, both through the substitution of fossil-intensive fuels and material and through their potential to capture and store carbon in the long-term perspective.

The overall aim of this thesis was to develop a methodology under a life cycle perspective to assess the climate impact of the sustainable use of forest biomass in bioenergy and material systems. To perform this kind of analysis a methodological framework is needed to accurately compare the different biological and technological systems with the aim to minimize the net carbon dioxide emissions to the atmosphere and hence the climate impact. In such a comparison, the complete energy supply chains from natural resources to energy end-use services has to be considered and are defined as the system boundaries. The results show that increasing biomass production through more intensive forest management or the usage of more productive tree species combined with substitution of non-wood products and fuels can significantly reduce global warming. The biggest single factor causing radiative forcing reduction was using timber to produce wood material to replace energy-intensive construction materials such as concrete and steel. Another very significant factor was replacing fossil fuels with forest residues from forest thinning, harvest, wood processing, and post-use wood products. The fossil fuel that was replaced by forest biomass affected the reductions in greenhouse gas emissions, with carbon-intensive coal being most beneficial to replace. Over the long term, an active and sustainable management of forests, including their use as a source for wood products and bioenergy allows the greatest potential for reducing greenhouse gas emissions.

Key words: forest residues, fossil fuel substitution, forest management, radiative forcing, land use change, climate change, bioenergy

Dedicated to Emil and Oscar

"The best time to plant a tree was 20 years ago.
The second best time is now."

- Chinese proverb

SUMMARY

Human life on the earth depends on suitable climatic conditions, although the way we live is changing the climate. Human activities release greenhouse gases to the atmosphere as a result of providing housing, heat, mobility and industrial production. Man-made greenhouse gas emissions are the main cause of climate change, coming mainly from burning fossil fuels like coal, oil and fossil gas, but land-use changes also contribute significantly to total emissions. Climate scientists have observed that carbon dioxide concentrations in the atmosphere have increased significantly over the past century, compared to the pre-industrial era level, resulting in increased global surface temperature known as global warming. In order to prevent serious impacts on human life, research indicates that global warming needs to be limited to less than 2 °C and global efforts are being made to stay below this level.

Sustainably managed forests play an important role in any discussion of the mitigation of climate change, with the prospect of sustainably providing essential materials and services as part of a low-carbon economy, both through the substitution of fossil-intensive fuels and materials and through their potential to capture and store carbon in the long-term.

The overall aim of this thesis and the studies upon which it is based was to develop a methodology, from a life cycle perspective, to assess the climate impact of the sustainable use of forest biomass in bioenergy and bio-based material systems. For this, the development of systems analysis and scenario techniques is necessary to study how different bioenergy systems in the forest, heat, power and transportation sector could contribute to climate change mitigation. To perform this kind of analysis, a methodological framework is needed to accurately compare the different biological and technological systems with the aim of minimizing the net CO_2 emissions to the atmosphere and hence the climate impact. In such a comparison, the complete energy supply chains from natural resources to energy end-use services have to be considered and are defined as the system boundaries.

The results show that increasing biomass production through more intensive forest management or the use of more productive tree species combined with substitution of non-wood products and fuels can significantly reduce cumulative radiative forcing, in other words global warming. The emissions from intensified forest management result in very little radiative forcing in comparison to the negative radiative forcing from using the increased forest growth for biomass substitution. The biggest single factor causing radiative forcing reduction is using timber to produce wood material to replace energy-intensive construction materials such as concrete and steel. Another very significant factor is replacing fossil fuels with forest residues from forest thinning, harvest, wood processing, and post-use wood products. When fossil fuel is replaced by forest biomass, there are reductions in greenhouse gas emissions and radiative forcing, with carbon-intensive coal being most beneficial to replace. The climate benefits of fertilization are proportional to the increased rate of biomass production, in terms of shortened rotation lengths and increased harvest volumes. Because the substitution benefits of forest product use are cumulative, and the carbon sink in the forest biomass and soil is limited, the non-management and non-use of forest biomass becomes less attractive as the time horizon increases. Over the long term, active and sustainable management of forests, including their use as a source for wood products and biofuels, has the greatest potential for reducing net carbon emissions.

For future work it is recommended that this kind of analysis is performed on the landscape level. To improve accuracy, albedo changes due to forest management and climate change should be incorporated into the framework, using a spatially specific surface albedo model as well as a model to translate changed surface albedo into climate change effects.

Key words: forest residues, fossil fuel substitution, forest management, radiative forcing, land use change, climate change, bioenergy

SAMMANFATTNING

Jordens klimat är avgörande för vårt liv på planeten, men genom vårt sätt att leva förändras klimatet. Det mänskliga samhället släpper ut växthusgaser i atmosfären när man tillhandahåller bostäder, värme, mobilitet och industriell produktion. Antropogena växthusgasutsläpp är den främsta orsaken till klimatförändringen. Främst kommer utsläppen från förbränning av fossila bränslen så som kol, olja och fossila gaser, men förändringar i markanvändningen bidrar också avsevärt till de totala utsläppen. Klimatforskare har observerat att koldioxidkoncentrationerna i atmosfären har ökat avsevärt under det senaste århundradet, jämfört med den preindustriella erans nivå, vilket har medfört en ökad nivå i den globala yttemperaturen, även känd som global uppvärmning. För att förhindra allvarliga konsekvenser för människoliv indikerar forskning att den globala uppvärmningen måste begränsas till mindre än 2 °C och att globala ansträngningar görs för att hålla sig under denna nivå.

Ett hållbart skogsbruk spelar en viktig roll i minskningen av klimatförändringarna med möjligheten att på ett hållbart sätt tillhandahålla väsentliga material och tjänster som en del av en koldioxidsnål ekonomi, både genom substitution av fossil-intensiva bränslen och material samt genom deras potential att fånga och lagra kol i det långsiktiga perspektivet.

Det övergripande syftet med denna avhandling var att utveckla en metodik för att kunna bedöma klimatpåverkan av hållbar användning av skogsbiomassa i bioenergi och biobaserade materialsystem i ett livscykelperspektiv. För detta är en utveckling av systemanalys och scenarioteknik nödvändig för att kunna studera hur olika bioenergisystem inom skogs-, värme-, kraft- och transportsektorn kan bidra till att minska klimatförändringen. För att utföra denna typ av analys behövs en metodologisk ram för att kunna jämföra de olika biologiska och tekniska systemen med målet att minimera de totala koldioxidutsläppen till atmosfären och därmed klimatpåverkan. I en sådan jämförelse måste de kompletta energiförsörjningskedjor, från naturresurser till slutanvändningstjänster, betraktas och definieras som systemgränserna. Resultaten visar på att en ökad biomassaproduktion genom ett intensivt skogsbruk eller användningen av mer produktiva trädslag kombinerat med substitution av icke-träprodukter och bränslen kan minska kumulativ strålningsbalans, med andra ord global uppvärmning. Utsläppen från ett intensifierat skogsbruk resulterade i mycket liten strålningsbalans i jämförelse med den negativa strålningsbalansen från att använda den ökade skogstillväxten för biomassasubstitution. Den största enskilda faktorn som orsakade strålningsbalans reduktion var användning av timmer för att producera trämaterial för att ersätta energiintensiva byggmaterial så som betong och stål. En annan signifikant faktor var att ersätta fossila bränslen med skogsråvara från gallring, avverkning, träbearbetning och återanvändning av träprodukter. Det fossila bränslet som ersattes av skogsbiomassa påverkade minskningarna av växthusgasutsläpp och strålningsbalansen, varvid kol är mest fördelaktigt att ersätta. Klimatfördelarna med gödsling var proportionella mot ökad biomassaproduktion, när det gäller förkortade rotationslängder och ökade avverkningsvolymer. Eftersom substitutionsfördelarna med skogsproduktanvändning är kumulativa och skogsbiomassans och markens möjlighet att absorbera kol är begränsad blir icke-förvaltning och icke-användande av skogsbiomassa mindre attraktivt ju längre tidsperiod man tittar på. På lång sikt möjliggör en aktiv och hållbar förvaltning av skogar, inklusive deras användning som källa för träprodukter och biobränslen, den största potentialen för att minska de totala koldioxidutsläppen.

För framtida forskning rekommenderas det att utföra denna typ av analyser på landskapsnivå. För att förbättra noggrannheten ska albedo förändringar som sker på grund av skogsbruk och klimatförändringar införlivas i ramverket, med hjälp av en rumslig specifik albedo modell samt en modell för att översätta ändrade albedo ytor till klimatpåverkan.

Nyckelord: skogsråvara, substitution av fossila bränslen, skogsbruk, strålningsbalans, förändring av markanvändning, klimatförändring, bioenergi

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Växjö, January 2018
Sylvia Haus

APPENDED PAPERS

This thesis builds on the following papers, referred to by Roman numerals in text and appended in the thesis.

I. Haus, S., Gustavsson, L., and Sathre, R. (2014). *Climate mitigation comparison of woody biomass systems with the inclusion of land-use in the reference fossil system*. Biomass and Bioenergy, 65, 136-144.

II. Gustavsson, L., Haus, S., Ortiz, C. A., Sathre, R., and Le Truong, N. (2015). *Climate effects of bioenergy from forest residues in comparison to fossil energy*. Applied Energy, 138, 36-50.

   Gustavsson, L., Haus, S., Ortiz, C. A., Sathre, R., and Le Truong, N. (2016). Corrigendum to *Climate effects of bioenergy from forest residues in comparison to fossil energy*. Applied Energy, 170, 490-493.

III. Gustavsson, L., Haus, S., Lundblad, M., Lundström, A., Ortiz, C. A., Sathre, R., Le Truong, N. and Wikberg, P. E. (2017). *Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels*. Renewable and Sustainable Energy Reviews, 67, 612-624.

IV. Haus, S. and Trischler, J. (2017) *Climate impact of using abandoned farmland for biofuel production in the transportation sector*. Submitted to journal.

V. Haus, S., Poudel, B.C., and Bergh, J. (2017*) Time-dependent climate impact and the challenges of competing forest land use of producing timber construction systems and bioenergy*. Manuscript - to be submitted.

AUTHOR'S CONTRIBUTION

The contribution of Sylvia Haus to the papers included in this thesis was as follows:

I. Planned the study and scenarios together with the co-authors. Prepared the life cycle inventory and performed the climate impact calculations and prepared the data presentation (figures and tables). Wrote most of the paper with input from the co-authors.

II. Planned the study together with the co-authors. Prepared the life cycle inventory, performed the climate impact calculations and contributed to interpretation of the results. Wrote the paper together with the co-authors.

III. Planned the study together with the co-authors. Prepared the life cycle inventory, performed the climate impact calculations and contributed to interpretation of the results. Wrote the paper together with the co-authors.

IV. Developed the study and scenarios in cooperation with the co-author. Developed the simulation model, prepared the life cycle inventory and performed all calculations. Prepared the data and wrote most of the paper with input from the co-author.

V. Developed the study and scenarios in cooperation with the co-authors. Developed the simulation model, prepared the life cycle inventory and performed all calculations. Prepared the data presentation and wrote most of the manuscript with input from the co-authors.

TABLE OF CONTENT

ABBREVIATIONS

BST	biomass-based steam turbine
CH_4	methane
CHP	combined heat and power
CLT	cross-laminated timber
CO_2	carbon dioxide
CRF	cumulative radiative forcing
CST	coal-based steam turbine
DM	dry matter
FOCC	fuel oil-based combined-cycle
FOGC	fossil gas-based combined-cycle
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt hour
LCA	life cycle assessment
MeOH	methanol
Mt	megaton
MWh	megawatt hour
N_2O	nitrous oxide
ppbv	parts per billion by volume
ppm	parts per million
RF	radiative forcing
SOC	soil organic carbon
SRC	short rotation coppice
TWh	terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change

1. INTRODUCTION

1.1. Background

Climate change

It is increasingly recognized that climate change due to anthropogenic greenhouse gas (GHG) emissions is one of the greatest challenges facing our society, with major implications for both human and natural systems. Climate scientists have observed that carbon dioxide (CO_2) concentrations in the atmosphere have increased significantly over the past century, compared to the pre-industrial era level of about 280 parts per million (ppm). In 2016, the average concentration of CO_2 (403 ppm) was about 40% higher than in the mid-1800s, with an average increase of 2 ppm year^{-1} in the last ten years (IEA 2017a; Jackson et al. 2017). Significant increases have also occurred in the levels of the two other major GHGs, namely methane (CH_4) and nitrous oxide (N_2O). Most anthropogenic GHG emissions (approximately 75% of CO_2 emissions) come from combustion of fossil resources, while land-use changes account for the rest (IPCC 2007a).

Fossil fuels, including coal, oil and fossil gas, supplied approximately 81,4% of global primary energy in 2015 (IEA 2017), and their use is expected to increase in the future even if policy measures are implemented to reduce fossil fuel use (IEA 2013) (Figure 1). The largest use of fossil energy is for electricity and heat production, both globally and in the EU. Fossil fuel-based stand-alone power plants with low conversion efficiency dominate electricity production. Policy measures, however, are being implemented to increase the use of combined heat and power (CHP) plants (European Commision 2004). Coal accounts for about 40% of global anthropogenic CO_2 emissions and about 70% of the emissions from the global power sector (Burnard & Bhattacharya 2011). While coal is the most important fuel for electricity and heat production, oil is the most important fuel for transportation, accounting for 53% of total oil use globally in 2012 and for about 93% of transport energy globally and in the EU (IEA 2012; Van der Hoeven & Houssin 2015). Fossil fuels are expected to continue to dominate primary energy use. Forecasts from the International Energy Agency (IEA 2016b) show that under the current policy scenario, the New Policy scenario and the 450 Scenario, in 2040 the energy system will still heavily depend on fossil fuels, globally and in the EU, Figure 1.

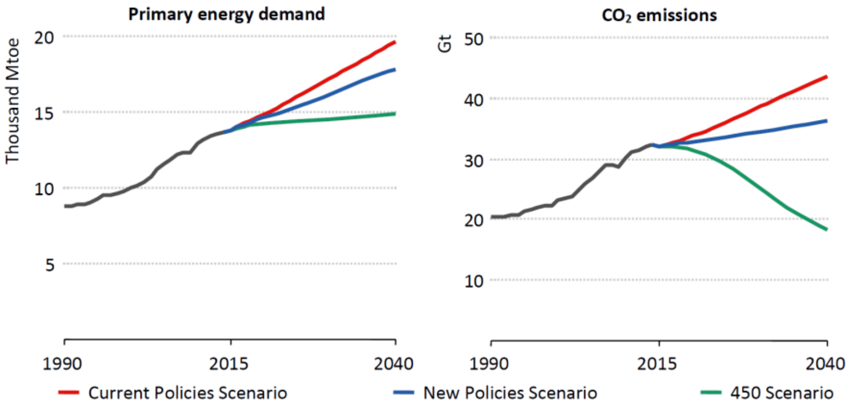

Figure 1. Historical and projected trends of global primary energy demand and related CO_2 emissions through 2040 with policy measures implemented for reducing the use of fossil fuel (IEA New Policies Scenario and 450 Scenario) (IEA 2016b)

In order to prevent serious impacts on human life, research indicates that global warming needs to be limited to less than 2 °C and global efforts are being made to stay below this level. For example, an agreement was signed in Paris in 2015 by member countries of the United Nations Framework Convention on Climate Change (UNFCCC). This so-called *Paris Agreement* sets out the common goal to limit global warming and identifies ways in which this might be achieved. It aims to strengthen the global response to the threat of climate change, by:

> *"Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels." (UNFCCC 2015)*

The IPCC has developed a series of climate scenarios known as representative concentration pathways (RCP), quantified according to changes in radiative forcing over time (Van Vuuren et al. 2011). Radiative forcing measures the imbalance between incoming and outgoing radiation for the earth system. In the RCP2.6 scenario, radiative forcing peaks at ~3 W/m^2 and declines thereafter to 2.6 W/m^2 by 2100, as GHG emissions are reduced substantially. In the RCP4.5 Scenario, radiative forcing stabilizes without overshoot at 4.5 W/m^2 by 2100, as strategies are deployed to reduce GHG. In the RCP6.0 scenario, radiative forcing stabilizes without overshoot at 6 W/m^2 by 2100. In the RCP8.5 scenario, radiative forcing rises to 8.5 W/m^2 by 2100, as GHG emissions continue to increase as usual.

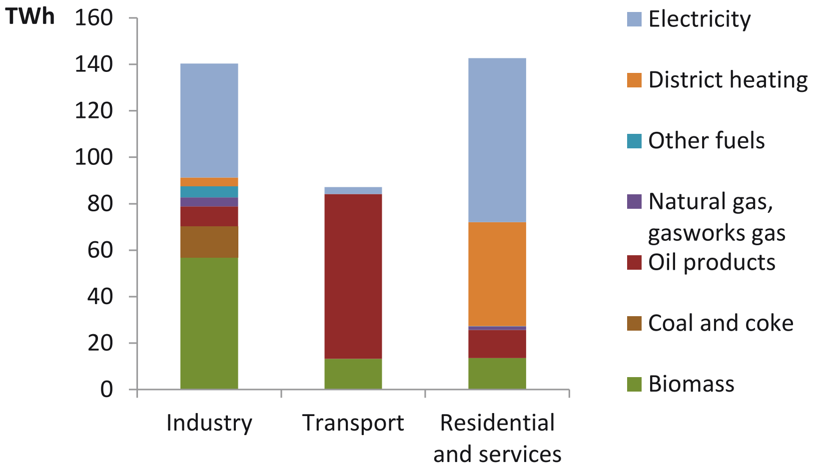

Figure 2. Total final energy use in Sweden 2016, per sector (Swedish Energy Agency 2017)

The role of bioenergy use in Sweden

Bioenergy is currently the largest renewable energy source, accounting for about 10% of the global primary energy supply in 2014 (IEA 2016b). Bioenergy is the leading energy source in Sweden today. The Swedish energy system has gone through a major transformation. In the 1970s oil was totally dominant. Today, oil is almost entirely a transport fuel, whereas bioenergy has taken over in district heating, and plays a major role in industry and in electricity production (Figure 2). The use of bioenergy in Sweden has increased from 40 TWh year^{-1} in the 1970s to around 140 TWh today. In

Sweden, the share of bioenergy is high compared with the global situation, accounting for 23% of the energy supply.

This is mainly based on energy coming from forest biomass, while agriculture-based biomass fuels are only used to a small extent (Ericsson & Werner 2016; Karlsson et al. 2017). Forest residues are increasingly used for energy purposes in Sweden. Currently 20% of all harvestable residues in Sweden are used for bioenergy (Routa et al. 2013; Skogsstyrelsen 2011), though there is great potential for increasing the extraction of forest residues. The Swedish Forest Agency (Skogsstyrelsen 2008b) estimates the potential harvest of branches and tops in Sweden to be in the range of 16 to 25 TWh year^{-1}. Potential stump harvest in Sweden is estimated to be in the range 21 to 34 TWh year^{-1}. Forest residues can be used in numerous ways for climate change mitigation and fossil energy use reduction (Hammar et al. 2015; Kilpeläinen et al. 2016; Routa et al. 2012). However, the climate benefits depend on how they are used and which types of fossil fuels are replaced, as well as what happens to the forest residues if they are left in the forest.

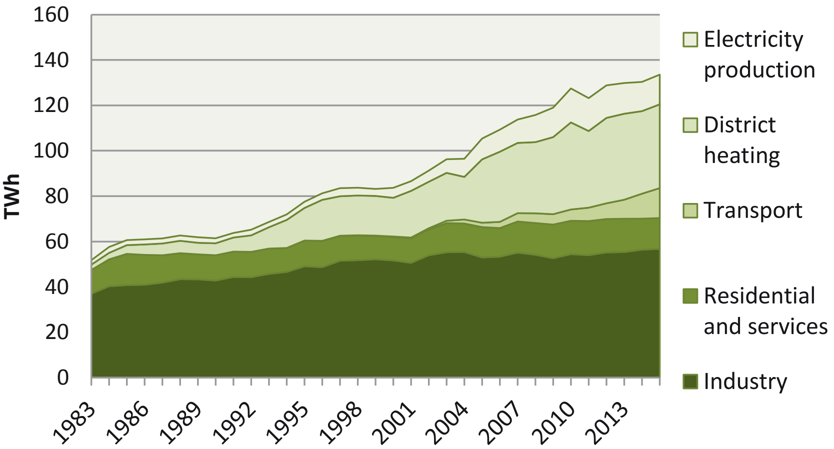

Figure 3. Total final bioenergy use in Sweden 2016, per sector (Swedish Energy Agency 2017)

Sustainable forestry and climate change mitigation potential

To tackle global warming, most countries of the world have signed an international treaty, the UNFCCC (United Nations Framework Convention on

Climate Change) in June 1992. The main purpose of the UNFCCC is to consider what can be done to reduce global warming, and to cope with whatever temperature increases are inevitable. The UNFCCC highlights two fundamental response strategies to address climate change: adaptation and mitigation. While adaptation aims to reduce the adverse impacts of climate change through a wide-range of system-specific actions, mitigation looks at limiting climate change by reducing the emissions of GHGs and by enhancing sink opportunities (IPCC 2014).

There is a large potential for biomass to be used in the electricity, industry, building, and transportation sectors, replacing fossil coal, oil or gas in each. Like wind, solar, and other renewable energy sources, biomass can have a positive impact on our atmosphere by lessening our dependence on climate change-inducing fossil fuels. Biomass energy differs from other renewables, however, in the extent to which its use is directly tied to the agricultural land, forests, and other ecosystems from which biomass feedstocks are obtained. Because of this close association, the use of biomass has the potential to result in a wide range of environmental and social impacts, both positive and negative, above and beyond its use as a substitute for fossil fuels. Impacts on soils, water resources, biodiversity, and ecosystem function will differ depending on what choices are made regarding the types of biomass that are used, as well as where and how they are produced. This is why biomass needs to be produced and harvested as sustainably as possible. In this sense, sustainability refers to choosing management practices that minimize adverse impacts and complement local land-management objectives.

Sustainably managed forests play an important role in any discussion of the mitigation of climate change, with the prospect of sustainably providing essential materials and services as part of a low-carbon economy, both through the substitution of fossil-intensive fuels and materials and through their potential to capture and store carbon in the long-term (Cintas et al. 2017; Koponen et al. 2015; Lundmark et al. 2014). Mitigation includes both reducing sources and increasing sinks of GHG, especially those for CO_2. In this respect, sustainable forest management activities may help to mitigate climate change in many ways, for example by reducing deforestation and degradation of forests, enhancing afforestation and reforestation activities and increasing the carbon density in forests. However, carbon sequestration in forest biomass can reduce the net CO_2 emissions only as long as the forest carbon stock is increasing. The capacity of forests to store increasing amounts of carbon is limited and forests eventually reach a dynamic equilibrium (Eriksson et al. 2007; Poudel et al. 2011). Furthermore, the forest carbon stock can be released to the atmosphere by natural disturbances like fire, storm damages and diseases (Blennow et al. 2010).

In order to be sustainable, bioenergy systems, including their supply chains, must be environmentally, economically and socially viable over both the short and long terms. Many groups have proposed indicators to evaluate the sustainability of supply chains but there is currently no internationally accepted framework for assessment. What is sustainability? There are many different views on what it is and how it can be achieved. The idea of *sustainability* derives from the concept of sustainable development, which became common language at the World's first Earth Summit in Rio in 1992. The original definition of sustainable development is usually considered to be:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland 1987)*

Since then, there have been many variations and extensions of this basic definition. The concept of sustainability is comprised of three pillars: economic (profits), environmental (planet) and social (people).

Greater use of wood-based materials from sustainably managed forests is increasingly identified as an effective means to reduce fossil energy use and to mitigate climate change. For example, it has been suggested that the increased use of wood products is suggested as an important potential contributor to climate change mitigation in the European Union (European Commission 2011). The IPCC (IPCC 2014) highlighted the role that wood product substitution can play in the ongoing efforts to create a built environment with low climate impacts.

A likely increase in the future demand for renewable energy sources may not be met by the current availability of forest land using current forest management strategies, as resources are limited and the use of resources in one application will reduce the amount in other applications and must therefore be combined with energy efficient systems.

1.2. Previous studies

Various studies have documented the climate change mitigation potential of using forest biomass for wood products and bioenergy to substitute fossil fuels and fossil-intensive materials.

The basic concept of using forest material to mitigate climate change was developed by Schlamadinger and Marland (Schlamadinger & Marland 1996). They provided a comprehensive theoretical analysis of the potential role of forest products in the global carbon cycle. They concluded, based on carbon flow modeling associated with various land use strategies, that using forest biomass for direct substitution of fossil fuels and fossil-intensive materials is an important strategy for reducing net GHG emissions, whereas sequestration or conversion of carbon is limited or only temporary. Schlamadinger and colleagues (Schlamadinger et al. 1997) developed a standard methodology to compare GHG balances of bioenergy and fossil energy systems. They highlighted the strong parallel between the cyclical flow of carbon in sustainably produced bio-based materials and bioenergy, versus the linear flow associated with carbon-intensive materials and fossil energy.

Various authors have used radiative forcing (RF) metrics to analyze the climate impact of forest residue use. Savolainen et al. (Savolainen 1994) compared the RF of using coal, fossil gas, peat, and forest biofuels from several different sources including forest residues. The forest residues gave the lowest RF of all the fuels, although the authors assumed a very rapid decomposition rate for biomass left in the forest. Zetterberg et al. (Zetterberg et al. 2004) used the approach to compare the use of peat, coal, fossil gas, and forest residues. Two simple biomass decay functions were used and compared. Using forest residues resulted in significantly lower CRF than using peat, coal or fossil gas. Holmgren et al. (Holmgren et al. 2007) compared the RF effects of using coal, fossil gas and forest residues for energy, considering the time dynamics of biomass decay as well as scenarios showing the significance of soil carbon and transport energy emissions. Using forest residues gave consistently lower RF than using coal, although using fossil gas gave lower radiative forcing for the first 15-20 years, after which forest residues gave lower radiative forcing. Repo et al. (Repo et al. 2011) used the Yasso07 model to determine the time profile of carbon emissions from forest residues and stumps left in the forest, and compared that to the instantaneous emissions from combustion of forest residues or fossil fuels. However, they did not consider the atmospheric dynamics of the emitted CO_2, and did not calculate RF. Sathre and Gustavsson (Sathre & Gustavsson 2011) compared the CRF of collecting and using forest residues and stumps for bioenergy, to the CRF of leaving the residues in the forest and using equivalent quantities of coal or fossil gas. They assumed that the natural decay of residues left in the forest follows a simple exponential function, with unique decay constants for each type of biomass. Levasseur et al. (2010) proposed the use of *dynamic characterization factors* for the global warming impact category of life cycle assessment, based on the CRF of different GHGs over different time horizons. Cherubini et al. (2011) calculated a GWP_{bio} defined as the CRF resulting from a unit of bioenergy divided by the CRF resulting from an equivalent amount of fossil energy. The GWP_{bio} notion was expanded by Pingoud et al. (2012) to include the substitution effects of wood-based products. As currently applied, however, the GWP_{bio} indicator gives simplified approximations of climate impacts, but does not incorporate comprehensive life-cycle emission modeling of specific forest stands and landscapes. Bergman (2012) developed a metric called *time-zero equivalent*, based on CRF, to consider the effect of timing of GHG emissions on the climate change impacts of building products.

1.3. Aim and objectives

The overall aim of this thesis and the studies underlying it was to develop a methodology from a life cycle perspective to assess the climate impact of the sustainable use of forest biomass in bioenergy and bio-based material systems. For this, the development of systems analysis and scenario techniques was necessary to study how different bioenergy systems in the forest, heat, power and transportation sectors could contribute to reducing GHG emissions and fossil energy use.

Specific objectives were to investigate the primary energy use, energy efficiency and climate impact of different bioenergy and material systems based on using forest residues for bioenergy and biofuel services, using forest biomass as a construction material in wood frame buildings, and using biomass from plantations of short rotation coppice (SRC) species on abandoned agricultural land for biofuel production.

The study was intended to explore following points:

- to compare and analyze the dynamic climate impact of bioenergy systems with different scenarios of forest management and biomass use, and different alternatives for the land-use in the reference system and their impacts on the climate in terms of radiative forcing (Papers I, III)
- to investigate the climate impact of using forest residues for bioenergy and biofuel production, with the focus on the impact of different decomposition rates, different supply systems and different conversion technologies in different geographical regions (Paper II)
- to analyze the dynamic climate implications and carbon balance implications of forest biomass production and land-use for producing wood materials for the construction sector (Papers I, III, V)
- to study the dynamic climate impact of potential biomass production on abandoned agricultural land for substituting fossil fuels in the transportation sector with the focus on carbon fluxes between biomass, soil and the atmosphere (Paper IV)
- to compare different ways of converting forest biomass into the different energy carriers, electricity, heat and transportation fuels (Papers II and IV)

The answers to these questions are presented in the appended papers I-V, which are summarized briefly in the next section.

1.4. Structure and outline of the thesis

The structure of the thesis is as follows: Chapter 2 discusses the methodological framework and the various approaches applied in this work and Chapter 3 provides results, followed by discussions in Chapter 4 and conclusions in Chapter 5. Chapter 6 highlights some ideas for future work.

This doctoral thesis is a synthesis of these five papers. Paper I discusses the inclusion of land-use in the reference system when conducting a dynamic life cycle analysis of forest biomass systems and a reference system. The dynamic profiles of GHG emissions were analyzed and the climate impact assessed using a matrix describing *cumulative radiative forcing* (CRF) of bioenergy systems estimated with differences in forest productivity, different starting points in the LCA and different alternatives for the land-use in the reference system. Increasing biomass production through forest fertilization combined with substitution of non-wood products and fuels can significantly reduce CRF. The emissions from intensified forest management resulted in very little radiative forcing in comparison to the negative radiative forcing from using the increased forest growth for biomass substitution.

The aim of the study described in Paper II was to understand the climate implications of using logging residues, stumps and thinnings to replace fossil fuels in electricity, heat and transportation systems. For this, the time profiles of primary energy use and CO_2 emissions were elaborated, CRF of bioenergy systems based on forest residues were estimated and compared to fossil-based energy systems where fossil fuels provide the same services while residues are left in the forest to decompose. We analyzed the sensitivity to varying decomposition rates of logging residues, stumps and thinnings in different locations in Sweden, and various bioenergy and fossil energy systems as well as the energy input needed for longer transport of the forest residues. The results show the largest primary energy and climate benefits when forest residues are collected and used efficiently for energy services. Using biomass to substitute fossil coal provides greater climate change mitigation benefits than replacing oil or fossil gas. Some bioenergy substitutions result in positive CRF during an initial period. This occurs for relatively inefficient bioenergy conversion pathways to substitute less carbon intensive fossil fuels, like bio-based transportation fuel used to replace diesel.

Paper III discusses the question of how the Swedish forest should be managed and how forest resources may be used effectively to mitigate climate change. We estimated the climate effects of directing Swedish forest management towards increased carbon storage in forests (more land set-aside for protection) or towards increased forest production (for the substitution of fossil fuels and other products), relative to a reference case of current forest management. We developed various scenarios of forest management and biomass use to estimate the carbon balances of the forest systems, including ecological and technological components, and their impacts on the climate in terms of radiative forcing. Scenarios with increased set-aside areas showed modest climate benefits compared to the reference case for the first several decades, but then showed increased climate impact as lower forest harvest leads to higher GHG emissions from energy and material systems. The most beneficial alternative in terms of climate in both the short and long term is a management strategy aimed at high forest production, a high residue recovery rate, and high utilization efficiency of harvested biomass. This shows that active forest management and efficient forest product utilization will provide more climate benefit, compared to reducing harvest and storing more carbon in the forest.

The aim of the study in Paper IV was to explore the primary energy, CO_2 and CRF implications of different apartment building construction systems using a time-dependent approach from a life cycle as well as land use perspective. The different construction alternatives are a reinforced concrete system, light-frame timber system, and massive timber structural system. The buildings are designed to meet the Swedish passive house standard, to have the same energy use in the operation phase and are designed to give the same building service. The wood in the different alternatives is supplied from Swedish conventional managed forest. The building systems use different amounts of wood with the reinforced concrete system using least wood. The analysis links the construction system to the overall climate change effect, based on CRF resulting from the atmospheric net CO_2 emissions due to forest carbon stock changes (living tree biomass, dead trees and soil) and land-use change, forest operations and logistic emissions, plus energy and material services provided by harvest biomass or non-woody biomass resources. The results show that the intensive wood-based construction system gives lower net primary energy use, GHG emissions and CRF compared to the concrete-based construction system in the long-term. The results show also that the land-use impact on life-cycle analysis of construction systems has a notable impact and should be considered in this kind of analysis. Overall, the cross-laminated timber-frame system results in the lowest climate impacts and natural resource use in the long-term when logging residues and stumps were used for bioenergy to replace fossil coal.

Paper V discusses the climate impact of potential biomass production on abandoned agricultural land in Denmark for substituting fossil fuels in the transportation sector. The following aspects were considered, (i) growth dynamics of different tree species growing on abandoned farmland at the stand level, (ii) temporary carbon storage in harvested biomass, (iii) changes in carbon content of the soil and dead wood, and (iv) the substitution effect of harvested biomass by converting biomass into biofuels and bio-based electricity to replace corresponding fossil fuel counterparts in vehicles. The annual net emissions of CO_2 for each scenario over a 240-year period were considered, and then time profiles of cumulative net CO_2 emissions and CRF as a proxy measurement of climate change impact were estimated. In the long-term, the results show the greatest potential for climate change mitigation when Grand fir is planted and the harvest biomass is used for bio-based electricity production. Producing DME to replace diesel fuel is the least beneficial pathway.

2. METHODOLOGICAL FRAMEWORK

One of the main objectives of this thesis is the development of an appropriate analytical methodology to compare carbon balances of forest-based and non-forest-based energy and material systems and to assess climate impact of bioenergy systems. Once developed, the methodology was used to assess the climate impact of different bioenergy and material systems and was further developed. The analyses mainly considered a long-term perspective to show the importance of temporal and spatial perspective, as the analyses were conducted at both stand level (Papers I, II, IV, V) and national level (Paper III).

2.1. Dynamic life cycle perspective

A comprehensive analysis of environmental impacts caused by a forest product or service requires a system-wide life cycle perspective. The Life Cycle Assessment (LCA) is one of the methods for assessing environmental implications of a product during its life cycle. The general framework and the guidelines for conducting a LCA of a material or service are described in the ISO 14040:2006 and 14044:2006 standards. In LCA, all emissions from the system are usually summed into a single pulse, irrespective of when in time they occur. With this approach, net changes in biogenic carbon stocks during the study period can be captured in the climate impact assessment, but not the temporary fluxes. Bioenergy is therefore generally assumed to be carbon-neutral within LCAs. However, this assumption has been questioned for disregarding the time lag between release and uptake of CO_2 in new plants.

For bioenergy systems with long rotations, this becomes especially important. There are several approaches for including timing of emissions in bioenergy scenarios in LCAs (Ericsson et al. 2016; Levasseur et al. 2010; Zetterberg et al. 2004). All approaches include a characterization model which converts the emissions to climate impacts. To be able to describe time-dependent impacts, it is necessary to record the timing of emissions in a time-distributed inventory.

Establishing effective system boundaries and defining an appropriate functional unit is one of the most important aspects in comparative analysis (Schlamadinger et al. 1997). System boundaries describe the activities included in the studied system and should be defined broadly enough to capture the significant impacts of interest, but should not be so broad as to make the analysis too uncertain. In this thesis, boundaries are defined depending on the goal of the analyses. A functional unit is a measure of the required properties of the studied system, providing a reference to which the analysis can be related. The functional unit can be defined at the level of a unit of forest or agricultural land (Papers I, IV, V), the level of delivered unit of biomass to a conversion plant (Paper II), number of buildings (Papers III, V), or energy service provided to the end-user (Papers I, V).

The limiting factor of the system can be the available biomass resource for energy or the available land for biomass production. This limit implies that use of biomass in one application will reduce the amount available for other applications. Different biomass uses may have different impacts, and the efficiency of replacing different fossil fuels in different sectors can vary. For example, using biomass in a large stationary plant such as a combined heat and power (CHP) plant to replace fossil-based electricity and heat (Paper II) is more climatically beneficial than substituting fossil transportation fuels with solid biofuels (Paper V).

The carbon flows of forest biomass from a life-cycle perspective include the phases of growth, processing, utilization, and return. In the growth phase, CO_2 is removed from the atmosphere through photosynthesis, and held as carbon-based compounds in tree tissues. The chemical bonds of these reactions result in accumulated solar energy. In the processing phase, tree biomass is harvested, transported, and refined to give it desired characteristics. The energy sources used for these processes may be fossil fuels. Carbon is temporarily stored in biomass fiber, until the biomass in form of energy or material is finally combusted. Upon combustion, the accumulated energy is released and used, and the carbon is ultimately released back to the atmosphere. All studies presented in Papers I-V were performed using a dynamic life cycle perspective, which can be divided into the following analytical elements:

- Dynamic modeling of biogenic carbon emissions
- Fuel supply system
- Fuel conversion systems
- Climate impact assessment

To explore the long-term system-wide flows of carbon associated with forests governed by different strategies for forest management and wood product use, we combined various analytical elements to better understand the climatic effects, in both the short and long term, of alternative strategies for forest management regimes, choice of tree species and wood product use. We conducted temporally-explicit modeling of the complete forest system to determine time profiles of net CO_2 emissions. This includes net exchanges of both the forest ecosystem as well as the technosystem (Figure 4).

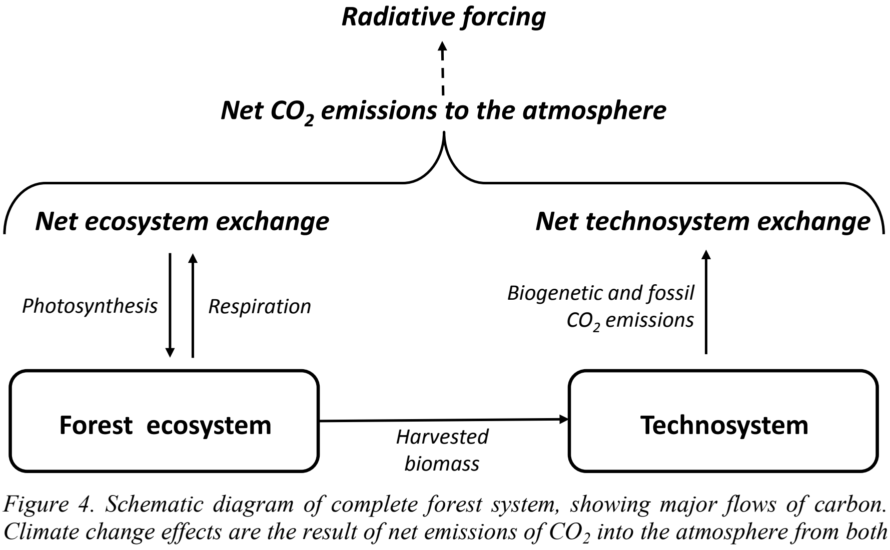

Figure 4. Schematic diagram of complete forest system, showing major flows of carbon. Climate change effects are the result of net emissions of CO_2 into the atmosphere from both the forest ecosystem and technosystem.

We considered net CO_2 emissions due to forest carbon stock changes (in living trees, dead wood and soils), forest operations and logistics emissions, and energy and material services provided by harvested biomass or by non-biomass resources. The forest ecosystem removes CO_2 from the atmosphere by photosynthesis, and emits it via respiration at various trophic levels. The technosystem emits CO_2 from biomass combustion and fossil fuel operations, and avoids emissions due to material and energy substitution. We estimated the resulting changes in concentration of atmospheric CO_2, and determined the CRF which is considered a proxy for overall climate impacts. This approach is shown schematically in Figure 4.

2.2. Forest ecosystem

Biogenic carbon modeling

In this thesis, various f different forest growth models were used to simulate the forest ecosystem. In Paper I, the forest biomass production of a Norway spruce (*Picea abies*) stand was modeled with the DT model, which was developed by Nilsson and Fahlvik (Fahlvik & Nyström 2006; Nilsson et al. 2011). The simulations were made for a conventionally managed forest stand and an intensively managed forest stand, where fertilization was applied in the young stand. In Paper III and V, the simulations of forest development and biomass harvest were generated with the Heureka simulator (Wikström et al. 2011), which is a forecast tool for forests and forestry on a large scale regional level. In Paper III, Simulations for Swedish productive forests were based on three forest management scenarios: Business as usual (BAU), Set-aside, and Production (Figure 5). The BAU scenario reflects current forestry practices, with the exception of the harvest level, which was largely kept at the same level as the growth. This does not correspond to current or historic harvest levels, which during the latest 10 years have varied between 70 and 85% of the total annual growth (Skogsdata 2015). In the Set-aside scenario, the protected area was doubled in the initial year and then kept constant during the simulation, while all other settings were equal to BAU. The Production scenario differed compared to BAU in several ways: no extensive or natural regeneration was included; planting of Scots pine (*Pinus sylvestris*) was replaced by the faster growing lodgepole pine (*Pinus contorta*) in 50% of the cases; and the number of fertilized hectares was twice that of the BAU scenario. The use of fertilization was determined by a series of default settings for site types, interval, site productivity, age, and mean height.

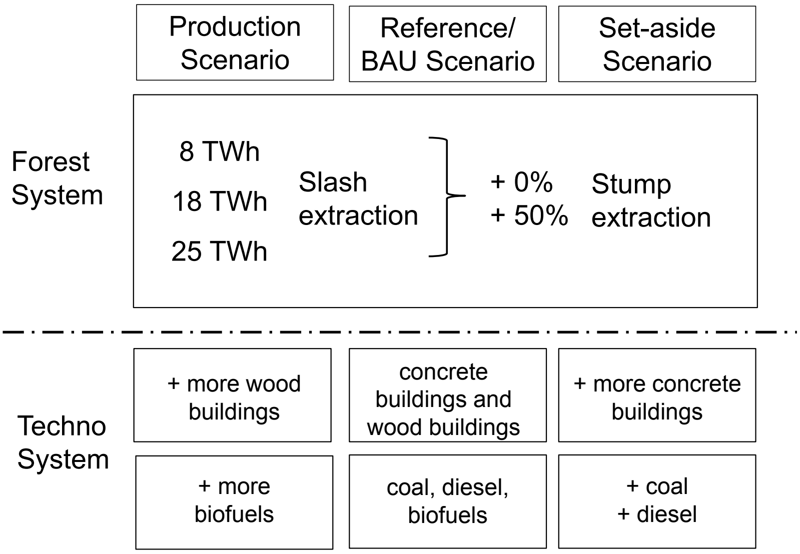

Figure 5. Overview of the different forest management scenarios in Paper II.

The current Swedish harvest of forest residues in thinnings and final fellings is about 8 TWh per year, which is based on an estimate from the Swedish Forest Agency (Skogsstyrelsen 2006). This harvest level was used as a reference for all scenarios. In addition, we estimated the climate implications of an increased harvest of forest residues at two higher levels corresponding to: (i) 50% of the logging residues in thinnings plus 80% of logging residues in final fellings, and (ii) 50% of stumps in final fellings (in addition to the logging residue harvest of (i)).

The parameters for the modeling of forest growth, the diameter, height and stand density in Paper IV come from the VIDAR model. This software, VIDAR 1.0 (Skovsgaard & Nord-Larsen 2012; VIDAR), has been developed for preparation of growth and yield tables for a number of common forest tree species in Denmark. Growth is predicted using a set of dynamic growth models developed on the basis of data from long-term trials conducted by the Danish Centre for Forest, Landscape and Planning (FLD), Faculty of Life

Sciences, University of Copenhagen. In the different bioenergy scenarios, we establish forest land in year 0 and assume the land is managed following either conventional Danish forest practices such as species-specific thinning and felling operations for Norway spruce (*Picea abies*), Grand fir (*Abies grandis*), the poplar clone PO42 (*Populus trichocarpa x Populus maximowiczii*), willow (*Salicaceae sp.*). In the Set-aside scenario, we assume that European beech (*Fagus sylvatica* L.) is planted in year 0 and then left untouched with the aim of carbon sequestration in the long-term. In the reference fossil scenario, we leave the farmland unused as it was before, that means no biomass is available to substitute fossil fuels for the transportation sector.

In Paper V, the simulations of forest development and biomass harvest were undertaken using the Heureka PlanWise simulator version 2 (Wikström et al. 2011). The simulations were rum using in five-year intervals for each scenario for the County of Kronoberg in Southern Sweden. These results were then linearly interpolated and used as annual input data for other modeling activities. Anticipated effects of climate change were applied in all simulations according to RCP 4.5 scenario (IPCC 2013). This study was built on a forest management scenario defined as Business as usual (BAU). The BAU scenario reflects current forest management practices with two thinning operations (at 35 and 45 years) from the start of the simulation and final felling at 65 years. We consider different land use practices, based on the combination of active management activities and unmanaged forest regime. We examine the consequences of three different forest residue recovery strategies: scenario 1, in which only stemwood is harvested and the logging residues and stumps are left in the forest; scenario 2, where the stemwood is harvested and the logging residues (foliage, branches, and tops - upper part of the stem of less than 6 cm diameter) are recovered while the stumps are left in the forest; and scenario 3 where stemwood, logging residues and stumps are harvested and recovered. When logging residues are recovered, we assumed that 100% of tops and 75% of branches and foliage are removed. When stumps are harvested, we assume around 90% of stumps and coarse roots are removed. The amount of tree needles harvested with the logging residues and thinnings may vary; the Swedish Forest Agency (Skogsstyrelsen 2008a) recommends leaving most of the needles in the forest to avoid nutrient depletion, except in nitrogen-rich regions where the needles should be removed. We assumed that 20% of tree needles were harvested with logging residues and thinnings, and the remaining needles fell off and remained in the forest. Small-diameter stemwood is typically used as pulpwood for paper production. We assume that the same amount of pulpwood should be produced in all scenarios.

Building System

There are several ways that harvested biomass can be used, each with unique services provided to society and with varying climate effects. In this work, life-cycle building CO_2 emissions are based on case studies of a multi-story apartment building constructed in Sweden using a reinforced concrete frame. The building is located in Växjö and has four stories with a total usable floor area of 1190 m^2, containing 16 apartments with living areas ranging from 42 to 78 m^2. We consider buildings made using a reinforced concrete frame, a wood-based light frame construction or wood-based cross-laminated timber construction (CLT). The buildings are constructed in accordance with Swedish building code for 2012 (BBR 2012) (Papers I, III) or under passive house specifications ((FEBY 2012) (Paper V). They are all designed to have the same building services as well as to have the same performance in the operating phase, this phase is not quantified in the analysis.

Fuel supply systems

Emissions from forest management activities including stand establishment and final stemwood harvest are based on Berg & Lindholm (Berg & Lindholm 2005), and are average values for all regions of Sweden. Emissions from manufacturing nitrogen fertilizer are based on Davis & Haglund (Davis 1999), while emissions from application of the fertilizer by helicopter are based on Mead & Pimentel (Mead & Pimentel 2006)

Logging residues (branches, tops and needles) are byproducts of final felling, requiring only marginal additional forest operations at the clear cut site for collection and forwarding to the roadside by a forwarder. In contrast, stumps must be lifted and sheared, and thinnings need to be felled before forwarding, thus requiring more fossil energy input per unit of delivered biomass. The stump system starts with excavating and forwarding in the forestry area. The stumps are split into pieces to ensure they are clean and dry and the material is then stored at the roadside. We assumed the use of shear-type stump harvesters in this study. When thinnings are harvested on sites with short forwarding distances, energy wood harwarders are most efficient, while in young stands of larger trees and longer forwarding distances, the traditional two-machine system with harvester and forwarder is a more economic option (Routa et al. 2013). In Sweden, the predominant system is a small one-grip harvester with accumulation equipment producing roughly delimbed tree sections, while terrain transport is carried out by a conventional forwarder.

After the biomass (logging residues, stumps or thinnings) has been collected and forwarded to a roadside landing, we assumed that it isto be chipped or crushed immediately at the landing. Once the biomass has been chipped it should be transported to the end-user within a few days to reduce dry-matter losses from biological activity. Typically a container truck is waiting at the roadside as the wood is chipped. Dry matter loss during forwarding, chipping roadside and transport may be between 2 and 15% (Wihersaari 2005). We assume dry matter losses to be 10% for forwarding and chipping at the roadside but we do not consider any transport losses. The chipped biomass is then assumed to be transported 100 km to a local end-user (*local system*), or 100 km to a terminal and then 250 km by train to the coast plus 1000 km by ship to an international end-user (*international system*). The same distances are assumed for forest residues in our southern, central and northern Sweden climate scenarios.

Table 1. Specific fossil fuel consumption (MJ fossil energy use per dry ton of delivered biomass)

	Fossil fuel use (MJ per dry t)		
	Logging residues	**Stumps**	**Thinnings**
Local system			
Recovery (lifting, felling, forwarding)	189 [a b d e]	569 [b e f]	233 [b e]
Roadside comminution	77 [b e]	96 [b e]	90 [b e]
Transport (truck, 100 km)	145 [c d]	145 [c d]	145 [c d]
Total	411	810	468
International system			
Local system to terminal	411	810	468
International transport (train, 250 km)	19 [c]	19 [c]	19 [c]
International transport (ship, 1000 km)	56 [c]	56 [c]	56 [c]
Total	486	885	543

[a] *(Lindholm et al. 2010);* [b] *(Thorsén et al. 2011);* [c] *(Gustavsson et al. 2011a);* [d] *(Eriksson et al. 2007);* [e] *(Wihersaari 2005);* [f] *(Jäppinen et al. 2014);* [g] *(Hamelinck & Faaij 2006)*

Fuel conversion systems

Fuels are converted to different energy carriers that provide suitable energy services. The three major energy carriers are electricity, heat and motor fuels. The energy carriers illustrate the energy amount after the conversion losses of central conversion plants. The final energy use relates to the amount of energy reaching end users after conversion.

In this thesis, the analyses are limited to modern large-scale high-efficiency conventional bio-based plants for CHP, electricity, heat or transportation fuel production based on existing or emerging technologies. In Table 2 the scale and conversion efficiency is given for selected existing and emerging technologies referred to in this thesis. Direct biomass combustion to produce heat is the most common use of biomass (Bauen et al. 2009). The combustion applications range from simple small-scale stoves for heating to complex modern industrial steam boilers to produce steam for industrial processes or electricity generation. A more energy efficient system than heat-only production is combined heat and power (CHP) production, which is widely used in district-heating and industrial systems.

Biomass gasification is an emerging technology that converts lingo-cellulosic materials to gaseous fuel for various purposes such as standalone electricity generation or CHP production. This technology is potentially important, due to its higher conversion efficiency with a wider range of raw materials. The gaseous fuel produced from gasification can also be upgraded to various types of biofuels such as biomethane, dimethyl-ether (DME) and methanol (MeOH) which respectively can substitute for fossil gas, diesel, and gasoline (Boding et al. 2003; Elam 2002; Nyström et al. 2007; Semelsberger et al. 2006; Thunman et al. 2008b).

Functional equivalence must be maintained when comparing biofuels and fossil fuels in the transportation sector. This depends on various factors including engine types and efficiencies (Papers II, IV). Engines using DME are expected to giver higher or equal efficiency to those using diesel (Joelsson & Gustavsson 2010). Also, using MeOH in spark-ignition engines can offer efficient and powerful performance due to its high octane rating. In our calculation, we assume that DME replaces diesel, methanol replaces gasoline, and biomethane replaces fossil gas at a ratio of 1:1 based on energy content.

Table 2. Characteristics of selected biomass-based conversion technologies. A minus sign indicates net demand of energy instead of energy production.

Technology	**Scale**	**Production efficiency (%)**			**Note**
		Heat	**Electricity**	**Motor fuel**	
Existing technologies					
Heat production	(MW_{heat})				
Wood chip boiler	7-50	108	-	-	a
Electricity production	(MW_{elect})				
BST	400	-	45.0	-	a
CHP production	(MW_{heat})				
BST	200	77.0	31.0	-	b
Emerging technologies					
Electricity production	(MW_{elect})				
BIGCC	500	-	50.0	-	c
CHP production	(MW_{heat})				
BIGCC	70	48.0	42.0	-	b
Biofuel production	$(MW_{biofuel})$				
DME	450	-15.9	-2.0	59.0	d
DME	800	-24.5	-5.6	66.0	e
Methane	450	0.2	4.3	64.0	d
Methane	800	-3.1	0.3	65.5	e
Methanol	450	-6.0	9.5	41.0	d
Methanol	800	-14.0	6.3	46.0	e

[a] (Danish Energy Agency 2010); [b] (Nyström et al. 2011); [c] (IEAGHG 2011) technology for 2030; [d] Indirect gasification (Thunman et al. 2008a), system with maximum electricity production using condensing steam turbine (Hansson et al. 2007); [e] Entrained-flow gasification , system with maximum electricity production using condensing steam turbine (Hansson et al. 2007)

2.3. Fossil system

Biogenic carbon modeling

In the fossil system, forest residues (logging residues, stumps and thinnings) are left in the forest (Paper II), the forest is left unmanaged (Paper I) or abandoned agricultural land is not converted to forestland (Paper IV) and fossil fuels are used for energy purposes. Biogenic emissions result from decaying biomass, and fossil emissions from energy services.

In the fossil-based system, the residues harvested in the bioenergy system are instead left in the forest, where they are decomposed by micro-organisms in the soil and release biogenic CO_2 to the atmosphere. The decay rate of these residues varies in time because their initial quality is changing to often lower qualities, which decompose more slowly. In this thesis, three different approaches were used to model decomposition rates. A simple exponential decay function (Papers I, II, and IV) as well as two more sophisticated process based models (Paper II) to estimate the decomposition of the forest residues. In Paper V, the modeling of the decomposition was included in forest growth modeling performed using the Heureka simulator (Wikström et al. 2011).

In the exponential decay model, logging residues stumps and thinnings are assumed to decay at a negative exponential rate, following Equation 1:

$$M_t = M_0 \cdot e^{-tk} \qquad (1)$$

where M_0 is the initial dry mass, M_t the remaining mass at time t, and k is a decay constant. We assumed a decay constant of 0.046 year^{-1} for stumps and coarse roots (Melin et al. 2009) and 0.074 and 0.170 year^{-1} for branches and needles, respectively (Palviainen et al. 2004).

The two process based models used were: the Q model (Rolff & Ågren 1999; Ågren et al. 2007) and the Yasso07 model (Tuomi et al. 2011; Tuomi et al. 2009). The process based models Q and Yasso07 were run for three climate regions in Sweden (Table 3). The Yasso07 model was also run for various stem diameter classes. The Q model was run for each climate region for branches and stumps and coarse roots.

Table 3. Climate input data for the Q model and for the Yass07 model

Region	**Temperature (°C)**	**Amplitude Temp (°C)**	**Precipitation (mm)**
South	5.7	21.5	706
Center	2.0	25.1	711
North	0.7	30.1	582

In the Q model the harvest residues decompose continuously and each litter fraction (branches, stump and coarse roots) decomposes at a specific rate depending on the quality of the litter. The model has been described in several papers and was used to estimate soil organic carbon (SOC) changes at both stand level and regional and national scales, especially for Sweden (Ortiz et al. 2013; Ågren et al. 2007). The Yasso07 model is a box model where litter of a certain quantity and quality enters one of the box pools in the model, depending on the solubility of the litter. In each box the litter is decomposed at a specific rate. When the specified litter fraction has decomposed, the remaining part of the litter moves to another pool, where it continues to be decomposed at a slower rate. The Yasso07 model was developed to estimate SOC changes at regional and national levels and is being currently used for SOC change estimates in the Finnish National Inventory of GHG (Liski et al. 2006; Monni et al. 2007; Peltoniemi et al. 2006).

Table 4. Fossil-based conversion technologies

		Conversion efficiency (%)		
Technology	**Scale**	**Heat**	**Electricity**	**Note**
Heat production	*(MW_{heat})*			
Coal boiler	50	89	-	a
Fossil gas boiler	20	105	-	b
Fuel oil boiler	50	90	-	a
Electricity production	*(MW_{elect})*			
CST	740	-	46.0	c
FGCC	420	-	58.0	c
FOCC	100-400	-	55.0	b
CHP production	*(MW_{heat})*			
CST	129	55.0	34.0	a
FGCC	199	44.0	46.0	c
FOCC	10-100	41.0	41.0	b

[a] *(Ahlgren et al. 2007);* [b]*(Danish Energy Agency 2012);* [c] *(Nyström et al. 2011)*

Fuel supply system

Fossil fuel used at energy conversion plants is normally derived from distant locations, requiring processes of extraction, transportation, processing and distribution. All these processes use energy, which increases the total primary energy use per unit of fuel used at conversion plants. In our study, the life cycle primary energy use of each fossil fuel is considered, and full fuel cycle CO_2 emission factors are based on Gode et al. (Gode et al. 2011).

Fuel conversion systems

Fossil coal, oil or gas used for electricity, heating or transportation purposes is replaced by forest residues. We consider CHP-plants as well as stand-alone heat and power plants using coal-based steam turbine (CST), fossil gas-based combined-cycle (FGCC) and fuel oil-based combined-cycle (FOCC) technologies. Table 4 shows the scale and conversion efficiency of selected fossil-based technologies.

2.4. Cumulative net emissions

The net ecosystem exchange (NEE, in units of tons of C) describes the CO_2 fluxes between the forest ecosystem and the atmosphere during year t, Equation 2.

$$NEE_t = (LTB_{t-1} - LTB_t) + (DW_{t-1} - DW_t) + (SC_{t-1} - SC_t) - HB_t \qquad (2)$$

where LTB is the carbon storage in living tree biomass which is defined as the sum of the aboveground and belowground carbon storage, DW is the carbon storage in deadwood, SC is the soil organic carbon and HB is the extracted harvested biomass. The carbon content of living tree and harvested biomass is assumed to be 50% of dry mass. A positive NEE corresponds to net carbon emission to the atmosphere, while a negative NEE corresponds to net carbon removal from the atmosphere.

In this thesis, two different approaches were used to calculate the emissions. The *Emission difference approach* (Papers I, III, IV) considers the climate impact of the difference in emissions ($\Delta\, Emissions$) between the biomass-based system and the fossil-based reference system. In contrast, the *Total emissions approach* (Papers II, V) considers the difference in climate impacts of the total emissions of the biomass system and the fossil reference system ($Emissions_{bio} - \; Emissions_{ref}$).

Applying the *Emission difference approach*, we calculated the difference in annual net carbon emissions for the biomass systems compared to the reference fossil system, as follows (Equation 3)

$$\Delta\, Emissions = \Delta\, NEE + \Delta\, Operation + \Delta\, Biofuel + \Delta\, Fossil \\ + \Delta Building \tag{3}$$

where Δ*NEE* is the net ecosystem exchange of the selected scenario minus that of the reference scenario, $\Delta Operation$ is the carbon emissions from forest management activities and logistics of the selected scenario minus that of the reference scenario, Δ*Biofuel* is the carbon emissions from bioenergy and biofuels of the selected scenario minus that of the reference scenario, Δ*Fossil* is the additional carbon emissions from fossil energy of the selected scenario minus that of the reference scenario, and Δ*Building* is the building-related emission of the selected scenario minus that of the reference scenario.

$$Emissions = NEE + Operation + Biofuel + Fossil + Building \tag{4}$$

where *NEE* is the net ecosystem exchange of the selected system, *Operation* is the carbon emissions from forest management activities and logistics, *Biofuel* is the carbon emissions from bioenergy and biofuels, Δ*Fossil* is the additional carbon emissions from fossil energy, and Δ*Building* is the building-related emissions.

It appears, superficially, that both approaches deliver the same results, but the way land-use is accounted for is different. For example, with conventional forest management, the CLT building (under passive house criteria) requires 2.6 ha of forest and the concrete building requires 1.1 ha of forest (Paper IV). The *Emission difference approach* attributes the reduced emissions (and CRF) of the biomass system to just 1.5 ha of forest (2.6 minus 1.1). But the *Total emissions approach* attributes the reduced emissions and CRF of the biomass system to the full land area, so the CRF reduction per ha is less.

2.5. Climate impact assessment

There are several approaches to quantifying anthropogenic climate impacts. A common method of comparing mitigation options is the GHG balance approach, where all GHG emissions that occur during a given time period are simply summed together regardless of when they occur. Cumulative net emissions are determined, beginning from zero emissions in the baseline year. A system with lower cumulative emissions at the end of the time period is considered to have less climate impact than a system with higher emissions.

This approach does not fully describe the complexity of the system, however, because the static sum does not take into account the temporal patterns of GHG emissions and the resulting dynamics of atmospheric radiative imbalance. Within any finite time period, the accumulated radiative imbalance, and hence the climate impact, depends not only on how much GHG is emitted but also on when it is emitted. The heterogeneity of stocks and flows over time reduces the effectiveness of static methods of analyzing and comparing the mitigation effectiveness of forest systems.

RF is a quantification of the greenhouse effect. This effect is caused by particular gases in the atmosphere with a peculiar property that allows short wavelength radiation (such as visible light and ultraviolet) to pass through, but restricting longer wavelength radiation (such as infrared) from passing. Solar radiation, as sunlight, passes through the atmosphere and is absorbed by the earth's surface. The solar radiation that is absorbed by the earth's surface warms up the surface and the atmosphere. That heat then radiates away from the earth, analogous to a fireplace radiating heat to those sitting near it. In the absence of GHGs that heat would radiate out into space, but the GHGs block part of the heat and trap it in the atmosphere. Some level of naturally-occurring greenhouse effect is beneficial, because it maintains the earth at a pleasant temperature; in the absence of GHGs in the atmosphere the planet would be much colder.

In the long term, the earth–atmosphere system remains in radiative balance, where the amount of incoming solar radiation absorbed by the system is balanced by the release of the same amount of outgoing longwave radiation. However, as we have increased the GHGs in the atmosphere in recent decades, we have created a radiative imbalance in which there is more incoming radiation than outgoing radiation. That imbalance is called *radiative forcing*. Thus radiative forcing is a measure of the rate of flow of excess energy entering the earth system. It describes the state of energy imbalance, where radiative energy inputs minus outputs yield a positive accumulation of energy in the earth system, leading to climate impacts that we experience. When summed over time, the accumulated energy can be termed *cumulative radiative forcing* (CRF), a measure of total excess energy trapped in the system, and a suitable indicator of climate change impacts. GHGs vary in their radiative efficiency, which determines their ability to accumulate heat. Per unit of mass, N_2O traps the most heat of these three gases, followed by CH_4 and then CO_2.

To estimate the RF implications of various forest management and bioenergy pathways, the following analytical elements have to be included in the analysis:

- temporally-explicit life cycle system modeling to determine GHG emission profiles;
- atmospheric decay modeling to determine residence of GHGs in the atmosphere;
- and time-dependent estimates of radiative imbalance due to atmospheric concentration changes of the GHGs.

We use the simple climate models described by Zetterberg (Zetterberg 1993), with updated parameter values from IPCC (IPCC 1997; IPCC 2013). The atmospheric decay of each annual pulse emission is estimated using Equation 4-6 describing the removal of CO_2, N_2O and CH_4, from the atmosphere by natural processes at varying time rates.

Once emitted, a GHG will continue to cause radiative forcing and trap heat in the earth system as long as it remains in the atmosphere. GHGs are removed from the atmosphere by natural processes, at time rates that vary according to the specific GHG. The decay over time of unit mass emissions of CO_2, N_2O and CH_4 is shown in Figure 6.

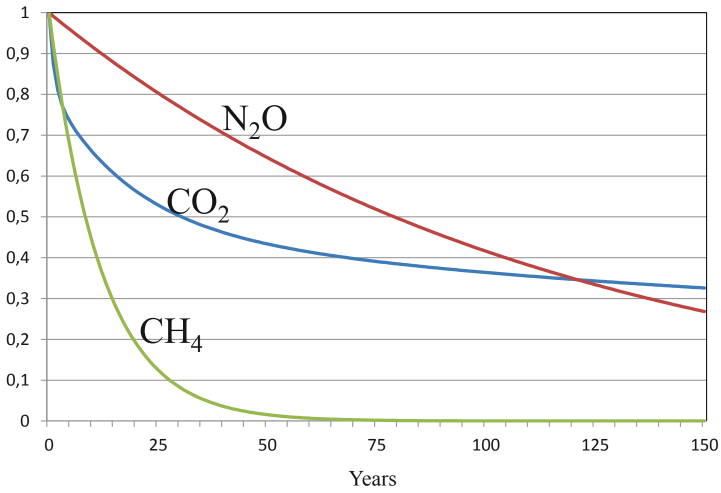

Figure 6. Estimated atmospheric decay of unit pulses of CO_2, N_2O *and* CH_4.

The emissions of CO_2, N_2O and CH_4 that occur during Year 0 when the fuel is combusted are typically treated as pulse emissions. The atmospheric decay of such pulse emissions can be estimated using Equations 4, 5 and 6 (IPCC 1997, 2001, 2007):

$$(CO_2)_t = (CO_2)_0 \times \left[0.217 + 0.259e^{\frac{-t}{172.9}} + 0.338e^{\frac{-t}{18.51}} + 0.186e^{\frac{-t}{1.186}}\right] \quad (4)$$

$$(N_2O)_t = (N_2O)_0 \times \left[e^{\frac{-t}{114}}\right] \quad (5)$$

$$(CH_4)_t = (CH_4)_0 \times \left[e^{\frac{-t}{12}}\right] \quad (6)$$

where t is the number of years since the pulse emission, $(GHG)_0$ is the mass of GHG emitted at Year 0, and $(GHG)_t$ is the mass of GHG remaining in the atmosphere at year t. These decay patterns are shown in Figure 6. The total atmospheric mass of GHG for each year of the simulation period is then determined by summing the emissions occurring during that year and the emissions of all previous years minus their decay during the intervening years.

The time profiles of atmospheric mass of each GHG are then be converted to time profiles of atmospheric concentration, based on the molecular mass of each GHG, the molecular mass of air, and the total mass of the atmosphere estimated at 5.148 × 1021 g (Trenberth and Smith 2005). Marginal changes in instantaneous radiative forcing due to the GHG concentration changes can then be estimated using Equations 7, 8 and 9 (IPCC 1997; IPCC 2013):

$$\mathrm{F}_{CO_2} = 5.35 \times \ln\left\{1 + \frac{\Delta CO_2}{CO_{2ref}}\right\} \tag{7}$$

$$\mathrm{F}_{N_2O} = 0.12 \times \left(\sqrt{\Delta N_2O + N_2O_{ref}} - \sqrt{N_2O_{ref}}\right) - f(M,N) \tag{8}$$

$$\mathrm{F}_{CH_4} = 0.036 \times \left(\sqrt{\Delta CH_4 + CH_{4_{ref}}} - \sqrt{CH_{4_{ref}}}\right) - f(M,N) \tag{9}$$

where F_{GHG} is instantaneous radiative forcing in W m^{-2} for each GHG, ΔGHG is the change in atmospheric concentration of the GHG (in units of ppmv for CO_2, and ppbv for N_2O and CH_4), and CO_{2ref}= 400 ppmv, N_2O_{ref}= 319 ppbv, CH_{4ref}= 1774 ppbv, and $f(M,N)$ is a function to compensate for the spectral absorption overlap between N_2O and CH_4 (IPCC 1997, 2001, 2007).

The estimated values of instantaneous radiative forcing are annual and global averages, allowing us to integrate across time and area to determine aggregate impacts. We estimate the cumulative radiative forcing (CRF) occurring each year in units of W s m^{-2} (equivalent to, J m^{-2}) by multiplying the instantaneous radiative forcing of each year by the number of seconds in a year. This operation converts the energy flow per unit of time of the radiative imbalance caused by GHGs into units of energy accumulated in the earth system per m^2 of tropospheric surface area per year. Results are presented as CRF (W s m^{-2}) per dry ton of biomass (or equivalent fossil services). In Papers I, IV and V, CRF is normalized to a unit hectare of forest land, to become Watt second per m^2 per ha. This expresses how much trapped heat due to global warming is avoided as a result of each hectare of forest land.

3. RESULTS

3.1. Biogenic carbon dynamics modeling

Stand level perspective

Total carbon storage can be divided into living tree biomass, soil carbon and dead wood, Figure 7 adapted from Paper V. During the 260-year study period, four rotations are covered, starting with final felling. The forest productivity is slightly increasing over time. The demand for pulpwood is assumed to be constant over time. Living tree biomass (t C), which is defined as the sum of the carbon stock in tree vegetation above ground (t C) plus the carbon stock in stumps and roots (t C), is the same for all recovery strategies and increases slightly with time (Figure 8a). The soil organic carbon stock depends on the amount of extracted residues (Figure 8b) and the patterns of final felling are visible. The carbon storage in dead wood (Figure 8c) is minor compared to the other carbon stocks and is independent of the recovery strategies due to the definition of dead wood in Heureka. All dead wood results refer only to the stem wood parts, including bark, above ground. Branches, foliage, tree tops, stumps and roots are treated as an input to the soil carbon model, if not extracted. Only mortality in established stands is transferred to the dead wood pool, mortality in young stands is transferred as litter to the soil carbon model.

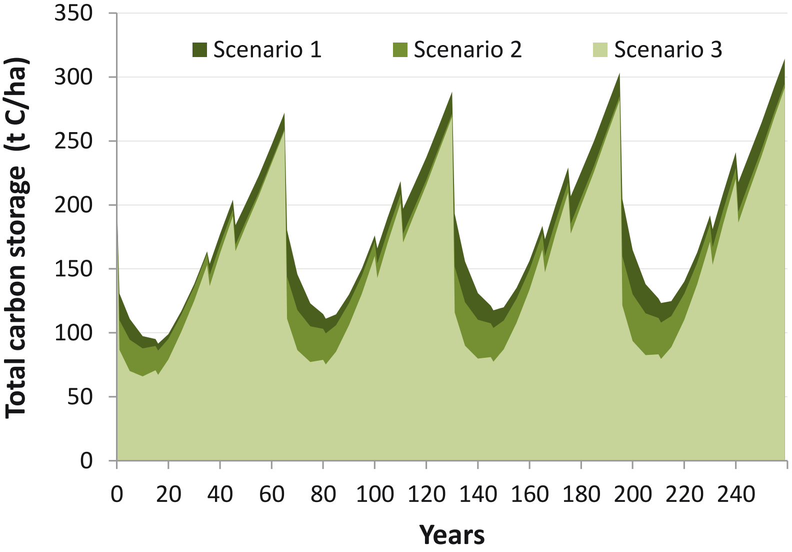

Figure 7. Overview and comparison of the forest production and carbon storage over time including living tree biomass, dead wood and soil carbon (ton C/ha) under the different forest residues recovery strategies 1) Managed only stem, 2) Managed, stem + forest residues, 3) managed, stem + forest residues + stumps

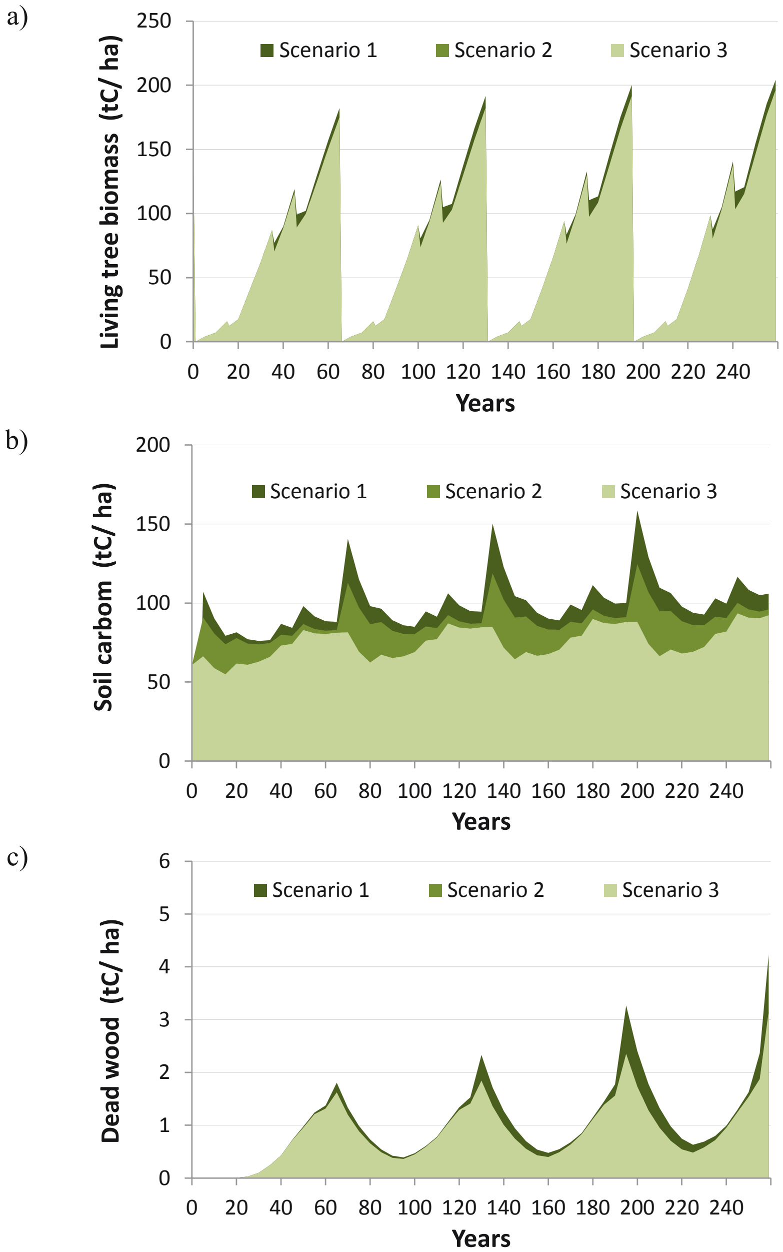

Figure 8. a) Carbon stock in the living tree biomass (tC/ ha), b) in the soil (tC/ ha) and c) in the dead wood (tC/ ha) under the different recovery scenarios

The impact of the forest management strategy on forest production is shown in Figure 9 for a conventionally managed Norway spruce stand, for a more intensively managed stand with fertilizer applications in the early years and for an unmanaged forest stand. Due to uncertainties regarding the long-term development of the living carbon stocks in an unmanaged stand, two scenarios are considered: the carbon stock remains constant at the 20% greater level, or the carbon stock reaches the 20% greater level, and then is slowly reduced by natural disturbances to be 20% less than the harvest level of the conventionally managed stand.

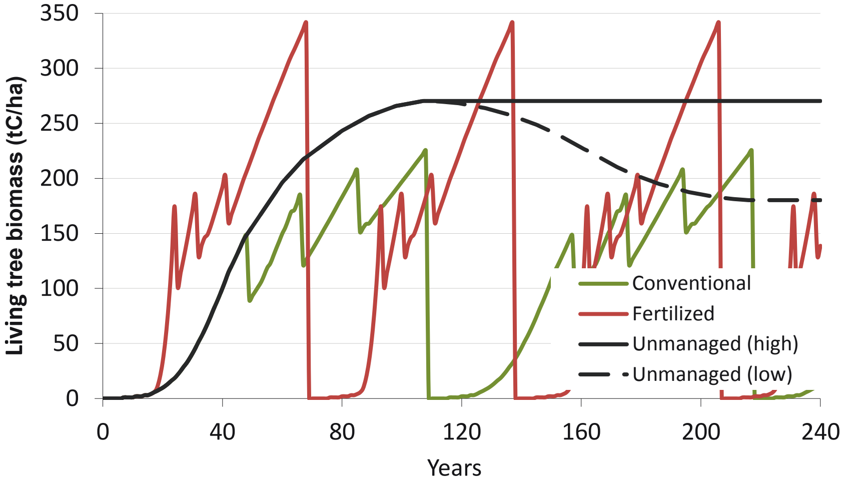

Figure 9. Living tree biomass stock as carbon (t/ha) under the different forest management regimes: a) conventional forest management, b) intensive forest management, including fertilization and c) unmanaged forestland, including a range of equilibrium values from -20% to +20% relative to the final carbon stock if the stand were harvested.

During the 240-year modeling period, two rotation periods for the conventional stand occur while three rotations occur for the fertilized stand. The three peaks that occur during the growth period are due to the three thinnings in each rotation period. The average carbon stock in living biomass is greater in the fertilized stand due to its more rapid initial development and its greater final yield. The rate of biomass production is greater in the fertilized stand due to its shorter rotation period and higher yield per rotation.

Figure 10 illustrates the impact of the choice of tree species on the biogenic carbon dynamics. In the different bioenergy scenarios we establish forest land in year 0 and assume the land is managed following either conventional Danish forest practices, such as species-specific thinning and felling operations for Norway spruce, Grand fir, Poplar and Willow, or is unmanaged for Beech. The modeling of the carbon dynamics for the Beech was based on assumption adapted from Paper I. The forest productivity is not increasing over time and no climate change is considered.

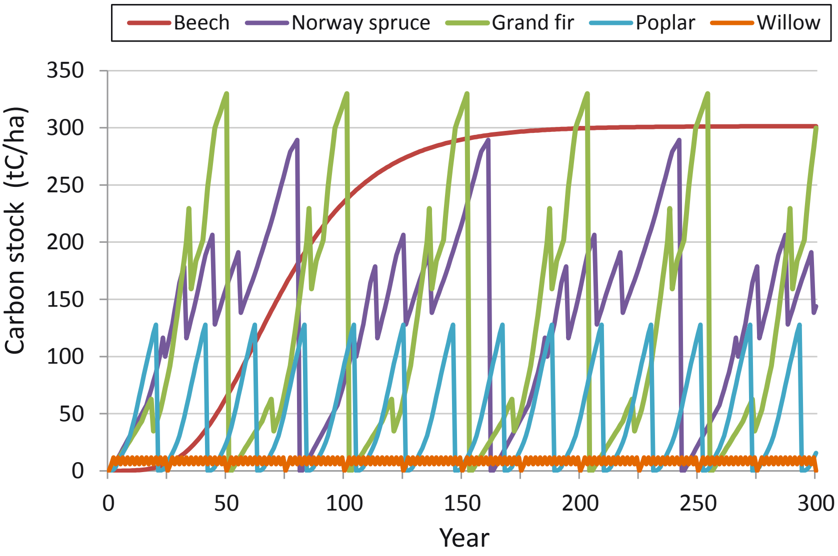

Figure 10. Living tree biomass stock of the different tree species planted on abandoned farmland

National level

A topic of active discussion in Sweden is how the forest should be managed. To answer this question, we need to change the spatial perspective of the study to the landscape or national level. The following results were estimated on a national level. The standing stock of stemwood and the total living tree biomass increase significantly over the simulation period (Figure 12). In the BAU scenario the stock increases 44% over 100 years. The corresponding increases are 82% and 56% for the Set-aside and Production scenarios, respectively. The living biomass stock for the Set-aside scenario started to diverge from the BAU scenario almost immediately as an effect of the net growth on set-aside land. The effect of changes in management in the

Production scenario appears several decades later, since the effect of the silvicultural measures to increase growth take time.

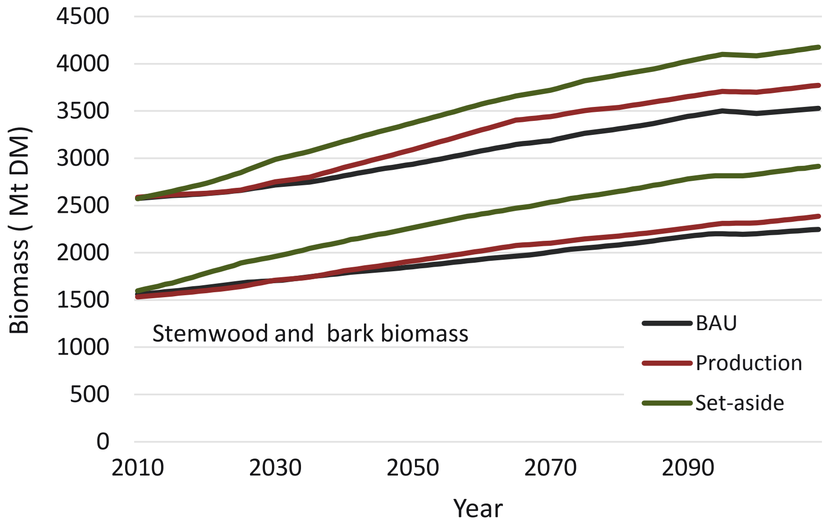

*Figure 12. Living tree biomass and standing stemwood biomass (Mt DM) in Swedish forests under three scenarios, 2010-2109***.**

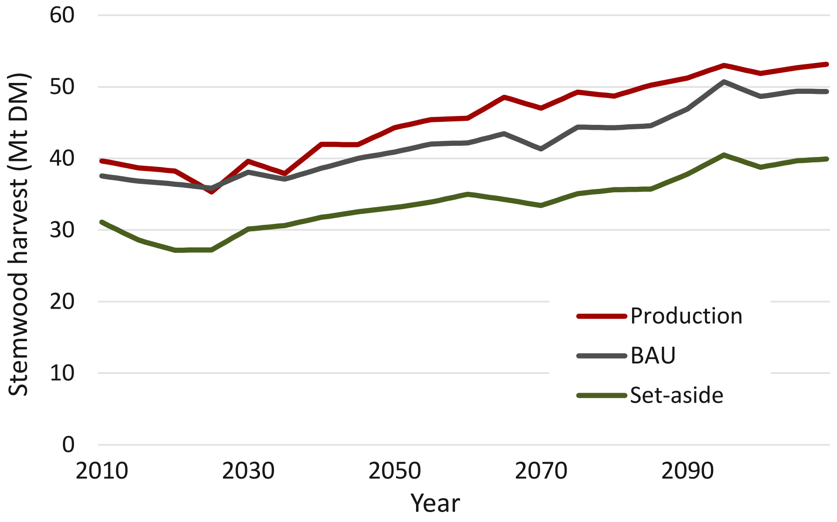

Figure 13. Stemwood harvest (Mt DM year^{-1}) from Swedish forests under three scenarios, 2010-2109.

The stemwood harvest is typically highest for the Production scenario (Figure 13), due to the high growth and since almost all of the annual growth is harvested. Harvest in the Set-aside scenario is limited on the one hand by the restriction of harvesting set-aside land, which decreases the available forest land that could be harvested, whilst, on the other hand, the growth in the Set-aside scenario reduces more in the long term than in the BAU and the Production scenarios. The Set-aside scenario harvest follows the same pattern as the BAU scenario but at a consistently lower level.

Figure 14 shows the potential harvest of logging residues and stumps in the BAU, Production and Set-aside scenarios with varying levels of residue extraction. In the Production scenario, the potential harvest increases to about 100 TWh year^{-1} by the end of the simulation period, if 80% of logging residues from final fellings, 50% of logging residues from thinnings, and 50% of stumps from final fellings are harvested. For the Set-aside scenario there is the potential to increase harvest to 36 TWh yr^{-1} if 80% of logging residues from final fellings and 50% of logging residues from thinnings are harvested.

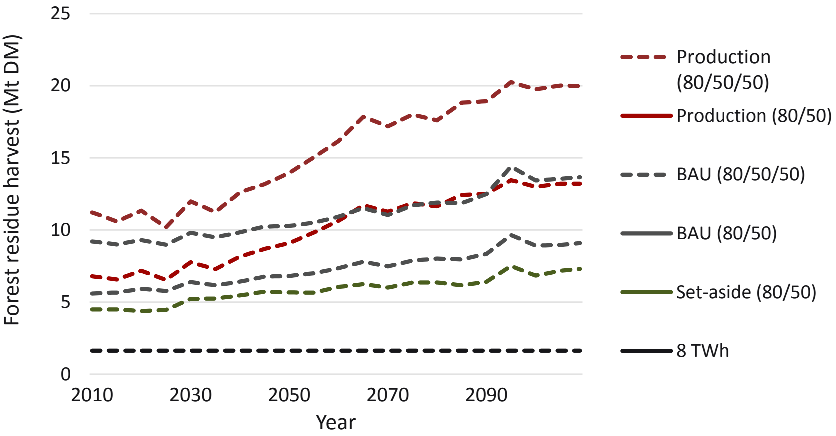

Figure 14. Potential harvest of logging residues and stumps (Mt DM per year) under three scenarios (BAU, Production and Set-side) with varying levels of residue extraction. 8TWh represents annual harvest of 8TWh of logging residues; 80/50 represents harvest of 80% of logging residues from final fellings and 50% of logging residues from thinnings; 80/50/50 represents the same logging residues harvest plus 50% harvest of stumps from final fellings.

3.2. Annual and cumulative GHG emissions

If residues are used for energy to replace fossil fuel, the biogenic carbon is emitted immediately to the atmosphere; in addition, there are some emissions from the fossil fuels used to recover and transport the biomass. If residues are left in the forest and not used as fuel, a corresponding amount of fossil fuel will be used instead resulting in immediate fossil emissions, followed by gradual emission of biogenic carbon from the decaying residues, Figure 15.

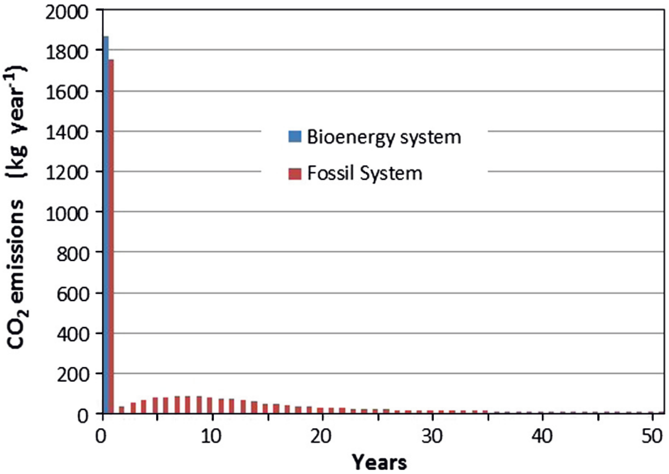

Figure 15. Biogenic carbon emissions for 50 years for the BST bioenergy and the CST fossil energy for 1 t (DM) delivered biomass coming from logging residues

Annual net CO_2 emissions over the 240-year simulation period are shown in Figure 16, with coal as the reference fossil fuel. The annual CO_2 emissions reflect the pattern of the forest rotation periods, showing negative emissions due to carbon uptake by growing trees, avoided emissions due to material and fuel substitution at thinning and harvest events, and positive emissions due to decaying biomass left in the forest after harvests. The positive emission spikes at years 119 and 188 of the fertilized stand, and year 159 of the non-fertilized stand, are due to the combustion of demolition materials from buildings built from forest harvests 50 years earlier. The negative emissions of the fertilized stand are of greater magnitude than the non-fertilized stand.

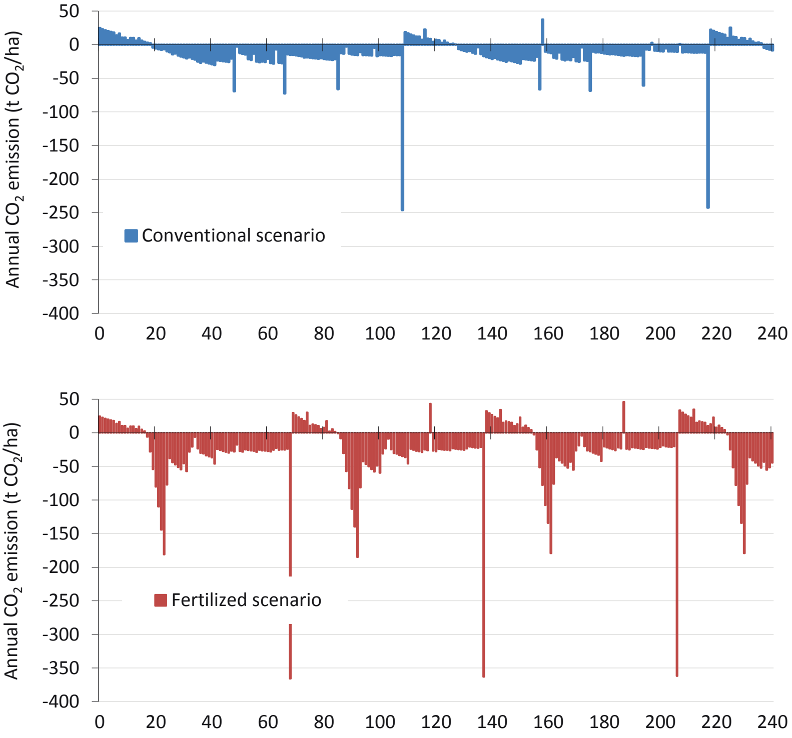

Figure 16. Annual net CO$_2$ emissions (t CO$_2$ ha^{-1}) for the Conventional scenario (blue) and the Fertilized scenario (red).

Figure 17 shows the cumulative net CO$_2$ emissions of a wood-intensive cross-laminated timber building system (CLT) system and a reinforced concrete building system with different forest residue recovery strategies: only stemwood harvesting (short dashed lines), stemwood and logging residue harvesting (long dashed lines) and stemwood, logging residues and stump harvesting (solid lines) to replace coal-fired CHP-BST heat and electricity production. Emissions for both systems show the cyclical pattern corresponding to the forest rotation period of 65 years. In the long-term the cumulative emissions from the concrete-based system is around three times higher as the emissions from the CLT system. The impact of the different amount of available biomass due to the different forest residues recovery scenarios is greater in the CLT system compared with the concrete system. Collecting logging residues and stumps give the lowest CO$_2$ emissions in both building systems.

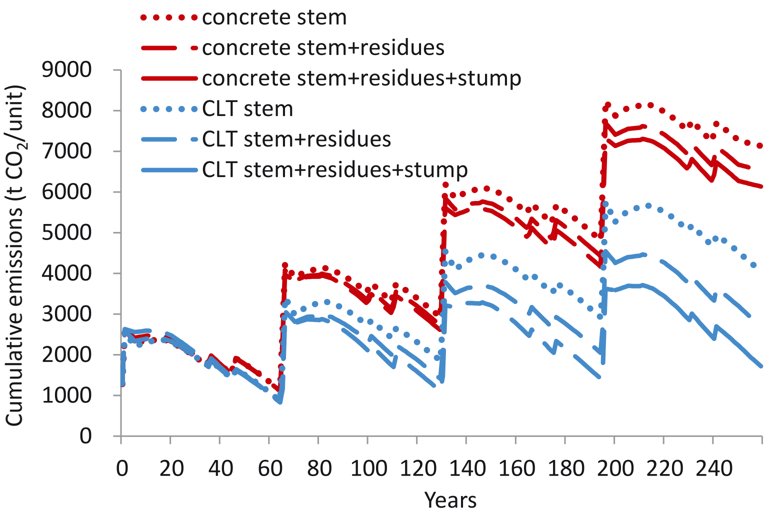

Figure 17: Cumulative net emissions (t CO_2) of a wood-intensive building system (blue) and a concrete-based building system (red) for different residues recovery strategies: only stemwood harvesting (short dashed lines), stemwood and logging residue harvesting (long dashed lines) and stemwood, logging residues and stump harvesting (solid lines) when coal-fired CHP-BST heat and electricity production is replaced.

The results in Figure 18 show that, in the short term, the carbon balance is almost equal for the BAU, Set-aside and Production scenarios. The scenario with increased set-aside area and the current level of forest residue harvest (Set-aside, 8TWh) results in lower cumulative carbon emissions compared to the reference case for the first 90 years, but then shows higher emissions as reduced forest harvest leads to higher carbon emissions from energy and material systems. For the reference scenario of current forest management (BAU 8TWh), increased harvest of forest residues delivers increased climate benefits. However, in the long-term, the Production scenario has significantly lower CO_2 emissions, largely due to the higher amount of available biomass for substitution, and especially with increased harvest of forest residues. This demonstrates that carbon balances of forest systems, including their biological and technological components, must be studied over longer periods to see the effect of implementing different strategies. Considering only shorter periods (e.g. 20 years) may lead to decisions that, in the long term, do not deliver the desired climate benefits.

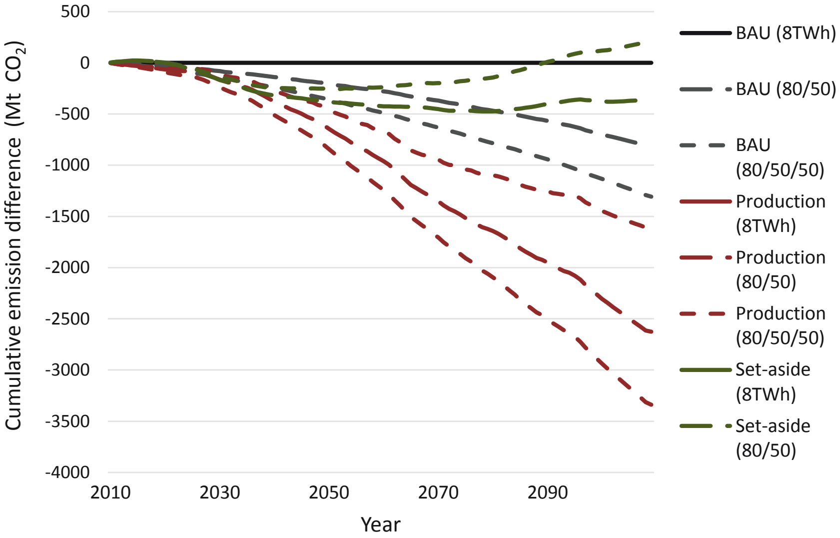

Figure 18. Difference in cumulative CO_2 emission (Mt CO_2) between BAU 8TWh and the other scenarios. The main energy and building alternatives are used. 8TWh represents annual harvest of 8 TWh of logging residues; 80/50 represents harvest of 80% of logging residues from final fellings and 50% of logging residues from thinnings; 80/50/50 represents the same logging residues harvest plus 50% harvest of stumps from final fellings.

3.3. Climate impact assessment

The climate benefits of more intensive forest management are presented in Figure 19, which shows the CRF resulting from the various scenarios with different assumptions for the land use in the reference system with fossil coal as the reference. The fertilized regime trends generally downward over time, as growing trees in each rotation remove carbon from the atmosphere, and harvested biomass leads to avoided fossil carbon emissions due to material and fuel substitution. The conventional regime also trends downwards, though less steeply because its growth rate is lower.

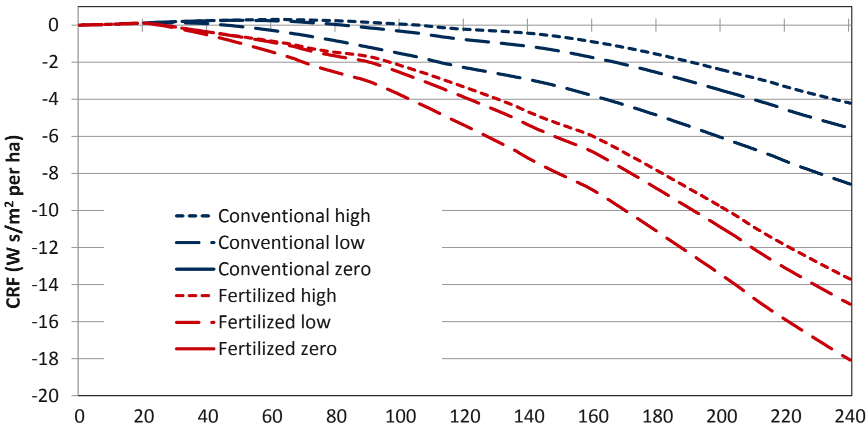

Figure 19. The CRF (W s m^{-2} ha^{-1}) for the Conventional scenario (blue) and the Fertilized scenario (red) with high and low carbon stock equilibrium assumption in the reference fossil system as well as the Conventional zero and fertilized zero scenarios without considering forestland-use. The starting point is a clear cut forest stand and the replaced fossil fuel is coal.

The *Conventional high* and *Conventional low* scenarios are calculated as the difference between the bioenergy system with conventional forestry and the fossil system with an unmanaged forest with high or low equilibrium carbon stocks, respectively. Similarly, the *Fertilized high* and *Fertilized low* scenarios are calculated as the difference between the bioenergy system with fertilized forestry and the fossil system with an unmanaged forest with high or low equilibrium carbon stocks, respectively. *Conventional zero* and *Fertilized zero* scenarios are defined as the difference between the bioenergy system with conventional and fertilized forestry, respectively, and the fossil system without considering any forest land use. Increasing biomass production through forest fertilization combined with substitution of non-wood products and fuels can significantly reduce CRF. The emissions from intensified forest management resulted in very little radiative forcing in comparison to the negative radiative forcing from using the increased forest growth for biomass substitution. The biggest single factor causing RF reduction was using timber to produce wood material to replace energy-intensive construction materials such as concrete and steel. Another very significant factor was replacing fossil fuels with wood residues from forest thinning, harvest, wood processing, and post-use wood products. The fossil fuel that was replaced by bioenergy affected the reductions in GHG emission and radiative forcing (Figure 20), with carbon-intensive coal being most beneficial to replace. The climate benefits of fertilization were proportional to the increased rate of biomass production, in terms of shortened rotation lengths and increased harvest volumes. Because the substitution benefits of forest product use are cumulative, and the carbon sink in the forest biomass and soil is limited, the non-management and non-use of forest biomass becomes less attractive as the time horizon increases. In the long term, active and sustainable management of forests, including their use as a source for wood products and biofuels, has the greatest potential for reducing net carbon emissions.

Figure 20 shows the difference in CRF between the bioenergy systems and various corresponding fossil systems. Covering a 300-year period following the energy use in Year 0, the curves show the long-term climate effects of using 1 ton of biomass from forest residues, minus the emissions from corresponding fossil energy systems that are avoided by bioenergy use. The base case condition is defined as including logging residue recovery, with international transport, and Q decay model with climate for central Sweden. Using biomass to substitute fossil coal can provide greater climate change mitigation benefits than substituting oil or fossil gas. Some bioenergy substitutions result in positive CRF, i.e. increased global warming, during an initial period. This occurs particularly for relatively inefficient bioenergy conversion pathways to substitute less carbon intensive fossil fuels, e.g. DME used to replace diesel. More beneficial bioenergy substitutions, such as efficiently replacing coal, do not cause such initial positive CRF, and instead provide climate benefits beginning in the first year of energy use.

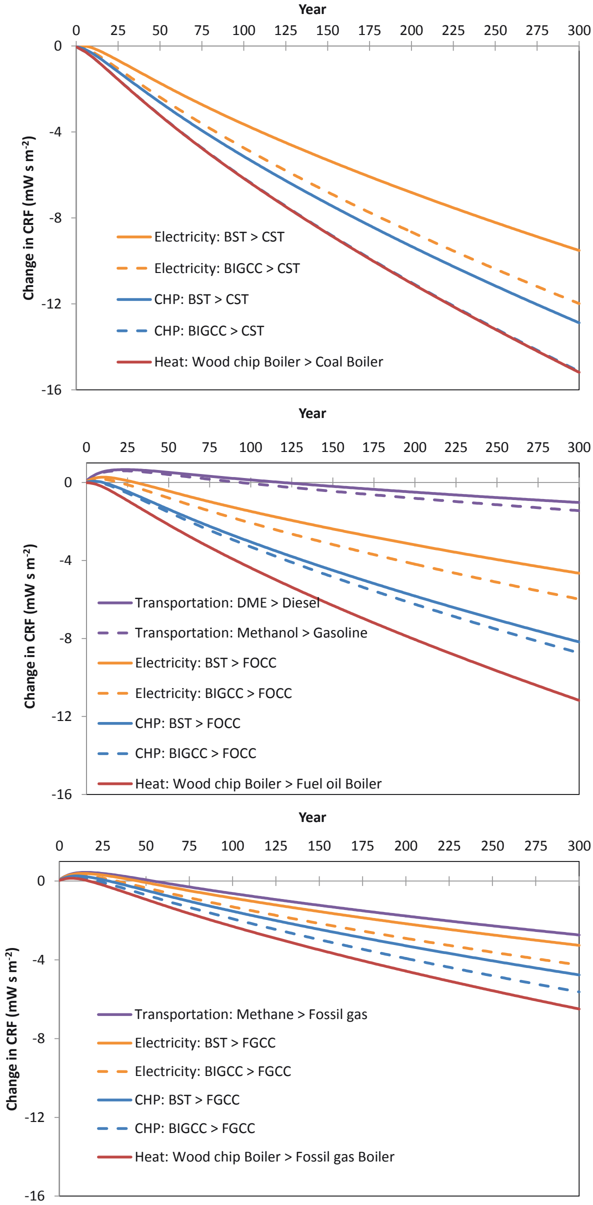

Figure 20. Change in CRF (mW s m^{-2}) over a 300-year period due to the substitution of 1 dry ton of biomass for corresponding fossil energy systems using coal (top), oil (middle) and gas (bottom), (base case conditions: logging residues, international transport, Q decay model, with climate for central Sweden).

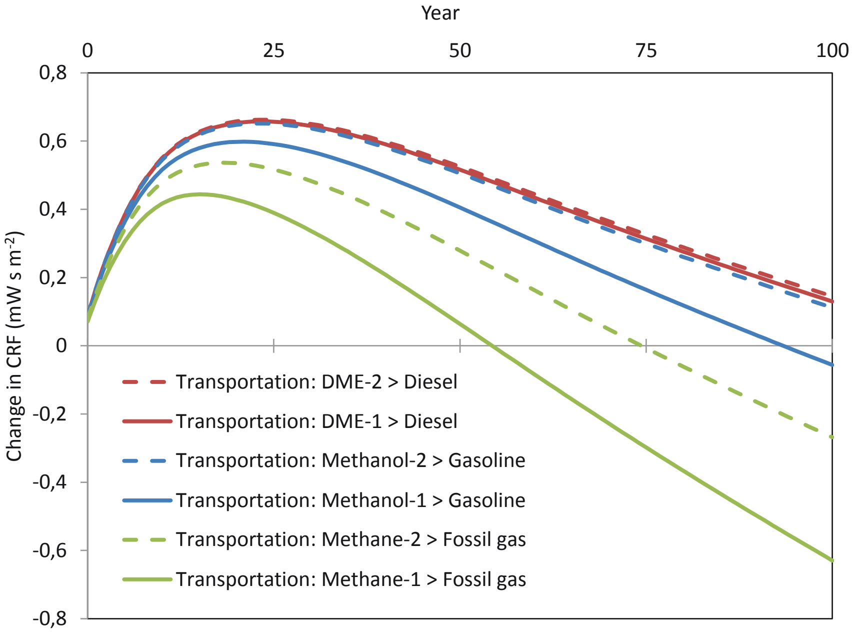

Figure 21. Change in cumulative radiative forcing (mW s m^{-2}) over a 300-year period due to the substitution of 1 t DM of biomass for corresponding fossil energy systems using oil and gas to provide transportation fuels, under base-case conditions (logging residue, international transport, chipped haulage, Q decay model, central climate). The bioenergy systems marked "1" (solid lines) are shown in previous figures, and are based on indirect gasification at a scale of 450 MW$_{biofuel}$. Those marked "2" (dashed lines) are based on entrained flow gasification at a scale of 800 MW$_{biofuel}$.

Figure 21 shows the change in CRF due to the substitution of forest residues for various transportation fuels. The bioenergy systems marked *1* (and represented by solid lines) are based on indirect gasification at a scale of 450 MW$_{\text{biofuel}}$. Those marked *2* (represented by dashed lines) are based on entrained flow gasification at a scale of 800 MW$_{\text{biofuel}}$. Using forest residues to produce transportation fuels results in significant initial CRF, followed by gradual reductions. Producing DME to replace diesel fuel is the least beneficial option, and continues to cause positive CRF (increased global warming) for over 100 years.

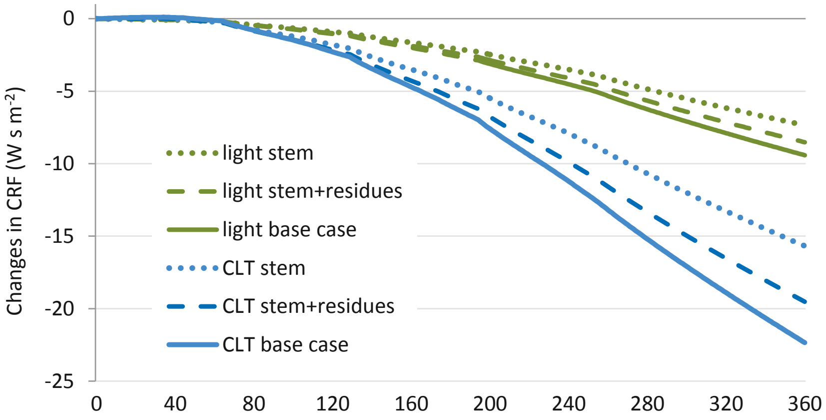

Figure 22: Changes in CRF between the reinforced concrete as the reference system and the CLT and light-frame building system for the different forest residues recovery strategies when only stemwood is harvested (short dashed line), when additionally logging residues are recovered (long dashed line) and when stemwood, logging residues and stumps are harvested (solid line). Coal is replaced.

Figure 22 shows the changes in CRF between the CLT building system and the concrete building system (blue) and the changes in CRF between the light-frame building system and the concrete building system (green) with varying levels of harvest residue collection. All scenarios provide immediately climate benefit. The impact of the choice of harvest scenario is greater for the CLT system and less important in the light-frame building system. The best long-term climate benefit can be reached by using a more wood-intensive building structure system like the CLT in combination with a more-intensive harvest residue strategy.

Figure 23 shows the difference in CRF between the BAU 8 TWh scenario and the other scenarios, with the main energy alternative (heat and electricity produced in a CHP plant using either coal-based or biomass-based steam turbine technology) and the main building alternative (building frame made of either reinforced concrete or CLT). The difference is small between the BAU and Set-aside scenarios. The Production scenario results in consistently lower CRF, the extent of which depends on residue recovery. As more biomass residues are recovered and used for bioenergy, an increasing climate benefit is delivered.

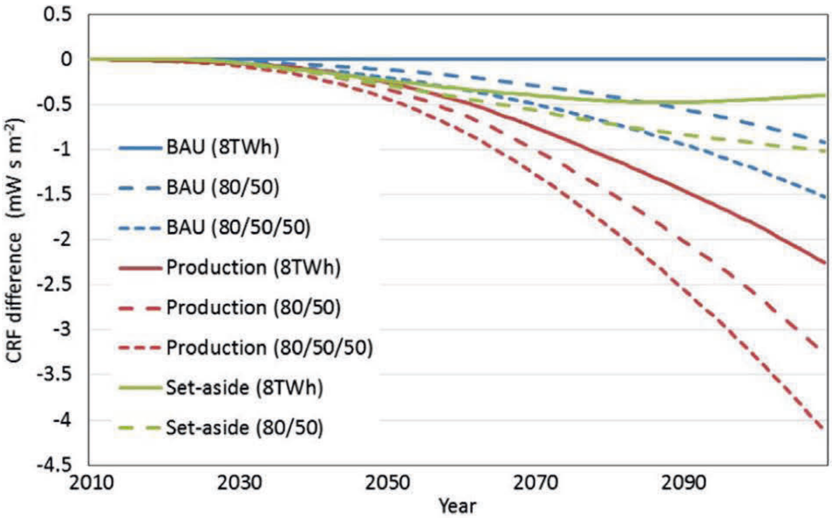

Figure 22. Difference in CRF (mW s m^{-2}) between BAU 8 TWh and the other scenarios. Main energy and building alternatives are used. 8TWh represents annual harvest of 8 TWh of logging residues; 80/50 represents harvest of 80% of logging residues from final fellings and 50% of logging residues from thinnings; 80/50/50 represents the same logging residues harvest plus 50% harvest of stumps from final fellings.

4. DISCUSSION

This thesis focuses on the development of a methodological framework froma life cycle perspective to assess the climate impact of the sustainable use of forest biomass in bioenergy and bio-based material systems. Numerous factors, such as land-use, forest management, the choice of natural resource as well as the choice of the replaced fossil fuel and its conversion system influence the climate impact of bioenergy systems.

The findings presented in this thesis show that one of the most important climate change mitigation strategies to reduce long term carbon emissions is the use of biomass to substitute fossil energy and carbon intensive materials in the energy and building sector. Harvesting stemwood, harvest residues, and stumps increases the potential substitution benefits and, therefore, the total carbon emission reductions, thus delivering climate change mitigation benefits. However, an alternative is to increase biomass stock in the forestland by leaving a forest unmanaged or less managed and to leave all harvest residues in the forest. This alternative is likely to be beneficial in the short term. The capacity of forests to store increasing amounts of carbon is, however, limited and forests reach a dynamic equilibrium (Taeroe et al. 2017). Furthermore, the forest carbon stock can be released to the atmosphere by natural disturbances like fire, storm damage and disease, which can cause mortality if the stand is dense (Blennow et al. 2010). Harvest residues left on site decompose and release carbon into the atmosphere in the long term.

Increasing the intensity of forest management delivers greater reductions in climate change impact, due to greater biomass production leading to more material and energy substitution of non-wood products and fuels. The additional emissions from intensified forest management, including manufacture and application of fertilizer, result in very little radiative forcing in comparison to the avoided radiative forcing from using the increased forest growth for biomass substitution. The climate benefits of fertilization are largely proportional to the increased rate of biomass production resulting from shortened rotation lengths and increased harvest volumes. The chosen location modeled here is in northern Sweden because the great expanse of boreal forest is located in northern Sweden. Forest growth on mineral soils in boreal regions is often limited by a low availability of nitrogen, thus fertilization has a very strong effect in these regions. Fertilization has less impact in southern Sweden compared to the north (Sathre et al. 2010)

Collecting forest residues and using them efficiently to provide energy services, delivers great climate benefits. The climate benefits depend largely on the type of fossil fuel to be substituted, and on the effectiveness of the energy conversion technologies. Biomass decay rates, supply systems and transport distance have less influence on climate benefits. Using biomass to replace fossil coal provides greater climate change mitigation benefits than substituting biomass for oil or fossil gas in the long term. Some bioenergy substitutions can even result in positive CRF, in other words increased global warming, during an initial period. This occurs for relatively inefficient bioenergy conversion pathways to substitute less carbon intensive fossil fuels, like transportation fuel used to replace diesel. More beneficial bioenergy substitutions, such as efficiently replacing coal, result immediately in reduced CRF.

The changing utilization of forest biomass is increasingly discussed in Sweden, and linked to issues such as shrinking markets for newsprint and future production of biofuels in the transport sector. A basic question in this context is: how do we develop competitive and resource-efficient uses for Swedish forest biomass based on the current and future needs of society? For example, it appears inefficient to use forest biomass to produce transportation fuels, which entails large conversion losses as compared to using conventional fossil gas and oil, while at the same time continuing to use fossil gas and oil for the production of electricity and heating, where the forest biomass could be used much more efficiently. A more effective solution would instead be to decrease the use of fossil energy, including gas and oil, in the electricity and heating sectors by creating biomass-based energy supply systems.

Uncertainties

Climate impact assessments involve relatively simple models of complex natural processes, thus they are subject to some uncertainties. The calculations of RF assume relatively minor marginal changes in atmospheric GHG concentrations, such that radiative efficiencies and atmospheric decay patterns of the gases remain constant. However, significant increases in the atmospheric concentration of CO_2 can be expected during the coming decades and centuries. Increased atmospheric CO_2 concentration will decrease the marginal radiative efficiency of CO_2, but will also decrease its marginal atmospheric decay rate. These will have opposite and therefore offsetting effects on radiative forcing, thus we expect this uncertainty to be minor (Caldeira & Kasting 1993). More sophisticated modeling could account for expected future trajectories of GHG concentrations and their effects. Furthermore, the estimation of CRF by integrating instantaneous radiative forcing over time ignores the feedback effect that the accumulated energy will have on future outgoing radiation. Radiative forcing is a measure of the radiative imbalance given that atmospheric temperatures remain unchanged.

The analyses presented in this thesis considered existing fuel conversion systems as well as future prospects for various technologies. Obviously, the future is uncertain, but some trends can be assumed. Some of the emerging technologies included, such as biomass gasification, are promising. However, biomass-based gasification technologies are under development, and inherent uncertainties exist in terms of technical performance.

How biomass, sun and wind can be used optimally on a long-term basis for electricity, heating and transportation fuels depends in part on technological development, and it is difficult today to assess which pathway is best. Therefore, it may be advantageous to strive for flexibility and avoid heavy dependency on capital-intensive, long-lived energy structures. At the same time, it is important to consider whether we envision solutions based only on today’s established concepts and production systems, and how they influence our thoughts about future possibilities. It is easy to hold on to existing technologies that have been developed and refined over time, especially if they have, thus far, been rewarding. More challenging, but ultimately essential, is to envision systems that are appropriate for future conditions, and to create a framework for the implementation of robust, forward-looking energy and building systems.

5. CONCLUSIONS

In this thesis, a time-dependent approach for conducting LCA was developed and both the timing and the magnitude of GHG fluxes were considered in climate impact assessments. Taking this approach, temporal CO_2 fluxes between the soil, biomass and atmosphere connected to various bioenergy systems are included. This methodology was used to investigate the time-dependent climate impact of the sustainable use of forest biomass in various material and energy systems.

The forest is the basis for all analyses described in this thesis.

- Increasing the intensity of forest management results in greater production of biomass, which allows for more replacement of fossil energy and fossil-intensive materials. Greater production of biomass can be achieved further through increased recovery of forest residues (thinnings, logging residues and stumps) or by changing to more productive tree species.

- The results show large climate benefits when forest residues are recovered and used efficiently for energy services instead of left in the forest to decompose. The climate benefits depend largely on the type of fossil fuel to be substituted, and on the effectiveness of the energy conversion technologies. Biomass decay rates, supply systems and transport distance have less influence on climate benefits Using forest residues to replace fossil coal provides greater climate change mitigation benefits than substituting biomass for fossil oil or fossil gas.

- Wood-frame building materials use less energy and emit less CO_2 to the atmosphere over their life span than the materials used for concrete-frame building construction. Less fossil energy is needed to manufacture wood products compared with alternative building materials. Using wood instead of concrete avoids non-energy process emissions from cement calcination or other industrial processes. Forest biomass by-products and post-products can be used as bioenergy or biofuel to replace fossil energy and fossil fuels.

- A strategy aimed at high forest production and harvest, high residue recovery rate, and high efficiency utilization of harvested biomass, will give the best climate benefits compared to increasing set-aside land for carbon sequestration in managed forest ecosystems.

Bases on the findings presented in this thesis, the overall conclusion of the studies is that sustainable forest management with high forest production and harvest, high residue recovery rates, and high efficiency utilization of harvested biomass, will deliver the greatest climate benefits compared to increasing set-aside land for carbon sequestration in managed forest ecosystems.

6. FUTURE RESEARCH

To build on the work presented in this thesis, the research could be expanded to perform climate impact assessments of using bioenergy from the stand level to the landscape level perspective. Studies using stand level calculations typically consider dynamic carbon modeling over one or several rotations. The growing forest stand sequesters carbon until it is released into the atmosphere by either biomass decay or combustion, so there will be always a difference in timing of carbon emissions and sequestration. Where forest management activities are coordinated across a whole landscape or region to obtain a continuous flow of wood biomass, dynamic carbon modeling at the landscape level is more appropriate (Cintas et al. 2016; Eliasson et al. 2013). The large shifts that are observed at the stand level, from net carbon sequestration to net carbon emissions at harvest, are not observed at the landscape level. Carbon losses in some stands are balanced by carbon gains in other stands, so that across the whole forest landscape the carbon stock follows a trend line that can increase or decrease, or be roughly stable over time. The intuitive conclusion from this, that stand level and landscape level assessments of the carbon balance of forest bioenergy can give different results, has been confirmed in various studies (Berndes et al. 2013; Cintas et al. 2016).

To achieve more precise climate impact assessment modeling, the potential effects of albedo changes should be considered. Changes in land surface albedo, e.g. between forested and harvested land, may change the balance of solar radiation and hence radiative forcing, particularly in boreal forest regions such as Sweden (Betts 2000; Marland et al. 2003). Harvested forestland may have a higher albedo, reflecting more incoming radiation back into space, thus giving climate benefits relative to non-harvested set-aside forestland. To improve accuracy, albedo changes due to forest management and climate change should be incorporated into the framework, using a spatially specific surface albedo model as well as a model to translate changed surface albedo into climate change effects.

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