THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

On the contribution of forest bioenergy to climate change mitigation

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

Greenhouse gas (GHG) emissions have to be drastically reduced to keep global warming below 2 degrees. Bioenergy can play a role in climate change mitigation by substituting for fossil fuels. However, climate benefits associated with forest-based bioenergy are being questioned, and studies arrive at contrasting conclusions, mainly due to diverging methodological choices and assumptions. This thesis combines three papers to bring together different methodological perspectives to improve the assessment and understanding of the contribution of forest bioenergy to climate change mitigation. The thesis concerns carbon balances and GHG-mediated climate effects associated with the use of forest biomass for energy in Sweden. More specifically, the focus is on methodological choices including definition of spatial and temporal system boundaries, and character of forests and forest product markets, e.g., forest owners' responses to changes in demand for forest products, and how different assessment scales and metrics capture the difference in timing between emission and sequestration of carbon in forests that are managed with long rotations.

The results show that the assessed climate benefits of promoting forest bioenergy systems can differ depending on the scale of the assessment, the forest structure, market prospects for bioenergy and other forest products, and energy system developments. Based on these findings, we recommend that assessments intending to support policy-making (i) consider how an increase in bioenergy demand affects the forest carbon stock at the landscape level, i.e., the scale at which forest operations are typically coordinated; (ii) be context-specific rather than feedstock-specific; (iii) consider changes in forest management driven by increased bioenergy demand, which can affect forest carbon stock and climate change mitigation; (iv) combine the assessment with energy system modeling to understand the size and development of bioenergy demand and different technology pathways; and (v) acknowledge short-term vs. long-term benefits, as some bioenergy systems could be associated with initial forest stock losses but great long-term benefits that can be overlooked if the temporal scope is too narrow. The latter is especially relevant when the ultimate goal is a long-term climate target, e.g.., the 2-degree target.

This thesis also shows that the Swedish forest sector can make an important contribution to the 2045 goal of climate neutrality, i.e., no net GHG emissions to the atmosphere, by supplying forest fuels and other products while maintaining or enhancing carbon storage in vegetation, soils, and forest products. The results indicate that the neutrality target can only be reached by 2050 if the net carbon balance effect from the forest is considered. Additionally, measures to enhance forest productivity can increase the output of forest products (including bioenergy) and also enhance carbon sequestration in forests and products, reaching net negative emissions earlier.

All in all, studies intending to support policy- and decision-making may provide more relevant information if the focus is shifted from assessing individual bioenergy systems to consider all forest products and how forest management planning as a whole is affected by bioenergy incentives - and how this in turn affects carbon balances in forest landscapes and forest product pools. Studies should preferably employ several alternative scenarios for critical factors, including policy options, forest product markets, and energy technology pathways.

Keywords: Forest bioenergy, forest management, GHG balances, climate change, forest supply, carbon budget, energy systems.

List of Publications included in the thesis

I. Cintas O, Berndes G, Cowie AL, Egnell G, Holmström H, Ågren GI (2015) The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. Wiley Interdisciplinary Reviews: Energy and Environment.

II. Cintas O, Berndes G, Cowie AL, Egnell G, Holmström H, Marland G, Ågren GI. Carbon balances of bioenergy systems using biomass from forests managed with long rotations: insights from stand and landscape level assessments. To be submitted.

III. Cintas O, Berndes G, Hansson J, Poudel B, Bergh J, Börjesson P, Egnell G, Lundmark T, Nordin A. The potential role of forest management in Swedish scenarios towards climate neutrality by mid-century. Submitted to Forest Ecology and Management.

Olivia Cintas is the principal author; Cintas performed the data collection and analysis and wrote the three papers. Göran Berndes is the academic supervisor; Berndes and Cintas formulated the research questions and methodology approaches jointly. Berndes also contributed to the analysis and writing. Annette Cowie contributed to formulating the research questions and editing in **Papers I** and **II**. Göran Ågren and Hampus Holmström contributed to forest data & modeling and editing in **Papers I and II**. Julia Hansson constructed the transport scenarios in **Paper III** and provided edits. Forest input data in **Paper III** was provided by Bishnu Poudel, Johan Bergh, Tomas Lundmark, and Annika Nordin. Paudel contributed to the writing, and Bergh, Lundmark, and Nordin also provided editing support. Gustaf Egnell provided input the formulation of the research questions and also editing for all papers, Greg Marland provided ideas and editing in **Paper II**, and Pål Börjesson contributed edits to **Paper III**.

Publications not included in the thesis

I. Cintas O, Berndes G, Egnell G, Holmström H, Ågren GI World Bioenergy 2014. The climate benefits of increased forest bioenergy use in Sweden: evaluation at different scales; World Bioenergy 2014 Proceedings, Svebio, Stockholm, p. 133-139. (2014)

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1 - Introduction

Climate change is one of the greatest challenges humankind has to face. At the United Nations conference on climate change in Paris (COP21), 195 countries reached the historical agreement to hold global warming “well below” 2 degrees Celsius and drive efforts to limit the temperature to 1.5 degrees. The agreement also aims at having greenhouse gas (GHG) emissions peak as soon as possible and reaching GHG neutrality (“a balance between anthropogenic emissions by sources and removals by sinks”) in the second half of this century (UNFCCC, 2015).

Global warming is nearly independent of the timing of CO_2 emissions and mainly driven by cumulative CO_2 emissions (Allen et al., 2009; Knutti & Rogelj, 2015; MacDougall et al., 2015; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009). Based on this, the Intergovernmental Panel on Climate Change (IPCC) has estimated global cumulative “carbon budgets,” the amount of CO_2 that can be emitted since the industrial revolution for a specific probability of keeping the temperature increase below a given level of warming (Collins et al., 2013). Rogelj et al. (2016) reviewed carbon budget estimates and suggest the remaining CO_2 budget for a likely chance of keeping warming below 2 degrees is about 600 – 1250 $GtCO_2$, which is equivalent to about 15 to 30 years of current levels of emissions, 40 $GtCO_2$ $year^{-1}$ (Le Quéré et al., 2014).

Staying within such a carbon budget will require strong mitigation efforts (IPCC, 2014). Strategies to abate GHG emissions include: (i) efficiency measures; (ii) substitution of fossil fuels with non-fossil energy sources; (iii) promotion of carbon sinks, including forest protection and measures to enhance carbon sequestration and storage in vegetation and soil, and also carbon capture and storage (CCS) in deep geological formations. Bioenergy is expected to contribute significantly to abating CO_2 by substituting for fossil fuels (Creutzig et al., 2015; Röder & Thornley, 2016); solid biomass can substitute for coal, biogas for natural gas, and biofuels for oil and diesel, with rather small changes in technology and infrastructure. Bioenergy can also be combined with CCS, so-called BECCS, to achieve negative emissions (Cao & Caldeira, 2010); however, this technology has not yet been applied at scale to operational commercial plants.

Stabilization scenarios in line with the 2-degree limit have bioenergy contributing 10 to 245 EJ yr^{-1} to global primary energy supply by 2050 (Creutzig et al., 2015). Currently, bioenergy demand is estimated to be around 50 EJ (10% of the world total primary energy supply), of which two-thirds is traditional biomass used for cooking and heating in developing countries (IEA., 2014). Creutzig et al. (2015) also estimated the sustainable technical potential for bioenergy to be, with medium agreement, 100-300 EJ by 2050 and argued that realizing this potential will require: (i) reducing traditional biomass demand; (ii) making use of forest and agriculture residues; (iii) optimizing forest harvesting (increase harvest intensity when annual biomass extraction level is less than annual growth); and (iv) making use of dedicated plantations to produce bioenergy feedstocks. An increased harvest intensity and demand for land could lead to higher pressure on ecosystems with environmental and social risks**,** e.g., biodiversity loss or carbon stock depletion (Creutzig et al., 2015; Röder & Thornley, 2016). In this thesis, the focus is on forest bioenergy in the context of climate change mitigation.

1.1 The role of forest bioenergy in climate mitigation.

Biomass production through photosynthesis is part of the carbon cycle, i.e., the flow of carbon between different pools: the atmosphere, the ocean, the biosphere including all ecosystems, the pedosphere including soils, and fossil fuels. Figure 1 (based on IEA Bioenergy (2010)) refers to the biosphere as consisting of the terrestrial biotic pool and the soil organic carbon (SOC), which exchanges CO_2 fluxes with the atmosphere. Atmospheric CO_2 moves into the biosphere via photosynthesis. Some of the biospheric carbon is released back into the atmosphere via plant respiration, and some is converted into SOC. Some of the latter is also released to the atmosphere by soil respiration, and then CO_2 is captured again by biomass regrowth. In contrast, burning fossil fuels increases the amount of CO_2 in the atmosphere by releasing carbon that has been stored for millions of years.

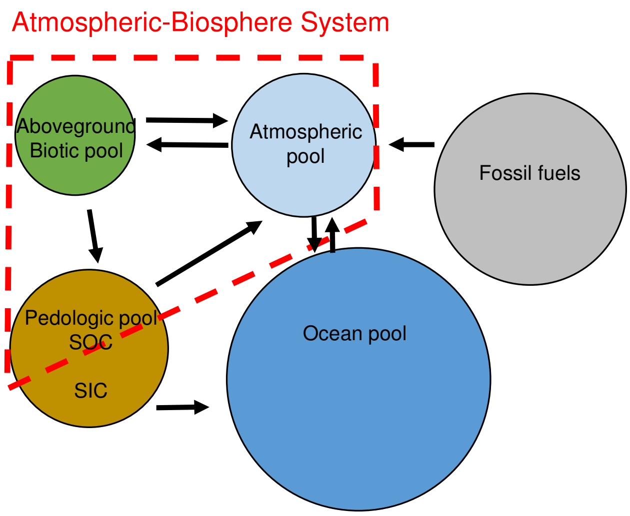

Figure 1: The five principal carbon pools and fluxes between them, based on IEA Bioenergy (2010)

Biomass extracted to provide products affects the biospheric carbon stock, temporarily perturbing the balance between the atmosphere and biosphere, but it does not increase the amount of carbon in the joint system, cf. Houghton et al. (1983). The magnitude of the CO_2 flux imbalance and the temporal dynamics were evaluated in the 90s (Leemans et al., 1996; Schlamadinger & Marland, 1996; Schlamadinger et al., 1995) in order to explore the potential climate change mitigation impact of bioenergy. Traditionally, bioenergy and particularly forest bioenergy – the focus of this thesis – have been considered CO_2-neutral, ignoring the temporal imbalance between atmosphere and biosphere. This assumption relies on the fact that the carbon released from biomass combustion has previously been captured from the atmosphere by vegetation growth.

The carbon neutrality assumption is also motivated by the United Nations Framework Convention on Climate Change (UNFCCC) and its framework for national GHG inventories. The IPCC has recognized that GHG emissions related to forest bioenergy could be reported as either land-use change[1] emissions from the relevant forest or energy system emissions from the relevant combustion, but not both. In order to avoid double counting, the IPCC has proposed a guideline where these emissions should be reported as changes in carbon stock in the forest and placed in the land-use change and forestry sector when the biomass is harvested, independently of the final use of the forest product (IPCC, 2006). Following these guidelines, emissions from biomass combustion are not considered in GHG inventories and bioenergy is thus assumed to be carbon neutral in this context.

With the bioenergy carbon neutrality assumption, the low fossil carbon emissions typically associated with the supply chain of forest-based bioenergy (lower than other crop-based fuels, see JRC (2013)) make forest bioenergy seem like an attractive option for displacing fossil fuels in energy systems. Nevertheless, there is concern that promotion of forest bioenergy by policies that do not consider the carbon imbalance and, thus, do not acknowledge forest carbon losses could lead to the overexploitation of biomass resources, especially for biomass from long-rotation forestry[2] (Searchinger et al., 2009). Mitigation strategies associated with biomass may also lead to trade-offs between extracting biomass to substitute for fossil fuels and promoting carbon sinks by leaving biomass on the ground.

In addition, the urgency for climate change mitigation and the need to reduce GHG emissions as soon as possible have directed attention to short-term GHG mitigation balances and the quantification of the timing of emission benefits related to the use of bioenergy, e.g., Cherubini et al. (2011); Fargione et al. (2008); Haberl (2013); Holtsmark (2012); Pingoud et al. (2016); Röder and Thornley (2016). The climate benefits of bioenergy are often presented by comparing biosphere/atmosphere fluxes with fossil fuel emissions. The contribution of forest-based bioenergy systems to climate change mitigation is debated and the promotion of bioenergy is being reconsidered and scaled back in some countries in response to concerns that bioenergy implementation may not be as effective in providing GHG emissions savings as initially expected. The debate is partly a consequence of that studies that attempt to quantify net GHG balances arrive at contrasting conclusions due to diverging methodology approaches. In the European Union, biospheric[3] emissions associated with bioenergy were set to zero in Directive 2009/28/EC (Renewable energy Directive –RED). This has however been questioned not the least in relation to short-term GHG effects, see Agostini et al. (2013). All in all, there is a need to understand the role of forest bioenergy in the climate change context and the influence on methodology choice.

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[1] Land-use change refers to the anthropogenic emissions caused by changes in the way the land is used or in the amount of existing biomass stocks.
[2] In this thesis, long-rotation forestry refers to trees that need 80 or more years to grow before harvest.
[3] In the European Union, the term “biogenic” emissions is used instead of "biospheric”

1.2 Aim and scope

This thesis aims at an improved assessment and understanding of how an increased demand for bioenergy will affect carbon balances in forest carbon stocks and consequently the contribution of forest bioenergy to climate change mitigation. This thesis considers the carbon balances and GHG-mediated climate effect associated with bioenergy from long-rotation managed forest. The focus is on the Swedish forest, but many of the results and the associated discussions have wider relevance. The questions addressed in this thesis are:

1. To what extent are parameters and methodological assumptions critical in assessing forest biomass carbon balances, and how should they be considered? (**Papers I-III**)
    - To what extent does the choice of spatial scale affect bioenergy carbon balances, and what scale is most relevant in a specific context? (**Papers I** and **II**)
    - Which parameters and forest dynamics are critical in assessing carbon balances of conceptual versus real forest landscapes? (**Paper I** and **II**)
    - How do different temporal scales and metrics capture the timing-of-emissions effects of forest bioenergy? (**Papers I** and **III**)
2. What is the potential of the Swedish forest to contribute to the mitigation of climate change?
    - What is the role of the Swedish forest sector in relation to the national GHG neutrality goal by 2050? What is the potential of the Swedish forest in achieving the 2-degree limit? (**Paper III**)

The focus of this work is on carbon balances and the associated climate impact. Other climate forcers (e.g., albedo, black and organic carbon, and ozone precursors) are not included in the analysis. Similarly, other impacts, e.g., on biodiversity, are also left out.

The forest area is assumed to be constant, and afforestation as a consequence of an increasing demand for bioenergy is not considered. The geographical focus of this study is Sweden, and the results only apply to forest biomass under Swedish forest conditions. However, the methods can be used for forest biomass of different origin.

1.3 Outline of the thesis

This thesis consists of an extended summary and three appended papers. The extended summary is divided into six chapters. Chapter 2 discusses different methodological choices concerning spatial and temporal system boundaries for assessing forest bioenergy systems; this chapter also presents the Swedish context. Chapter 3 describes the design of the analysis and the methods used to quantify carbon balances associated with forest products at different scales and using different climate metrics. Chapter 4 presents the key findings and discusses them according to each research question. Conclusions are drawn in Chapter 5, and potential further work is presented in Chapter 6.

1.4 Contribution of the thesis

Studies assessing carbon balances associated with forest-based fuels arrive at diverging conclusions strongly influenced by choice of methodology. In this thesis, we bring together different approaches and perspectives from different fields to bridge the gap between different methodological choices (see Figure 2), for the purpose of increasing our understanding of forest bioenergy carbon balance modeling. In particular, we bring together: (i) different spatial scales for assessments of the same forest bioenergy system to understand to what extent results can be influenced by the choice of spatial boundaries (**Papers I** and **II**); (ii) conceptual and real landscapes, including forest dynamics in the conceptual landscape assessment (**Papers I** and **II**), such as forest owners' responses to price signals; and (iii) different climate metrics, introducing the concept of an emissions budget as a basis for forest bioenergy assessment (**Papers I** and **III**). Overall, the thesis contributes to improved bioenergy carbon balance assessments to provide a better understanding of forest sector responses to bioenergy demand increases, in the context of climate change mitigation.

In addition to this methodological contribution, the thesis also provides an understanding of the role of Swedish forestry, including the potential future supply of forest bioenergy, in the development of the Swedish energy system, in the context of the 2-degree limit (**Paper III**).

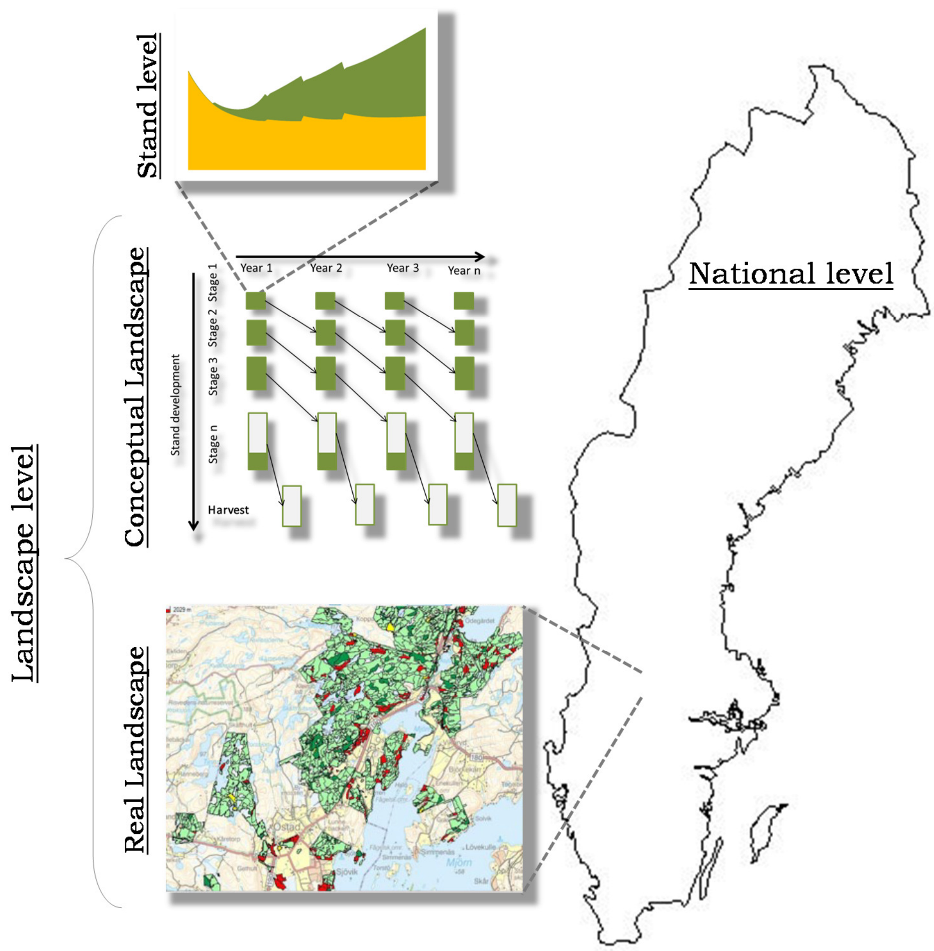

Figure 2: Forest assessments at different scales: stand, conceptual landscape, real landscape, and national. Real landscape figure from © *Lantmäteriet, i2014/76.*

2 - Background

2.1 Evaluating the climate impact of forest bioenergy: Methodological options

Evaluations of forest bioenergy in a climate mitigation context diverge depending on the methodological approach, including with respect to spatial (see Table 1) and temporal system boundaries.

Spatial system boundaries

Table 1: Spatial system boundaries for forests

Spatial scale	Definition used in this thesis
Forest stand	A forest area subject to distinct forest operations at specific times (e.g., thinning or final felling)
Forest landscape	A mosaic of forest stands managed to supply a continuous flow of wood to the forest industry.
• **Conceptual Landscape**	• A landscape generated by combining identical stands of varying age
• **Real landscape**	• A landscape generated by using data from all the stands within that landscape

Studies of forest-based fuels/other products can either focus on specific products or the forest system itself. Two spatial scales are common, the stand level and landscape level; for an overview, see Berndes et al. (2013); Lamers and Junginger (2013). The environmental impact associated with a product is often assessed using life cycle assessment, which considers impacts related to all stages of a product: from raw material extraction, to production, use, and disposal. With this tool, and the associated standards such as ISO 14040 (ISO, 2006), forest carbon losses due to harvest of biomass are attributed to the use of a particular wood product. This can be interpreted as an attempt to identify products with their localized impacts and specific forest operations, which is typically associated with stand assessments (e.g., Cherubini et al. (2013b)). Alternatively, when management activities are coordinated across the forest to obtain a continuous flow of multiple forest products, all parts of the forest may be considered without specifying any concrete location within the forest system (Eliasson et al., 2013). The latter is typically associated with landscape assessments.

Studies that use the forest-stand scale in quantifying the timing of bioenergy benefits (e.g., Cherubini et al. (2011); Helin et al. (2013); Holtsmark (2013); Schulze et al. (2012)) acknowledge the carbon neutrality of the rotation period taken as a whole. However, as the neutrality is applied to the stand level, there will always be a timing difference between sequestration and emissions since the carbon first needs to be sequestered in the growing stand before it can be released into the atmosphere by either biomass decay or combustion (most studies instead actually apply the opposite logic: the carbon in forest biomass needs to be lost to the atmosphere before it can be incorporated in the growing forest again). The authors argue that even though bioenergy from long-rotation forest can be *carbon* neutral, – when the management intensity in the stand is the same as in the initial condition, i.e., a stand managed as historically -, it is not *climate* neutral due to the temporal carbon imbalance. Some studies aligned with the stand perspective model a constant supply of forest products by considering "consecutive" stands: every year a new stand ready to be harvested is brought into the forest system to assure a continuous biomass supply (e.g., Zetterberg and Chen (2014)).

Other studies assess a constant supply of forest-based products/bioenergy by looking at conceptual representations of the landscape level (Eliasson et al., 2013; Jonker et al., 2013; Pingoud et al., 2016), where the net growth in the forest is considered. Such studies investigate the interrelation between the carbon dynamics at the stand level and the effect it has on the total carbon stock in the forest (e.g., Eliasson et al. (2013); Jonker et al. (2013)), arguing that carbon stock losses in one stand can be compensated by biomass growth in another stand within the same forest landscape. Moreover, if harvest intensity is increased, carbon stock losses could be lower than the extra biomass removal, and the climate benefit of such a forest system will depend on the displacement factors, i.e., the carbon emissions avoided by substituting non-wood products with the harvested forest products.

Conceptual landscapes are, however, simplifications of real landscapes, which generally have an unequal distribution of age classes and stands of different sizes. Real landscape studies could present a variety of forest managements to support bioenergy systems with different climate impacts that depend on factors such as forest age class distribution, interrelations among forest products (Hudiburg et al., 2011; Lundmark et al., 2014; Melin et al., 2010), and also market effects (Abt et al., 2012; Nepal et al., 2012; Sedjo & Tian, 2012). Researchers who focus on market mechanisms argue that a higher demand for forest-based fuel could affect the interrelations among forest product outputs in the short term, but could also motivate forest-owners to expand forest areas (or decide not to convert their forests into other land use, e.g., pasture production) or to change towards more intensive forest managements in order to increase forest production in the long run (Miner et al., 2014). Another type of studies present results from real landscapes at the regional/national level, comparing potential forest supply with future demand for bioenergy and evaluating the trade-offs among carbon sinks and sources in analyzing the mitigation potential of the national forest (Kallio et al., 2016; Lobianco et al., 2016).

Temporal system boundaries

The climate impact associated with forest bioenergy can be assessed by using different metrics/indicators and different temporal system boundaries. The temporary carbon imbalance between atmosphere and biosphere has traditionally been presented either as carbon emissions/sequestrations or as carbon stock changes (e.g., Eliasson et al. (2013); Holtsmark (2015)) associated with different harvest intensities. The climate impact could be assessed at different points along the cause–effect chain, i.e., moving from GHG emissions to climate change and damages (Fuglestvedt et al., 2003), to increase the relevance for policy makers. Global warming potentials (GWP) are widely used to allow for emissions of different GHGs, with different atmospheric lifetimes, to be measured on a common scale. The GWP for a given gas is defined as the integrated radiative forcing (RF) of a pulse of emissions of that gas relative to an equivalent integration for CO_2. The GWP requires a time horizon to be specified, which means using directly implies a choice about temporal scope; the 100-year time horizon is often used by environmental assessments as it was adopted by the UNFCC and the accounting under the Kyoto protocol. It has, however, been criticized as arbitrary and lacking a meaningful climate impact representation.

Some studies avoid those problems by using other metrics. For instance, Sathre and Gustavsson (2011) and Haus et al. (2014) use cumulative radiative forcing (CRF) to quantify the warming effect of using slash (tops and branches) and stumps for energy purposes, and Zetterberg and Chen (2014) use the global average surface temperature for the same purpose. Cherubini et al. (2013a) discuss the use of different metrics based on radiative forcing (RF) and the absolute global temperature change potential (AGTP) for pulse emissions and sustained emissions for a variety of biofuels. Except for GWP, all the metrics can be used to assess both short-term and long-term time frames. The choice depends on the objective of the study and can affect conclusions about the effects associated with bioenergy systems, e.g., Sedjo (2011).

2.2 The Swedish context

Swedish national climate policy seeks ambitious reductions in GHG emissions. In 2009, the Swedish government presented the goal of climate neutrality, i.e., no net GHG emissions to the atmosphere, by 2050 (Government offices of Sweden, 2009a). The relevant government committee has since, following COP21, proposed that the schedule be tightened up, with 2045 as the target year (Swedish Government Official Reports, 2016). Analyses show that to reach that goal, the energy sector has to undergo drastic change (Swedish Environmental Protection Agency, 2012). For instance, the ambition is to have a vehicle fleet independent of fossil fuels by 2030 (Government offices of Sweden, 2009b).

Forest bioenergy is expected to play a major role in the transition towards fossil-fuel-independent road transport by 2030 and climate neutrality by 2050. In 2013, bioenergy contributed 23% of the total primary energy supply (470 PJ), with about 85% coming from forestry (slash and forest industrial residues). The largest share was used in industry, where bioenergy corresponded to 38% of final energy use, and in district heating, where 60% of the total energy supply was bioenergy. Biofuels accounted for about 10% (29 PJ) of transport fuel in 2013 (Swedish Energy Agency, 2015) and are expected to increase drastically in the transport sector to supply a possible future demand of 54-72 PJ of total fuel use in the transport sector by 2030 (Government offices of Sweden, 2009b). The potential future bioenergy demand will increase the pressure on Swedish forests.

2.2.1 Swedish forest

The Swedish forest has been utilized for centuries. Earlier, forests were exploited for agriculture and mining activities, and in the mid-18th and early 19th centuries, the sawmill and pulpmill industries expanded rapidly to lay the foundation for the subsequent industrialization. Back then, massive operations logged untouched forest resources. The Swedish forest has consequently changed dramatically during the last 150 years. The process of converting virgin forests to managed forests affected the standing volume and the forest structure, from multiple age and size structures to a more uniform structure with even-aged and young forest stands. The first forestry acts regulating Swedish forest management focused on long-term management planning to sustainably maintain an increasing timber supply (Barklund, 2009). Today's forest stock is approximately 50% greater than in the 1930s (Figure 3).

In the current Swedish Forestry Act equal importance is given to production goals and environmental goals (Swedish Forest Agency, 2016a). Forest owners are responsible for achieving these goals, i.e., ensuring a reliable yield of timber production while preserving biodiversity (Swedish Forest Agency, 2016b).

Nowadays, forest constitutes almost 70% of the land area in Sweden, more than 28 million hectares, of which about 22 million hectares are actively managed productive forest. The ownership structure is diverse: 50% of Sweden's forests are owned by private individuals, 25% by large forest companies, and 25% by the state. Swedish forests are typically managed as even-aged stands that are regenerated through planting, subjected to pre-commercial thinning, and felled after approximately 100 to 150 years. Harvesting activities are coordinated across the forest landscape to deliver a steady flow of biomass for multiple products (Lundmark et al., 2014).

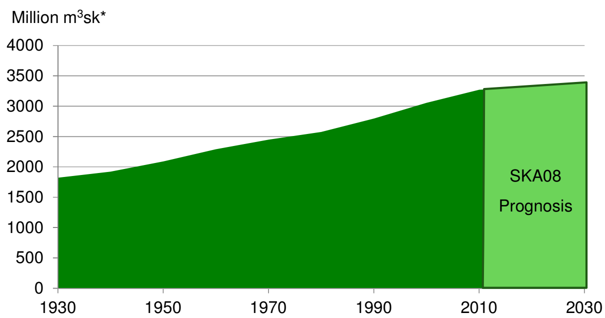

Figure 3: Development of standing stock of Swedish timber (Skogindustrierna, 2016).* m^3sk Forest cubic meters

Total standing volume is approximately 3.0 billion m^3, consisting of 39% *Scots pine,* 42% *Norway spruce*, and 12% birch. On average, the total annual harvest amounts to about 94 million m^3, while the total annual growth amounts to about 116 million m^3, or 5.3 m^3 ha^{-1} (Swedish Forest Agency, 2014). The harvested stemwood is mainly used by the pulp and paper and sawmill industries. Residues from harvested biomass, i.e., slash and stumps, are to some extent used for energy, and the rest is left in the forest to decay. Forest residues thus constitute a potential source of additional bioenergy.

3 - Method and design of the analyses

This section describes the modeling framework (Figure 4) used in **Papers I-III** to assess the carbon balances and GHG-mediated climate effect of using biomass from long-rotation forestry for energy in Sweden. The framework's core consists of two linked assessments, (i) a forest assessment, to quantify the biospheric carbon balances associated with forest management; and (ii) a forest products assessment, to quantify forest products flows (including bioenergy products) up to (and including) the point when the carbon in the products is oxidized and released as CO_2 into the atmosphere.

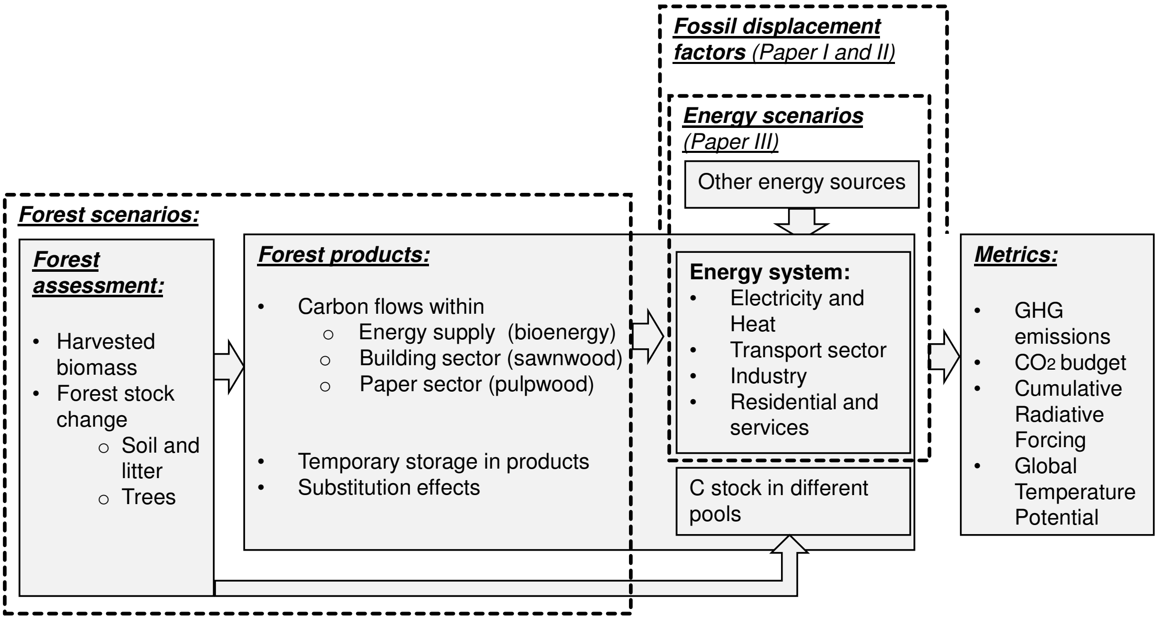

Figure 4: Modeling framework description. Forest assessments are performed with the Q model and Heureka or Hugin. Forest products assessments are performed with CAfBio 1.0 or CAfBio 2.0 (cf. adapted from figure 1 in Paper I and III).

The modeling framework is used to assess forest scenarios regarding harvest intensity and forest management. For each, it calculates, on an annual basis, the forest bioenergy supply and the associated carbon stock changes in forest pools (tress and soil-and-litter), and forest products (Figure 4). In **Papers I** and **II**, forest bioenergy is assumed to displace fossil fuels, whereas in **Paper III**, the forest-based energy is combined with energy scenarios where the description of the bioenergy demand is provided, and the displacement effect is inherent in each scenario. In both cases, the emissions associated with either avoided fossil fuels or the entire energy system are considered. Table 2 provides an overview of the modeling framework used in each paper.

Table 2: Description of the method used in each paper.

		Paper I	Paper II	Paper III
	Aim	**Describe how methodological choices and assumptions affect the climate effect of Swedish forest energy***	**Assess the carbon dynamics at the landscape level using different methodological choices***	**Evaluate the role of the Swedish forest in low carbon scenarios***
Models	Forest scale: **Stand**	Q model	Q model	-
	Forest scale: **Conceptual Landscape**	Q model	Q model	-
	Forest scale: **Real Landscape**	PlanWise	PlanWise	-
	Forest scale: **National landscape**	-	-	Hugin
	Forest products:	CAfBio 1.0	CAfBio 1.0	CAfBio 2.0 (including exports of Swedish forest products)
Energy scenarios	**Counterfactual scenarios** (Bioenergy – Reference +DF**)	DF: Displacement factor for natural gas and coal	DF: Displacement factor for natural gas and coal	-
	Energy scenarios	-	-	Global Swedish energy scenarios
Output	**Metrics**	Carbon stock changes, cumulative radiative forcing, global temperature change	Cumulative carbon emissions	GHG emissions, global temperature potential, Swedish carbon budget

*Short version of the aim in each paper

**DF: Displacement factors, i.e., the carbon emissions avoided as a consequence of using the forest products

In **Papers I** and **II**, results are presented as the net effect – comparing a reference with a bioenergy scenario – in order to understand the consequences of establishing bioenergy systems. In **Paper III**, results are presented in absolute terms to describe national accountability. Results can be presented in terms of: (i) carbon stock changes in the different pools; (ii) GHG emissions; (iii) cumulative radiative forcing (CRF); (iv) global mean temperature change (ΔT); and (v) utilization of the national emissions budget (see Table 2).

3.1 Forest assessments at different scales:

The assessments of carbon dynamics are made at three different spatial scales: the stand, landscape, and national scale (see Figure 2). The forest stand level is the scale at which forest operations are conducted; the forest landscape level is the area on which forest management across a mosaic of forest stands is coordinated to supply a continuous flow of forest products. For landscape assessments we distinguish between conceptual landscapes and real landscapes.

Three models are used: the Q model for assessments of forest stands and conceptual landscapes, PlanWise for assessments of real forest landscapes, and Hugin for national landscape assessments. The models are only briefly explained here; for more information see the appended papers.

The outputs from these models (i.e., carbon in harvested biomass and inter-annual changes in carbon stored in soil, litter, and tree biomass) are accounted for, and carbon in the harvested biomass is used as input data for the CAfBio model.

3.1.1 Stand level

The version of the Q model (Ågren et al., 2008) consists of a stand-level basal area growth model that responds to climate conditions and specified management practices. The predicted basal area is converted into tree biomass fractions (needles, branches, stems, and stump-coarse root system) by using the Marklund allometric functions (Marklund, 1987). Litter is continuously formed from needles and branches as well as from stems and stumps generated at forest thinning and final harvest. A decomposition model based on the continuous-quality concept (Agren & Bosatta, 1998) is used to calculate the carbon in litter, which is allocated to a subsystem of the soil organic matter pool (Eliasson et al., 2013).

The forest stand is modeled as an even-aged stand established by planting seedlings: the model accounts for all carbon flows on an annual basis, including regeneration, three thinning events and final harvest, when the stand is clear-cut and regenerated. The carbon flow evaluation can be initiated when trees are established after a final harvest event, in order to capture the effect of management on forest growth (one full rotation period as in **Paper I**) or at the time of the first final harvest (as in **Paper II**) in order to investigate the effects of introducing biomass extraction for energy as a new component in the management of an existing forest.

The forest scenarios generated with the Q model are representative for Norway spruce (*Picea abies* (L.) Karst) stands in Southern Sweden (Växjö; 56.87° N, 14.81° E), managed with a rotation period of 100 years and with an average forest production around 7 m^3 ha^{-1} $year^{-1}$. This scenarios are used for stand and conceptual landscape-level assessments

3.1.2 Conceptual landscape

The stand-level results from the Q model are used to build a theoretical forest landscape by combining time-shifted single stands to obtain a uniform age distribution at the landscape level. The landscape is assumed to have a homogeneous site quality, i.e., stands that are subject to the same management have identical growth development. The number of stands is equal to the length of the rotation period, i.e., 100 years, and, each year, the oldest stand is harvested and becomes a newly planted re-growing stand in the subsequent year.

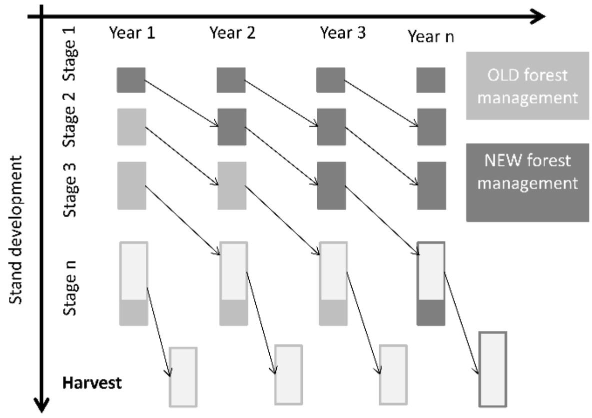

Figure 5: Conversion from one forest management regime to a new one in the forest landscape (cf. adapted from Figure 2 in Paper I).

The introduction of a new forest management (i.e., new harvest intensity or management practice that affects forest growth) is modeled by assigning a different carbon dynamic profile (either a new harvest level with new soil carbon dynamics or different growth profile) to a forest stand in the intervention year (harvest or replanting). During a time period corresponding to the rotation period of a stand, the forest landscape goes through a transition towards a new state characterized by the new forest management. This is illustrated in Figure 5; each year, one new stand is regenerated and the new forest management is applied to it, until the last stand has been felled and replanted under the new forest management regime. After the full rotation period, the forest landscape reaches a new equilibrium, and the annual removal is equal to the annual growth again.

3.1.3 Real landscape

The Heureka PlanWise software (Wikström et al., 2011) is used to quantify the carbon balances for real Swedish forest landscapes subject to different management planning depending on different demands for forest products (used in **Papers I** and **II**). Management alternatives consist of a sequence of silvicultural and harvest activities generated to mimic forest management across landscapes by profit-driven forest companies in the region. PlanWise is an optimization application that supports forest management planning pertaining to objectives relating to timber production, economics, environmental conservation, recreation, and carbon sequestration (Wikström et al., 2011). It has a core of empirical growth and yield models (stand and individual tree growth), which are based on Swedish National Forest Inventory data and validation in long-term experimental plots. Forecasts involve growth models (Fahlvik et al., 2014) as well as mortality and in-growth models.

The real landscape scenarios presented in this thesis (more information in **Paper I** and **Paper II**) were developed to support the assessment and analysis of forest managements in a 9,171-

hectare landscape surrounding Skellefteå (64.5°N) in northern Sweden. The initial average growing stock is 121 m3 ha-1 of 73% Scots pine, 22% Spruce, and 5% Broadleaves (Holmström et al., 2012), with a 3.7 m3 ha-1 year-1 average production potential and 100-year planning horizon.The outcome of each scenario corresponds to the best-adapted management in the Skellefteå forest landscape, i.e., the optimally profitable forestry regime providing a continuous flow of sawtimber, pulpwood, and biomass for energy over time. All scenarios simulate forest management activities that potentially enable changes in rotation period, thinning frequency, and harvesting intensity at thinnings and final fellings. Others (explicitly stated) also includes fertilization and the use of genetically improved seedlings.

3.1.4 National landscape

HUGIN (the old version of PlanWise) is mainly used for strategic planning at the regional and national level to forecast forest biomass growth, timber yield, and potential biomass harvest (Lundström & Söderberg, 1996). In **Paper III**, we use Hugin's output related to forest carbon stock changes and volume of harvested biomass for different levels of sustainable harvesting at the national level. The model system is based on sample plots from the Swedish National Forest Inventory and follows all the different stages and events in the forest management cycle: initial state, stand establishment, growth of established stand, silvicultural treatments, and harvest (Lundström and Söderberg, 1996; Poudel et al., 2011). The growth simulators consist of series of algorithms defining various conditions in Swedish forestry and are constructed to be valid for the whole country for all types of stands and within a wide range of management alternatives.

The scenarios concerning the national scale, represent forest management regimes for 22.7 million ha of production forest within Sweden. These scenarios are based on the Swedish Forest Agency (2008). See more information in Forest management and forest biomass flows in **Paper III**.

3.2 Forest products

The CAfBio 1.0 model is used in **Papers I** and **II** to model the flows of biomass carbon within the forest industry and the society in which the forest products are used. CAfBio accounts for the carbon in harvested biomass obtained as output from the Q model, PlanWise, or Hugin. The harvested biomass in CAfBio is allocated to the production of sawnwood, wood-based panels, and paper (designated harvested wood products, HWP), and bioenergy products. CAfBio takes into account the losses in the production processes. The residence time for carbon in the HWP pool is modeled using the gamma decay function described by Earles et al. (2012). The carbon in discarded HWP is either emitted to the atmosphere via incineration, transferred to new products via recycling or transferred to landfill, assuming a methane correction factor of 0.95 and degradable organic carbon factor of 0.5 (Earles et al., 2012). The CAfBio 1.0 model also considers the supply chain GHG emissions for wood products and fossil fuels, as well as the fossil carbon displacement effects of wood product use, taking into account incineration of wood products at the end of the service lifetime.

The CAfBio 2.0 model (updated version of CAfBio 1.0) used in **Paper III** further distinguishes between biomass carbon flows associated with forest products consumed domestically and exported products consumed abroad. The residence time for carbon in the HWP pool is modeled using *Equation* 12.1, in the IPCC guidelines (IPCC, 2006), treating each product category separately. Half-life values are set to 35 years for sawnwood, 25 years for wood-based panels, and 2 years for paper products (same values for Sweden and abroad). CAfBio 2.0 is combined with energy scenarios to consider energy-related GHG emissions from the energy sector. The model also accounts for the fossil carbon displacement effects of exported wood products (including biofuels), taking into account incineration of wood products at the end of their service lifetime.

3.3 Climate metrics

3.3.1 Cumulative radiative forcing and absolute global temperature potential

Results in **Paper I** are presented in terms of CRF and AGTP. These are calculated following the procedure in Supplementary Material Section 8.SM.11 in the IPCC Fifth Assessment Report I (Myhre et al., 2013b):

The radiative forcing (RF) describes the net change in the energy balance of the Earth system induced by some imposed perturbation, in this case the change in GHG concentration, given that other processes within the troposphere remain unchanged. The RF time profile associated with a unit pulse emission is calculated for each gas (Myhre et al., 2013b), and the total RF impact is calculated for an emissions scenario spanning over several years by using convolution of the emissions and the RF for a pulse emission of the gases in question (Aamaas et al., 2013; Myhre et al., 2013a). In other words, the RF in a particular year is obtained by adding the RF due to that year's emissions to the amount of RF from previous years' emissions remaining in the atmosphere. Then, RF is integrated over time to obtain the cumulative RF (CRF). Positive values reflect warming and negative values reflect cooling.

The Absolute Global Temperature Change Potential (AGTP) is defined as the change in global mean surface temperature at a chosen point in time in response to an emission pulse (Myhre et al., 2013a; Shine et al., 2005). The AGTP is calculated for each gas (Myhre et al., 2013b), and the global surface temperature change (ΔT) profile for a given bioenergy scenario is calculated by using convolution of the GHG emissions and the AGTP (Aamaas et al., 2013; Myhre et al., 2013a). In other words, the ΔT in each particular year is obtained by adding the AGTP due to that year's emissions to the amount of AGTP from previous years' emissions remaining in the atmosphere.

3.3.2 Carbon budget

Results in **Paper III** are evaluated based on the carbon budget approach. The global carbon budget used is based on Rogelj et al. (2016), who propose that – taking into account contributions from other anthropogenic forcings – policymakers should associate a budget for carbon dioxide of 590-1240 Pg CO_2 from 2015 onwards with a greater than 66% likelihood of limiting the increase of global mean temperature to less than 2 degrees (Rogelj et al., 2016).

For our purposes, we set the global CO_2 budget from 2015 and forward to the average of this range, 915 Pg CO_2.

Sweden's share of this global budget is calculated using the method proposed by Gignac and Matthews (2015). The method aligns with the contraction and convergence strategy framework (Meyer, 2000) but also allows for consideration of historical responsibility, i.e., addresses emissions inequalities among countries not considered in the contraction and convergence framework.

Emissions from fossil fuels are distinguished from net emissions associated with forest management and land-use change (LUC) in order to clarify the importance of carbon sequestration in the Swedish forest. Thus, one CO_2 budget is estimated considering only fossil fuels (fossil CO_2 budget), and another CO_2 budget is estimated considering both fossil fuels and forest management and LUC (net CO_2 budget).

To estimate each budget, we first calculate future emissions (see Figure 6a and c) by setting the global CO_2 emissions in 2015 (similar to 2014 and based on Le Quéré et al., 2014) to decrease linearly to reach zero in the year when cumulative emissions are equal to the global CO_2 budget (915 Pg CO_2 in our case). We also calculate the world emissions per capita by using the world population prospects by DeSA (2013) (see Figure 6b and d). Second, the Swedish emissions per capita in 2015 are set to decrease linearly from the current level until the convergence year, in which Swedish annual emissions correspond to Sweden's share of that year's global emissions if these were distributed proportionally per capita (see Figure 6b and d). From that year and onwards, all countries will decrease their emissions at the same pace. The total Swedish emissions are calculated from the Swedish per capita emissions (see Figure 6a and c); and the Swedish CO_2 budget is set to be equal to the cumulative emissions from 2015 until they become zero. The convergence year is set to 2050.

Additionally, the Swedish historical responsibility is calculated as the cumulative difference (from 1990 until convergence) between the Swedish annual emissions in a given year and Sweden's share of that year's global emissions if they were distributed proportionally based on country population size and equal per-capita emissions (Neumayer, 2000) (see differences between the world and Swedish per capita emissions in Figure 6).

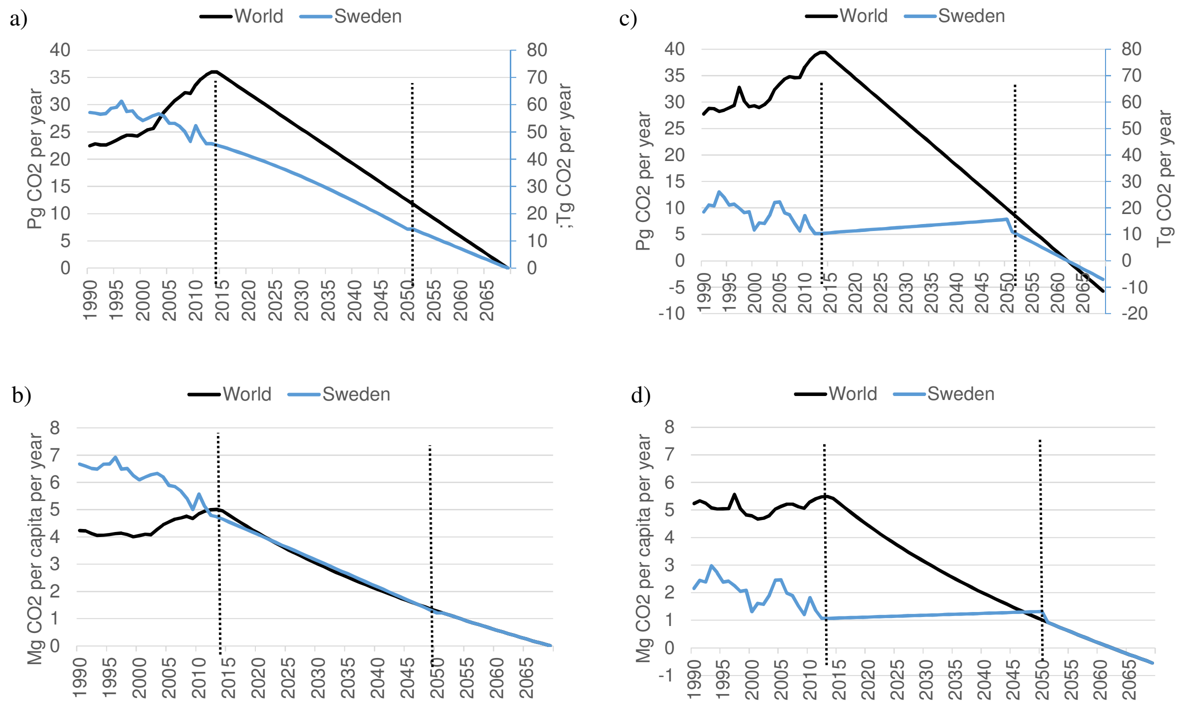

Figure 6: World and Swedish emissions following a linear decrease to zero and a convergence year in 2050 when considering a) total fossil emissions; b) per capita fossil emissions; c) total fossils and forest management and LUC emissions; and d) per capita fossils and forest management and LUC emissions. Based on Gignac and Matthews (2015)

The resulting CO_2 budgets are presented in Figure 7. The fossil CO_2 budget for Sweden from 2015 onwards is calculated to be 1.24 Pg CO_2. If historical responsibility is considered, the budget is reduced to 0.88 Pg CO_2 because Swedish historical per capita emissions are higher than the world's per capita emissions from 1990-2015, see Figure 6b. The net CO_2 budget for Sweden from 2015 and onwards corresponds to 0.54 Pg CO_2 (lower than the fossil budget because the initial net emissions in 2015 are lower than the initial fossil emissions). If historical responsibility is considered, the net CO_2 budget will increase to 1.9 Pg CO_2 due to the strong effect of the historic forest carbon sink in Sweden, that significantly reduces Swedish emissions per capita to below the world's average emissions per capita, see Figure 6d. Many countries would instead see their net CO_2 budget reduced due to historic net carbon losses from forests and other ecosystems.

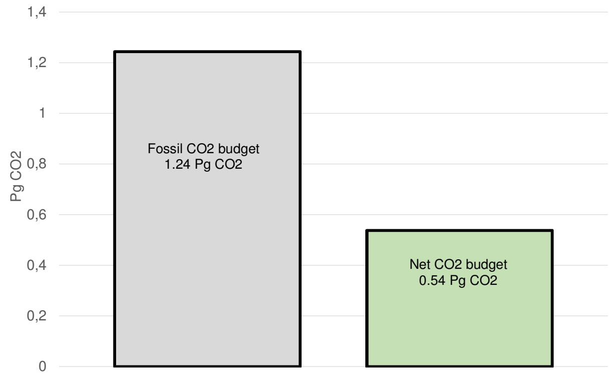

Figure 7: Fossil CO_2 budgets and net CO_2 budgets for Sweden (from 2015 onwards) based on the contraction and convergence approach with convergence year set to 2050 (cf. Figure 4 in Paper III).

4 - Results and discussion

The results presented and discussed in this section are based on **Papers I-III**. They are described and organized according to each research question; some of the results are taken directly from the papers while others have been added to this thesis.

4.1 Carbon balances

Research question 1: To what extent are parameters and methodological assumptions critical in assessing carbon balances associated with forest biomass, and how should they be considered?

4.1.1 Forest Scales

To what extent does the choice of spatial scale affect bioenergy carbon balances, and which scale is more relevant in a specific context?

Papers I and II found that the forest scale chosen for the assessment affects the assessment output. This challenges the conclusions by Cherubini et al. (2013b), who argued that different scales yield the same results.

<u>At the stand level</u>: carbon emission dynamics at the stand level are given by a pulse of emissions at the time biomass is harvested and used for bioenergy. In Figure 8, the carbon emissions associated with managed forest systems to supply pulp and sawnwood are represented by an emission pulse at the time when forest biomass is harvested and used as bioenergy, gradual emissions as carbon in soil-and-litter and HWP decays, and carbon sequestration by biomass growth. These emissions increase as more biomass is harvested and used for energy (BIO1), because the carbon in forest biomass will be released immediately into the atmosphere, instead of being left in the forest to decay (see difference in soil-and-litter carbon between the REF and BIO1 scenarios in Figure 8).

When stand-level assessments are used to quantify the timing benefits of bioenergy, the design of the stand-accounting approach introduces a bias in the results. As pointed out by Cowie et al. (2013), the timing of carbon emissions depends on when to start the accounting related to the first harvest (see different start-up times in **Papers I** and **II**). Assessments starting at the time of the first biomass extraction will always introduce initial carbon emissions, e.g., Cherubini et al. (2016); Cherubini et al. (2011).

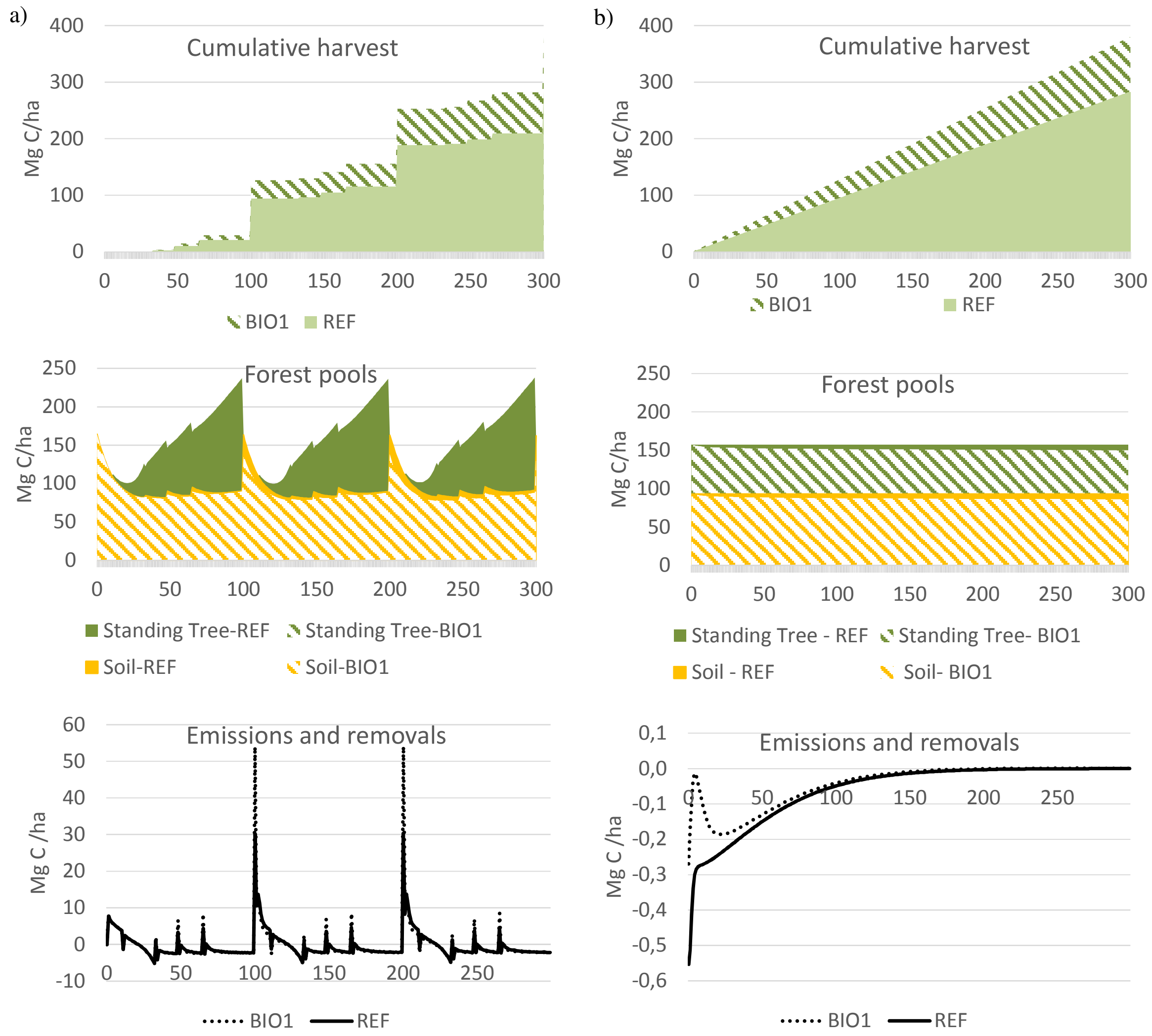

Figure 8: Carbon stock changes and carbon emissions for two scenarios: REF (with only sawnwood and pulpwood production) and BIO1 (as REF but 80% of the slash will be removed to be use as bioenergy) for two forest scales: stand (a) and landscape (b).

This pattern is scaled up when a constant supply of forest products is modeled by assuming consecutive stands, i.e., every year a mature new stand is brought into the system. Situation that will result in initial carbon emissions – the stand level carbon profile is introduced every year – which increases up to the point when sufficient stands are being considered to introduce a higher sequestration effect (see further in **Paper II**).

To understand the carbon consequences of increasing harvest intensity due to an increase in forest bioenergy demand, the bioenergy system is compared with a reference system, which includes the forest system and fossil fuels (Buchholz et al., 2014; Soimakallio et al., 2015). Figure 9 shows the comparison between REF and BIO1 assuming that bioenergy substitutes for natural gas. The net carbon stock effect of forest residues removal is shown as sudden carbon losses from the soil and litter pool at thinning and final harvest, followed by a gradual gain as residues left in the forest in the REF scenario decay. The net comparison also illustrates the influence of the accounting design on the carbon balance calculations: the so-called forest carbon debt is an unavoidable outcome when accounting commences at the year of extraction, unless the average carbon displacement efficiency of bioenergy is above one.

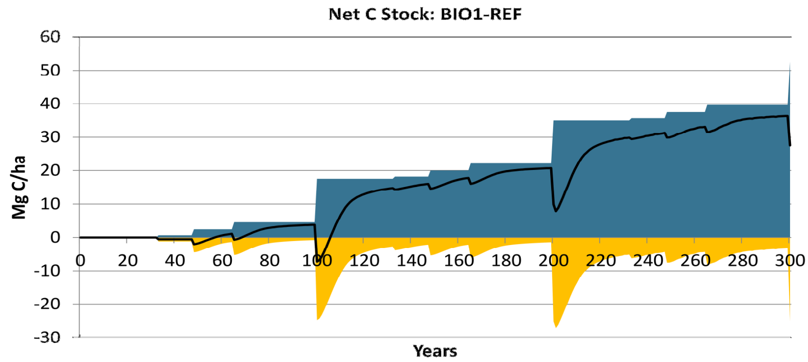

Figure 9**:** Net carbon stock effect of shifting from REF to BIO1 and bioenergy displacing natural gas (cf. adapted from Figure 3 in Paper I).

At the landscape level: Carbon balances in forest landscapes typically reflect a trend of increasing, decreasing, or relatively stable carbon stocks. The drastic ups and downs in carbon stocks shown at the stand level do not appear at the landscape level because carbon growth in some stands balances carbon losses in other stands (Figure 8).

It is important to distinguish between forest states. Carbon in harvested biomass from a managed forest in a steady state and a sustained-yield harvest (harvest equals growth), illustrated in the REF scenario (see constant carbon stock on forest pools in Figure 8), will be the same amount as the carbon captured and stored in the forest stock that year. Carbon fluxes between biosphere and atmosphere will be neutral if the carbon in the products is released immediately after harvest (see **Paper II**). The emissions can also be delayed if harvested biomass is used in long-lived products. Figure 8 shows carbon removals during the first decades because carbon is stored in sawnwood and pulp and paper for years before it is released into the atmosphere at the end of the products' lifetimes. Carbon emissions associated with forest products from a managed forest in transition (i.e., BIO1 introduces a new harvest level across the landscape) are greater than the carbon added to that stored in forest pools, i.e., soil-and-litter and trees, that year. As a matter of fact, there is a carbon transfer from the soil-and-litter pool to the bioenergy pool. Hence, forest products from a managed forest in transition, where the only change is that more biomass is extracted, will have initial carbon losses.

However, these carbon losses are much lower than the ones shown at the stand level (for the same amount of harvested biomass, Figure 8). Similarly, stand-related approaches, e.g., consecutive stands or expanding system boundaries (e.g., Cherubini et al. (2013b); Zetterberg and Chen (2014)), which are masked by the stand dynamics, show these differences in magnitude. Assessments that start at the time of the first biomass extraction and assume that a new stand is ready to be harvested every year have been criticized as being "*..based on the unrealistic assumption that trees are first burned and then grown...* " (WBA 2012). Results from these assessments could be misleading when they are generalized to represent the landscape level, because they do not capture all carbon fluxes between atmosphere and biosphere (as investigated in **Paper II**).

Paper II shows that the stand – and stand-related approaches – can only represent a realistic landscape in very specific situations. Such situations include when an unmanaged forest in a steady state is converted into managed forest and when non-forested landscapes are afforested. In both cases, the fact that the stands that have not been affected by the forest operations driving the transition (clear-cut in the first case and planted in the second) are not considered in the assessment until after one full rotation period does not affect the carbon balances since those stands do not have any or very little carbon exchange with the atmosphere.

In contrast, the landscape assessment can capture all carbon flows in the forest landscape throughout the accounting time period because all carbon gains and losses in the forest production area (landscape) are accounted for. It can therefore support quantification of changes that may occur in association with forest landscape transitions, and similarly it can identify unsustainable practices. In addition, including all the stands within the landscape throughout the accounting period avoids the bias the stand-accounting approach brings to the results. While stand-level assessments are useful to evaluate the effect of distinct forest operations and carbon dynamics at the stand level (Lundmark et al., 2016; Sathre et al., 2010), the results cannot just be scaled up to represent the whole landscape. We therefore argue that where management activities are coordinated across the whole landscape to obtain a continuous flow of wood to the forest industry, the landscape scale can be more appropriate for quantifying the carbon balance for forest-based bioenergy.

4.1.2 Conceptual landscapes vs. Real landscapes

Which parameters and forest dynamics are critical for assessing carbon balances associated with conceptual versus real forest landscapes?

Conceptual landscapes: Figure 10 shows the net comparison between several bioenergy systems and a reference system. The carbon balances consist of a stable line that will bring carbon savings depend on several factors: (i) the displacement factor; when coal is displaced, the net carbon savings are practically instantaneous, while they appear later when natural gas is displaced; (ii) the level of harvest residues removed; slash (BIO1) results in net carbon savings earlier than when stumps (BIO2) are also used, but in the longer term harvesting stumps in addition to slash brings greater carbon savings from fossil fuel displacement because of the greater total biomass output; (iii) If forest owners, in addition to extracting slash for energy, invest in measures to enhance forest growth (BIO+ scenarios), the net carbon savings are obtained slightly earlier and increase faster. In the latter, the pace for implementation of growth-enhancing measures is also important. Lower slash extraction rates or faster landscape-wide implementation of growth-enhancing measures would result in net carbon savings being obtained sooner (Nilsson et al., 2011; Poudel et al., 2012; Sathre et al., 2010).

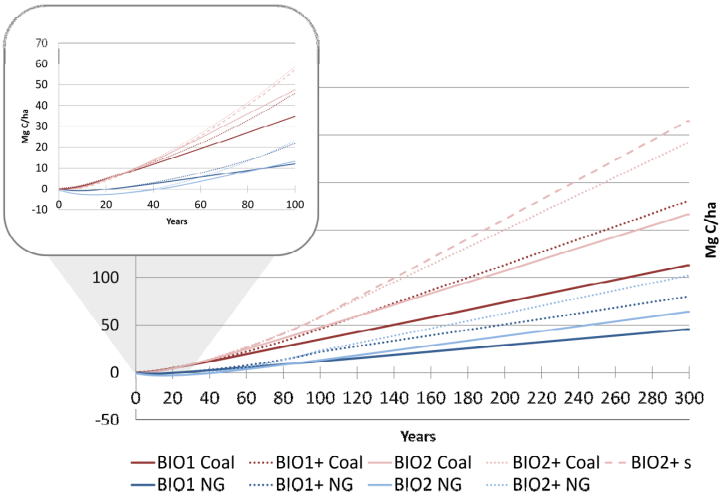

Figure 10**:** Net carbon stock comparison for the forest scenarios, for natural gas (NG) and coal scenarios at the conceptual landscape level (cf. Figure 5 in Paper I). Each line represents the net difference between the bioenergy-adapted scenario and the reference scenario, BIO1: 80% slash removal; BIO2: 80% slash +50% stumps removal; BIO1+: as BIO1 but with enhanced growth and additional stemwood used for bioenergy; BIO2+: as BIO2 but with enhanced growth and additional stemwood used for bioenergy; BIO2+s: as BIO2 but with enhanced growth and additional sawtimber used for sawnwood and the rest for bioenergy.

<u>Real landscapes</u>: real landscapes represent unequal distributions of age classes and stand sizes. **Paper I** shows that carbon balances can vary significantly for the same bioenergy system when operating in different real Swedish forest landscapes. Forest structure (e.g., age class and species distribution) and natural conditions influence the net carbon effect of forest bioenergy.

Moreover, an anticipated bioenergy demand increase can incentivize investments in increased forest production, which could result in higher or lower carbon stock. Figure 11a and Figure 11b show how the net carbon stock for two different bioenergy systems in the same landscape depends on the size of the bioenergy demand increase (given as price signals) and forest owners' views on emerging bioenergy markets. This is in line with Abt et al. (2010); Blennow et al. (2014); Conrad et al. (2011); Philip Davies et al. (2013).

Figure 11 shows that forest owners' responses to an expected increase in bioenergy demand (BIO) lead to a slightly shorter rotation period, with slightly higher pulpwood production and lower sawtimber production. The amount of slash for bioenergy increases, leading to less carbon input to the soil compared to the reference forest management (BAU in Figure 11a). The difference in forest carbon stock between BIO and BAU significantly reduces the net carbon savings of natural gas displacement. However, when coal is displaced, the net carbon savings are immediate (Figure 11b).

If the demand for bioenergy increases even further, boosting the price, more intensive forestry including higher fertilization[4] and the use of genetically improved seedlings is implemented.

[4] Notice that only 1.25% of the area is fertilized each year, and carbon emissions from the use of fertilizers are negligible.

This change will also lead to shorter rotation periods and considerably increased sawtimber, pulpwood, and forest fuel extraction, resulting in less carbon storage in soil and standing trees compared to BAU (but higher than in BIO). This carbon loss is outweighed by the combined effect of the extra sawnwood and bioenergy output so that immediate carbon savings are obtained (Figure 11b).

These results suggest that to understand the consequences of using forest biomass, total carbon balances, including displacement factors, are a better indicator than forest stock changes.

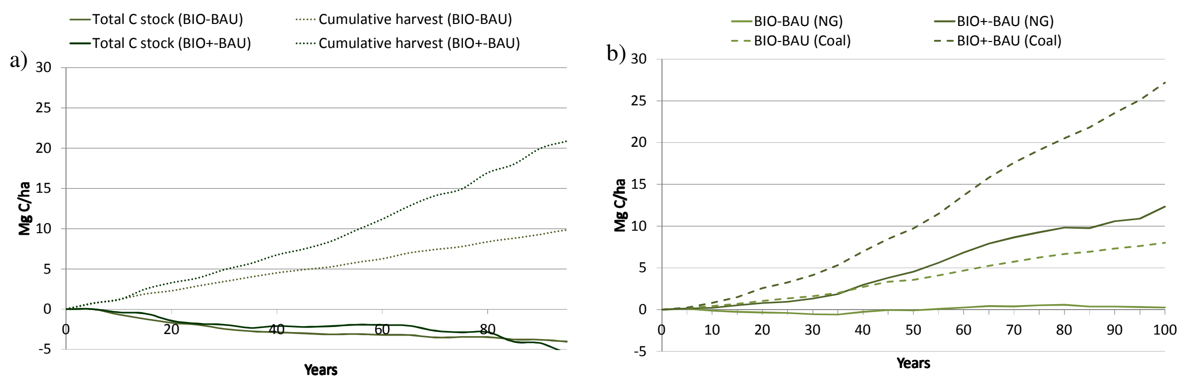

Figure 11: a) Net forest carbon stock (difference between BIOs and BAU) over time in forest pools and cumulatively in the harvested biomass at real landscape level (cf. adapted from Figure 9 in Paper II); b) Net carbon stock (difference between BIOs and BAU over time, when natural gas is displaced and coal is displaced (cf. adapted from Figure 11 in Paper II). BAU: conventional forest management with constant sawnwood and pulpwood production, with 40% of slash removals at final fellings. BIO: as BAU with increased slash removals. BIO+: as BIO with enhanced growth due to fertilization and genetically improved seedlings).

Market prospects for not only bioenergy but for all forest products can affect carbon balances. Forest owners adapt forest management planning to current and anticipated markets to maximize their expected financial outcome considering all forest products (Abt et al., 2012; Miner et al., 2014; Nepal et al., 2012). **Papers I** and **II** further illustrate that carbon balances for different bioenergy systems in one such landscape can vary significantly depending on market developments for other forest products. This finding stresses the need to include all forest products in carbon balance assessments associated with bioenergy incentives.

Our results reveal a strong link between thinning frequency and sawnwood markets in Swedish forestry. A declining demand for pulp and paper will not significantly affect forest management – including thinning intensity – and, in combination with an increasing bioenergy demand, will increase slash removal, leading to a lower forest stock but higher total net carbon stock (Figure 12b). Instead, a slightly decreasing future demand in sawnwood together with an increasing demand in bioenergy will result in longer rotation periods and more thinning residues for bioenergy with higher forest carbon stock (Paper I and Figure 12a). The net carbon effects depend on the context and nature of price drivers, e.g., whether bioenergy competes due to strong policy support or due to declining demand (and prices) for other forest products. Further, in a scenario where national demand for forest products goes down, the carbon effects of international developments causing this decline may cause forest carbon stocks to increase or decrease abroad.

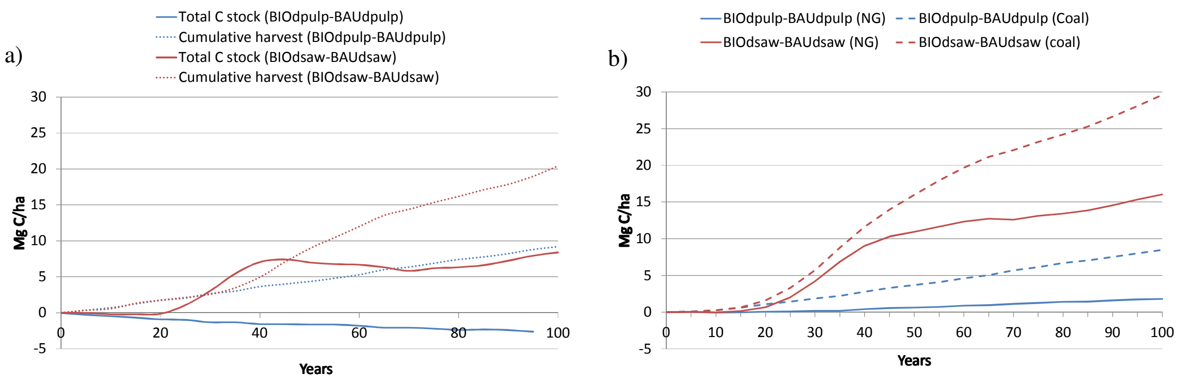

Figure 12: a) Net forest carbon stock (difference between BIOs and BAU) over time in forest pools and cumulatively in the harvested biomass at real landscape level (cf. adapted from and Figure 6 in Paper I and Figure 9 in Paper II); b) Total net carbon stock (difference between BIOs and BAU) over time, when natural gas or coal is displaced (cf. adapted from and Figure 7 in Paper I and Figure 11 in Paper II). BAUdpulp: represent a forest management with constant production of sawnwood and declining pulpwood; BIOdpulp: as BAUdpulp with increase slash removals. BAUdsaw: declining production of sawnwood and constant for pulpwood; BIOdsaw: as BAUdsaw with increase slash removals.

In short, the initial emissions attributed to establishing forest bioenergy systems and showed at conceptual landscape assessments can be present or not. Therefore, assessments of bioenergy systems should consider all forest products and all changes in forest management which might occur simultaneously at the landscape level.

Here, we have assumed that all forest owners behave rationally, which introduces a bias in the assessment of carbon balances and bioenergy supply potentials. In Sweden, half of the productive forest area is owned by small-scale private landowners. Eggers et al. (2014) conclude that owners of larger properties will more likely choose a more production-intensive management than small holders, who will be less inclined to change their forest management. Consequently, responses to changing conditions might be overstated.

4.1.3 Short term vs. long term impacts

How do different temporal scales and metrics capture the timing-of-emissions effects of forest bioenergy?

In **Paper I** we found that the net carbon stock, CRF, and ΔT figures show similar trends The climate benefits of some bioenergy systems are delayed compared with others depending on several factors, as seen before. However, in all cases, if climate warming effects are present, they can be reversed, and, in most of the cases, still provide great climate mitigation benefits in the medium term (Figure 13). The CRF and ΔT figures show earlier benefits of bioenergy use than the carbon stock figure (Figure 10) since the upfront emissions associated with fossil fuels and other GHGs are not included in the carbon stock graph. Nevertheless, in the modeled cases, the effect of these emissions is relatively small compared with biospheric carbon fluxes. CRF indicates later climate benefits than ΔT since it reflects cumulative effects, where the inertia of the climate system comes into play and the dynamics become less important.

These metrics could be more relevant when including other climate forcings and when assessing trade-offs between short- and long-term climate targets.

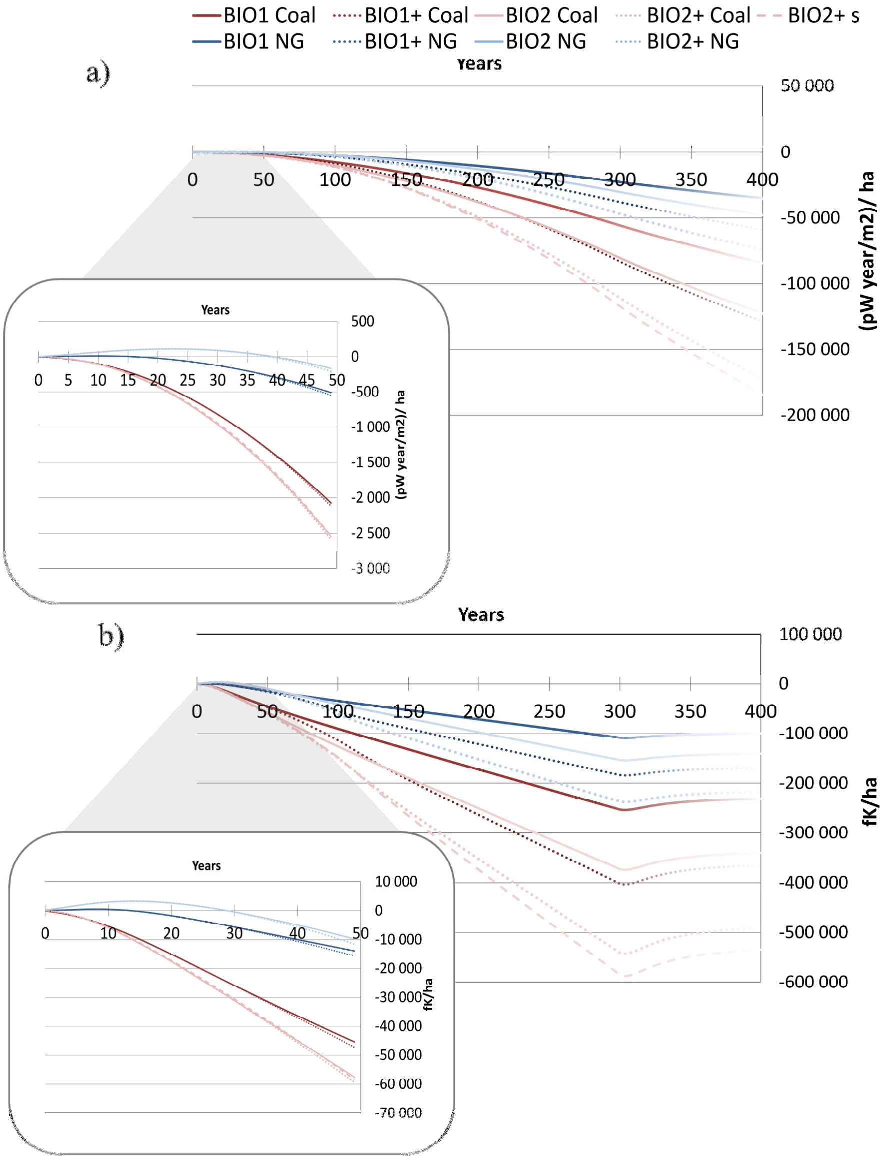

Figure 13: Net climate effects of the fossil and biomass-based systems implemented during 300 years at the landscape level. a) Net cumulative radiative forcing (CRF) in picowatt per hectare; b) Net change in temperature (ΔT) in fentowatt per hectare (cf. Figure 8 in Paper I). Negative values correspond to cooling. Each line represents the net difference between the bioenergy adapted scenarios and the reference scenario, i.e., BIO1: 80% slash removal; BIO2: 80% slash +50% stumps removals; BIO1+: as BIO1 but with enhanced growth and additional stemwood used for bioenergy; BIO2+: as BIO2 but with enhanced growth and additional stemwood used for bioenergy; BIO2+s: as BIO2 but with enhanced growth and additional sawtimber used for sawnwood and the rest for bioenergy.

Carbon budget:

As discussed above, some of the bioenergy systems are associated with initial net emissions, which in most of the cases revert over time. This fact raises the question whether the size of the initial emissions are within a safe level, or allowed budget, acceptable in order to provide further savings in the long term. Figure 14b illustrates that initial emissions associated with the establishment of a bioenergy system are within a hypothetical budget and will assure a low carbon energy source that will bring net carbon benefits after some decades. Figure 14a also shows the net emissions (emissions and removals) for each scenario separately; in the bioenergy scenario (BIO), the size of the forest sink decreases, but the net balance, including avoided fossil fuels, leads to higher climate benefits than in the reference scenario (REF). In addition, biospheric carbon emissions could be re-captured by, e.g., increased forest growth, extended forest area associated with the increased demand for bioenergy, or future decrease of harvest intensity; contrarily fossil emissions will remain in the atmosphere for centuries. BIO represents constant forest management. In a situation with a future energy system with increasing penetration of solar and wind, available storage options, and high electrification in the transport sector, the demand for bioenergy might become lower. This could lead to reduced harvest intensity and possibly increased carbon sequestration in forest, unless converted to other use. Increased harvest intensity could also be compatible with increased re-captured biospheric emissions if other changes in the forest take place in parallel, such as increased forest growth or extended forest areas.

Initial emissions are not only associated with bioenergy systems; they can also be used when establishing other low carbon intensity alternatives. Electric vehicles, for instance, will be associated with initial emissions if electricity is produced from fossil fuels while the electricity sector is transforming into low-carbon system. Similarly, Myhrvold and Caldeira (2012) estimate the warming effect associated with ramping up low-emission energy systems, e.g., solar, wind, carbon capture and storage, arguing that they will do little to diminish the climate impacts in the first half of this century but will contribute to savings in the second half of the century. This does not mean the transition towards low carbon intensive energy systems can wait but rather that establishing this technology and infrastructure will have associated emissions.

The carbon budget concept is found to be useful in assessing the effect of bioenergy incentives to meet long-term stabilization goals, e.g., the 2-degree limit, as presented in **Paper III**.

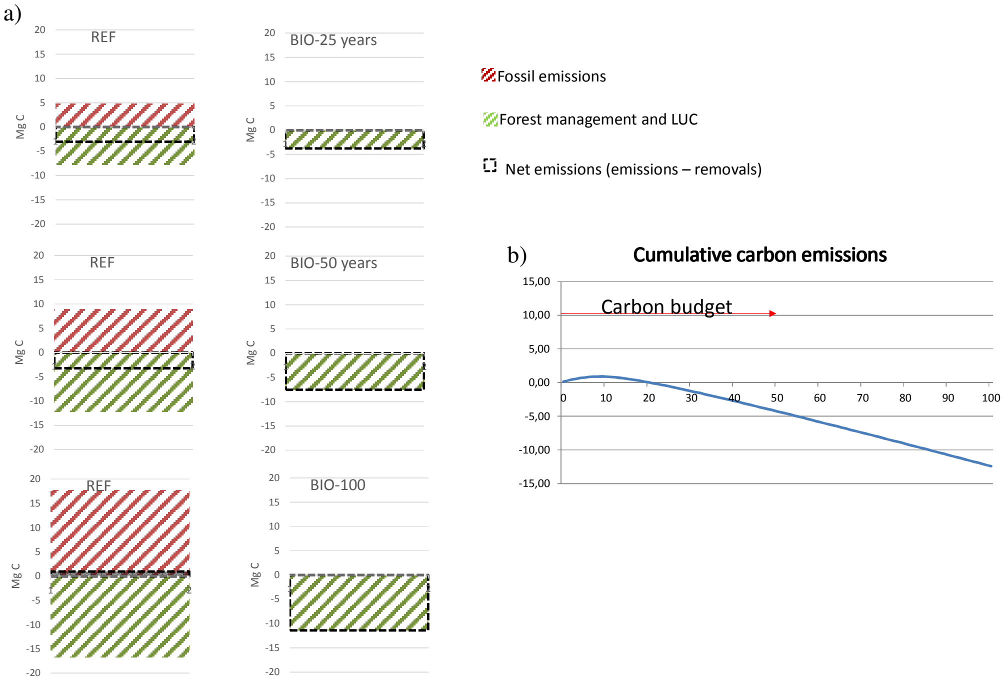

Figure 14: Conceptual carbon budget. REF: only stemwood removal + NG; BIO: as REF but with 80% slash removal. a) Cumulative carbon emissions after 25, 50, and 100 years; b) cumulative carbon emissions over time compared with a hypothetical carbon budget

4.2 Potential role of Swedish forest

Research question 2: What is the potential of the Swedish forest to contribute to the mitigation of climate change?

What is the potential of the Swedish forest sector in meeting the GHG neutrality goal by 2050? What is the potential of the Swedish forest in achieving the 2-degree limit?

Sweden has the vision of being independent of fossil fuels in road transport by 2030 (Swedish Government Official Reports, 2013) and GHG-emissions neutral by 2050 (Government offices of Sweden, 2009a). **Paper III** compares the size of the future bioenergy demand, in line with these political goals, with the potential supply of forest bioenergy, to estimate the gap between them (Figure 15). The results show that the Swedish forest sector makes a major contribution to these political goals by supplying bioenergy and also by keeping or enhancing atmospheric carbon storage in trees and soils. In all these scenarios, the GHG neutrality target is only reached before 2050 if the net balance effect from the forest is factored in (Figure 16).

Current forest management strategy already makes an important contribution in the net Swedish GHG balance; however, it will not provide sufficient forest biomass for the bioenergy use outlined in the national political agenda. New forest interventions are therefore needed.

Figure 15 shows that an increase in harvest intensity (BIO1 in Figure 15) could cover the estimated future biomass demand, assuming a certain share of domestically produced agriculture and waste- based biofuels in the transport sector, i.e., 3.6-9 PJ. (Börjesson et al. (2013) estimated that 36-43 PJ of biomass could be supplied by using crop residues, manure, organic waste, and biomass plantations on abandoned agriculture land.) The future domestic biomass demand could also be covered by re-directing 15-24% of the biomass dedicated to export pulp and paper to biofuels production. Again, the effect of decreased export of paper on non-domestic GHG balances will depend on whether the change is due to a global decrease in paper consumption or competition with other paper producers.

The forest biomass supply potential for bioenergy associated with more intensive forest management, including increased fertilization and genetically improved plant materials, could cover the total estimated bioenergy demand while still enhancing carbon sequestration in the forest (BIO2 in Figure 16). It could also provide biomass available for export or for additional domestic consumption (see Figure 15, BIO2 forest supply exceeds demand). The energy scenarios in line with the Swedish political goals (described in **Paper III**) are very ambitious, assuming a high level of efficiency improvements and other measures to reduce fossil fuel use. If all those assumed measures to reduce fossil fuel use are not implemented successfully, the demand for biomass could increase. In this case (assuming that there is no abatement measure implemented), BIO2 could supply enough fuel to cover 30% to 60% (2020-2050) of the total transport fuel demand. It could also cover a higher energy demand in the industry sector, for example an extra 70-108 PJ of biomass required as raw material in the chemical industry (Börjesson et al., 2013). The biomass could also be left in the forest, increasing its carbon stock.

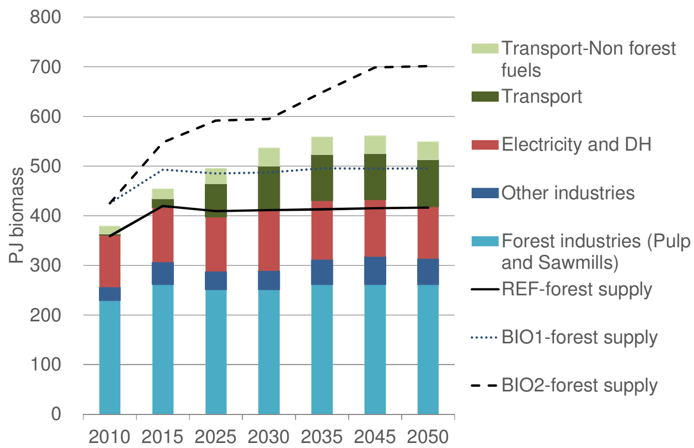

Figure 15: Comparison between forest biomass supply (black lines) REF, BIO1, and BIO2 and biomass demand for energy (cf. Figure 5 in Paper III). The bioenergy demand is disaggregated into: Forest industries including sawmills and pulpmills; Other industries (includes residential and services); Electricity and district heating (DH); Transport sector (road, aviation, and shipping). Transport sector demand is divided into demand for biofuels based on forest biomass and based on other feedstocks. REF: conventional forest management with 15% slash removal; BIO1 as REF but 20% of stumps and 35% slash removal; BIO2: as BIO1 with measures to enhance growth.

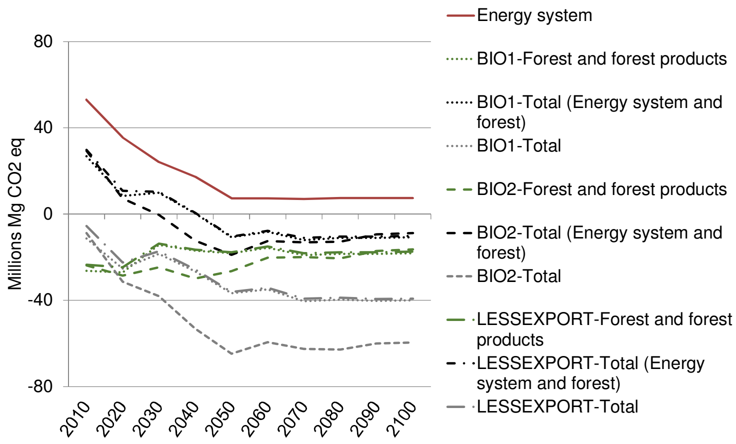

Figure 16: Net GHG emissions in Sweden with and without considering displacement effects of exported forest products (cf. adapted from Figure 10 in Paper III). Fossil fuels refers to emissions from the Swedish energy system; Forest and forest products refers to biomass growth and decay, soil carbon accumulation and oxidation, carbon storage in products, and emissions from combustion of biomass, biofuels, and discarded products;Total (Energy system and forest) excludes displacement effects abroad, which are included in Total. REF: conventional forest management with 15% slash removal; LESS EXPORT: as REF but with 15% of exported pulpwood to domestic bioenergy; BIO1: as REF but 20% of stumps and 35% slash removal; BIO2: as BIO1 with measures to enhance growth.

The carbon budget concept was used in **Paper III** to place the scenarios in the context of the 2-degree limit. When considering only the fossil fuel emissions in comparison with the fossil budget, the budget in the business-as-usual scenarios is claimed by mid-century; in the scenarios in line with the Swedish political goals, the fossil budget is only claimed if allocation of the global carbon budget takes into account historical responsibility for emissions, too.

When considering total Swedish net GHG emissions in relation to the net CO_2 budget – i.e., the CO_2 budget that includes both fossil fuel emissions and emissions associated with forest management and LUC – the outcomes of the business-as-usual scenario claim the net CO_2 budget (Figure 17). In contrast, the scenarios in line with the political targets will not claim the budget during the scenarios' period and instead create more CO_2 emission space (cumulative net emissions are -0.64 to -1.07 Pg CO2). This is due to the combination of strong reductions in GHG emissions associated with (mainly) fossil fuels and persistent carbon sequestration associated with forest management and the production and use of forest products. If historical responsibility for emissions is considered, the emission space is even larger, meaning that other countries might have more space for emitting and therefore more time to implement measures to reduce CO_2 emissions.

In addition, the effect of forest products abroad, including carbon storage and displacement of products, provides additional savings (2.5 to 4 Pg CO_2 cumulative emissions from 2015-2100). This magnitude is very similar to the emissions associated with GHG emissions abroad due to production of goods consumed in Sweden (5.7 Pg CO_2).

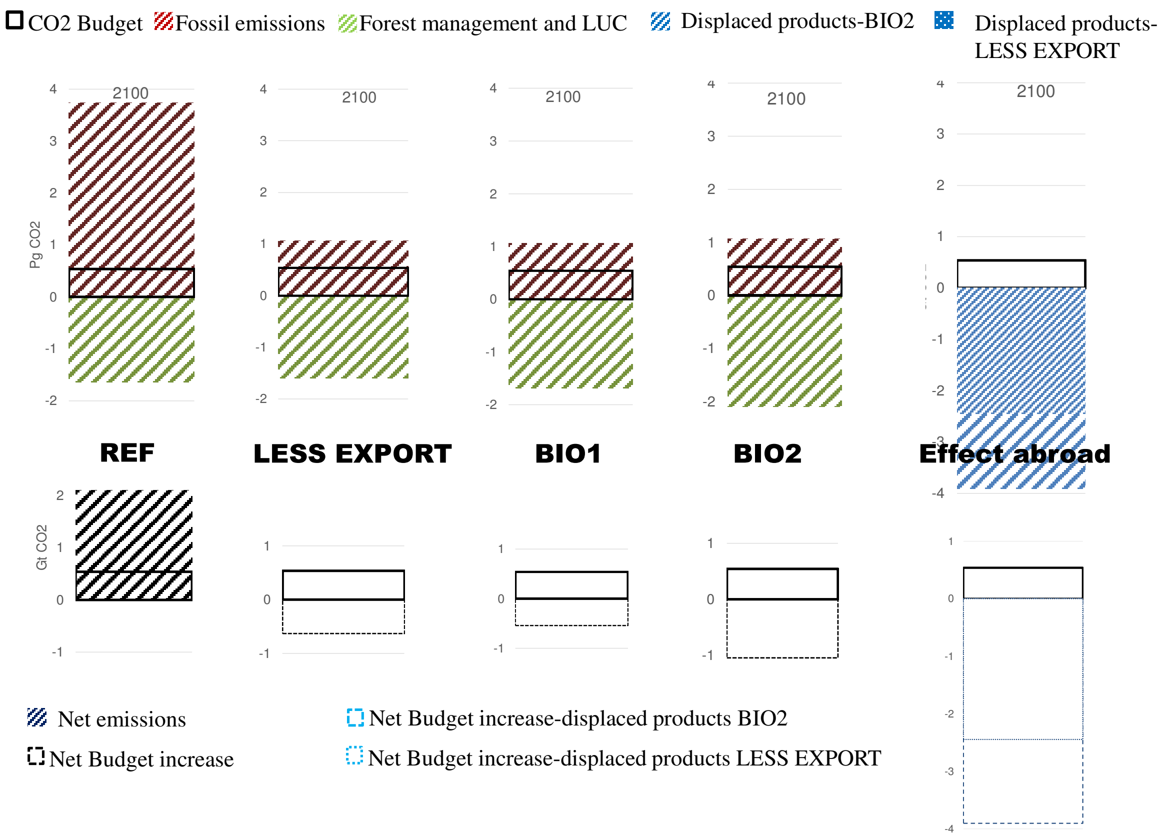

Figure 17: Comparison between the net CO_2 budget for Sweden and the cumulative emissions (fossil and LUC emissions in Pg CO_2) for the different scenario combinations (cf. Figure 11 in Paper III). REF: conventional forest management with 15% slash removal; LESS EXPORT: as REF but with 15% of exported pulpwood to domestic bioenergy; BIO1: as REF but 20% of stumps and 35% slash removal; BIO2: as BIO1 with measures to enhance growth.

5 - Summary and conclusions

The work presented in this thesis focuses on bringing together different methodological perspectives to improve the assessment and understanding of how an increased demand for bioenergy will affect carbon balances in forest carbon stocks and how this in turn influences the contribution of forest bioenergy to climate change mitigation.

5.1 How to improve the assessment of carbon balances of forest-based energy

We have investigated how to assess the climate-relevant effect of an increase in demand for forest bioenergy. As seen throughout this work, the conclusions about climate benefits of forest-based bioenergy systems depend greatly on methodological choices, parameter assumptions, and the forest dynamics included in assessments.

The choice of spatial scale, which depends on the questions being asked, will affect the results of the study. Based on our findings, we recommend that assessments intended to support policy-making evaluate how bioenergy incentives and increased demand for bioenergy affect the forest carbon stock at the landscape level. **Papers I** and **II** show how forest dynamics, including changes in forest management driven by increased demand for bioenergy, are better captured by the landscape approach (either conceptual or real) because it accounts for all carbon flows between biosphere and atmosphere throughout the accounting time period while the stand approach does not. In this context, efforts to relate a specific product with a localized impact, usually associated with stand assessment, can lead to misinterpretation of carbon dynamics.

Landscape assessments shows rather stable carbon balances with climate benefits that might come earlier or later depending on several factors. Assessments differ on carbon balances in different Swedish landscapes, suggesting that generalizations from individual studies should not be made. The climate effect of forest bioenergy systems is in part determined by forest structure and local conditions. Our results additionally show that not only biophysical conditions but other factors such as ownership structure, forest product portfolio, market prospects for all forest products, and forest management responses to market incentives for bioenergy can also affect climate benefits of using forest-based bioenergy. Therefore, we recommend that carbon balance assessments at the landscape scale should be context-specific and complemented with socio-economic modeling, including effects on parallel industries (wood products and energy) to capture their effect on forest carbon stocks and consequently on climate change. If it is not possible to combine carbon balance assessments with other models, then we recommend using scenario analyses, as done in **Paper III**, in which energy scenarios were used to capture the size and development of the bioenergy demand and how different forest managements could cover that demand. We also recommend using different scenarios including different developments for other wood products to get insights about market developments and their effect on forest management, as shown in **Paper II**.

5.2 Potential contribution of forest-based bioenergy to climate change mitigation

When moving from stand to landscape and continuing to the national level, the detailed carbon accounting shows that the timing of carbon emissions and sequestration becomes less relevant. Shifting the attention from assessment of flows to maintaining forest carbon stock to deliver forest ecosystem services – including forest products – will capture potential impacts associated with forest products while being much easier to evaluate.

Promoting bioenergy in addition to maintaining a rather stable forest carbon stock could lead to immediate climate benefits. **Papers II** and **III** present future scenarios in which intensification of forest bioenergy systems leads to increased biomass output and carbon sequestration by enhanced biomass growth. Hence, immediate net carbon savings are possible if the increase in demand is anticipated by forest owners.

It is equally important to find a balance between the objectives of maintaining forest carbon stock and leaving fossil fuels underground. Some bioenergy systems present initial carbon losses that could be greater than the achieved fossil carbon savings during some years but will bring important carbon savings in the long run. We therefore recommend that results from these assessments should consider short-term vs. long-term benefits. If climate targets limit short-term GHG emissions of bioenergy, then the policy could undermine the potential role of bioenergy in long-term targets, e.g., the 2-degree limit. Policies and incentives should rather focus on expanding low carbon energy technology for instance by promoting sustainable forest management.

Last but not least, forests are habitats for a range of species providing several ecosystem services. A broader sustainability perspective, considering other forest ecosystem services, such as air quality improvement, water purification, soil stabilization, and biodiversity conservation, and social services such as employment and recreation, should also be considered when designing bioenergy policy incentives.

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6 - Future work

The task of assessing bioenergy in the context of climate change mitigation is of course still not complete. In addition to assessing carbon balances and addressing the effects of other GHGs, understanding the climate consequences of using biofuels requires considering other climate forcers, such as albedo, too.

The establishment of bioenergy systems can in some instances cause a net increase in GHG emissions, despite displacing fossil fuels, at least for a period of time. Future work will further address the question of how promotion of bioenergy affects the development of energy systems. This will help to inform about the development of energy and climate policies and provide new insights concerning bioenergy implementation relative to the tradeoff between short term GHG targets and longer term goals such as the 2-degree target. For instance, early bioenergy implementation to displace fossil fuels, possibly causing initial increases in net GHG emissions, may support the buildup of other energy infrastructures than the promotion of forest carbon sinks primarily aiming at reaching near term GHG targets. Trade-offs between different land-use alternatives need to be analyzed for scenarios depicting different energy system pathways.

Further analyses of sustainable forest management are required. All the forest scenarios presented in this thesis represent management of even-aged stands that are harvested via clearcutting and regenerated through planting, which dominates in Sweden. However, other approaches to forest management, such as continuous-cover forestry, should also be investigated (see, e.g., Lundmark et al. (2016). More assessments are needed at the landscape and national level to understand trade-offs between forest carbon management, forest diversity, and forest product output. Further, the analyses made in this thesis can be repeated for other countries where conditions are different concerning, e.g., the energy system, forest resources, and the associated forest industry.

As seen in **Papers II** and **III**, an increased demand for biofuels in Sweden could affect the production of other forest products, leading to competition and also influence land use in other regions. Such dynamic effects need to be investigated further. Moreover, analyses of how bioenergy incentives cause competition for forest biomass should preferably consider alternative biomass sources such as crop residues and biomass from dedicated energy crops, so as to capture inter-connections between different sectors.

Paper III is an example of a study that compares forest biomass supply potentials with demand scenarios for various forest products. Such approaches need to be complemented with integrated cross-sector modelling to better inform how different energy and climate policy instruments may affect development in different sectors. As an example of such future research, a study is now underway that will combine policy scenarios with energy system modeling and geo-explicit land use/land cover assessments to investigate how bioenergy promotion may induce supply side responses in the forest and agriculture sectors, and how this in turn influences land use and LUC in Europe.

BECCS has received a lot of attention, including in the most recent IPCC report, as an option for achieving negative emissions with the potential to keep warming below 2 degrees. In order to investigate the role of large-scale deployment of BECCS in the European context, spatially explicit assessments of potential storage sites for captured CO_2 will be combined with the above-mentioned study for Europe.

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