THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Land-Use and Climate Effects of Bioenergy

**Carbon balances of Swedish forest bioenergy systems – and –
Geospatial biomass supply-and-demand matching for Europe**

Olivia Cintas

Cover: Combination of Figure 4a and b in the appended Paper IV: Total forest and agricultural residues in Europe.

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Abstract

In order to keep global warming below 2 degrees Celsius, greenhouse gas emissions have to be drastically reduced. Bioenergy can play a role in climate change mitigation by substituting for energy from fossil fuels; however, biomass is a limited resource associated with emissions from land use and land-use change. Climate benefits of using biomass for energy have been called into question, with studies reaching conflicting conclusions. These conflicts can in part be explained by differences in methodological approaches and critical parameters, as well as by differences among the assessed bioenergy systems, e.g., the geographic location and associated land use.

This thesis combines five papers to provide a better understanding of the interactions between biomass supply and demand and the implications for land use and for climate change and other environmental impacts. **Papers I** and **II** bring together different methodological perspectives to analyze the effects on land use, biomass production, and forest carbon balances of using forest bioenergy. The papers show how the climate benefits of forest bioenergy systems can depend on the scale of the assessment, structure of the forests studied, market prospects for bioenergy and other forest products, and energy system developments. **Paper III** analyzes the role of the Swedish forest sector in future energy scenarios and in reaching the 2050 goal of climate neutrality. The paper finds that the Swedish forest can make an important contribution by supplying forest fuels and other products while maintaining or enhancing carbon storage in vegetation, soils, and forest products. The results are placed in the context of the 2-degree target by allocating a CO_2 emissions budget to Sweden. **Paper IV** presents a geographical information system modeling framework (1,000 m resolution) for assessing and analyzing the availability and cost of forest and agricultural residues in relation to localized biomass demand for co-firing with coal. The paper shows that using agricultural residues reduces transport distances and thereby transport costs. **Paper V** extends the modeling framework used in **Paper IV** to include energy crops in assessing biomass availability and costs in the context of bio-electricity and bio-refineries, and considers potential environmental consequences associated with energy crops. The paper shows that lignocellulosic crops can complement residues and help mitigate a selected number of environmental impacts on agricultural land.

Keywords: Forestry, agriculture, residues, bioenergy, GHG balances, climate change, GIS, Sweden, EU.

Publications included in the thesis

This thesis is based on the work contained in the following papers:

Paper I: Cintas, O., Berndes, G., Cowie, A. L., Egnell, G., Holmström, H., & Ågren, G. I. (2016). The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. *Wiley Interdisciplinary Reviews: Energy and Environment, 5*(3), 351-369.

Paper II: Cintas, O., Berndes, G., Cowie, A. L., Egnell, G., Holmström, H., Marland, G., & Ågren, G. I. (2017). Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments. *GCB Bioenergy, 9*(7), 1238-1251.

Paper III: Cintas, O., Berndes, G., Hansson, J., Poudel, B. C., Bergh, J., Börjesson, P., Egnell, G., Lundmark, T. & Nordin, A. (2017). The potential role of forest management in Swedish scenarios towards climate neutrality by mid-century. *Forest Ecology and Management, 383*, 73-84.

Paper IV: Cintas O., Berndes G., Englund O., Cutz L., Johnsson F. (2018). Geospatial supply–demand modeling of biomass residues for co-firing in European coal power plants. *GCB Bioenergy*, 10,786–803.

Paper V: Cintas, O., Berndes, G., Englund, O., & Johnsson, F. Geospatial supply-demand modeling of lignocellulosic biomass for electricity and biofuels in the European Union. *To be submitted for publication*.

Contributions:

I. Olivia Cintas (OC) is the main author, with the main responsibility for formulating the research questions, designing the study, collecting data, performing the system analysis, analyzing results, and writing the paper. Göran Ågren (GÅ) generated forest data using the Q model, and Hampus Holmström (HH) generated forest data using Heureka. Annette Cowie (AC) and Gustaf Egnell (GE), HH, GÅ contributed ideas and discussion. AC, GE, HH, and GÅ contributed comments on the manuscript.

II. OC is the main author, with the main responsibility for formulating the research questions, designing the study, collecting data, performing the system analysis, analyzing results, and writing the paper. HH generated forest data using Heureka. AC, GE, Gregg Marland (GM), HH, and GÅ and contributed ideas and discussion. AC, GE, GM, HH, and GÅ contributed comments on the manuscript.

III. OC is the main author, with the main responsibility for formulating the research questions, designing the study, collecting data, performing the system analysis, analyzing results, and writing the paper. Bishnu Poudel (BP), John Bergh (JB), Thomas Lundmark (TL), and Annika Nordin (AN) provided forest data generated with the Hugin model; Julia Hansson (JH) provided data on the demand for biofuels in the transport sector. JH, BP, JB, Pål Börjesson (PB), GE, TL, and AN contributed discussion. JH provided editing and BP, JB, TL, and AN provided comments on the manuscript.

IV. OC is the main author, with the main responsibility for formulating the research questions, designing the study, collecting data, implementing the new modeling framework, analyzing results, and writing the paper. Luis Cutz (LC) provided biomass-demand data. Oskar Englund (OE) contributed to formulating the research questions and contributed ideas for the early phase of the modeling and discussion. LC wrote the text on the methodology to calculate biomass demand. OE, LC, and Filip Johnsson (FJ) contributed comments on the manuscript.

V. OC is the main author, with the main responsibility for formulating the research questions, designing the study, collecting data, implementing the new modeling framework, analyzing results, and writing the paper. OE provided data on the effectiveness with respect to mitigating environmental problems. FJ contributed discussion and comments on the manuscript.

Göran Berndes is the academic supervisor and has contributed to the formulation of the research questions and the discussion and writing.

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Göteborg, October 2018
Olivia Cintas

Table of Contents

1 -   Introduction

Climate change is one of the greatest challenges for humankind. At the United Nations conference on climate change in Paris (COP21), 195 countries reached the historical agreement to "strengthen the global response to climate change […] including by…[h]olding 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 major contribution to anthropogenic global warming is carbon dioxide (CO_2), mainly from burning fossil fuels—36.3 Gt in 2016—and from land use (LU) and land-use change (LUC)[1]—4.8 Gt in 2016 (Le Quéré et al., 2017). Strategies to mitigate climate change involve efficiency measures, replacement of fossil fuels with non-fossil energy sources, and promotion of carbon sinks, including forest protection and measures to enhance carbon sequestration and storage in vegetation and soil, and carbon capture and storage (CCS) in deep geological formations.

Bioenergy is expected to contribute significantly to abating CO_2 by substituting for fossil fuels, but it is also associated with emissions and other impacts from LU and LUC (Creutzig et al., 2015; IEA, 2017). Solid biomass can substitute for coal, biogas for natural gas, and biofuels for oil and diesel, with rather small changes in current technology and infrastructure. Bioenergy can also be combined with CCS, so-called BECCS, to achieve negative emissions (Cao & Caldeira, 2010; Smith et al., 2016). However, a shift from conventional energy sources to biomass-based energy sources could be a driver for LUC, which in turn is associated with environmental and biodiversity challenges.

A review of stabilization scenarios in line with the 2-degree limit by Creutzig et al. (2015), has bioenergy contributing 10 to 245 EJ yr^{-1} to the global primary energy supply by 2050. Currently, bioenergy demand is estimated to be around 50 EJ (10% of the global primary energy supply), of which around 60% is traditional biomass used for cooking and heating in developing countries (IEA, 2017). The potential contribution of bioenergy is controversial, and studies arrive at varying conclusions (100-1200 EJ) due to different assumptions regarding critical factors such as future diets, productivity developments in the forest and agriculture sector, and the extent to which sustainability criteria are considered (Slade et al., 2014). For instance, Creutzig et al (2015) estimated the

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[1] Land-use change (LUC) refers to land cover conversion (e.g., from forest into agricultural land) or change in land management (e.g., change in harvest intensities, cropping patterns, fertilizer inputs).

sustainable technical potential[2] for bioenergy to be, with medium agreement in the reviewed literature, 100-300 EJ by 2050, arguing that realizing this potential will require: (i) reducing traditional biomass demand; (ii) making use of residues from forestry and agriculture; (iii) optimizing forest harvests (increasing harvest intensity, which often means setting the annual biomass extraction levels equal to the net annual increment or to levels defined by sustainable forest management); (iv) using organic waste; and (v) making use of dedicated plantations to produce bioenergy feedstocks (energy crops).

Decisions concerning land conversion and changes in forest management for bioenergy will require trade-offs among different conflicting objectives (e.g., biomass output, climate change, soil, and water quality). LUC can affect climate change by (i) contributing to CO_2 emissions associated with changes in biospheric carbon stock or emissions from inputs to new management regimes; and (ii) affecting the ability of surfaces to reflect sunlight, the so-called albedo effect. Clear cutting a forest or converting to energy crops increases albedo (contributing to a cooling effect and mitigating the effect of deforestation), while introducing green energy crops on land covered with snow in dry seasons contributes to warming. In addition to climate change, an increasing demand for bioenergy could result in higher pressure on ecosystems, posing environmental and social risks, e.g., biodiversity loss or degradation of ecosystem services (Creutzig et al., 2015; Haberl et al., 2007; Schulze et al., 2012). But bioenergy can also contribute to energy security and employment (e.g., Berndes & Hansson, 2007; Souza et al., 2015; Nijsen et al., 2012) or to improving current degraded agricultural ecosystems, when bioenergy systems are integrated into agricultural landscapes (see e.g., Dimitriou et al., 2011; Ferrarini et al., 2017; Pedroli et al., 2013).

Understanding the impact of bioenergy systems on sustainable development is a relevant research area with uneven coverage in terms of the feedstocks and impacts considered (Robledo-Abad et al., 2017). Recently, a lot of attention has been paid to determining the timing and magnitude of the carbon emissions and sequestration associated with forest bioenergy. Those studies report diverging conclusions, mainly due to methodological choices rather than ecosystem- and management-related assumptions (Bentsen, 2017). Promotion of bioenergy is being reconsidered in response to the concern that bioenergy may not be as effective in reducing greenhouse gas emissions (GHG) as expected. For instance, in the European Union (EU), biospheric[3] emissions associated with bioenergy were set to zero in Directive 2009/28/EC (Renewable Energy Directive—RED) as well as in the proposal for the new directive (RED II), but this was called into question, see Agostini et al. (2013), and still remains unresolved Beddington et al. (2018); Searchinger et al. (2018).

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[2] The *sustainable technical potential* refers to what is technically feasible considering sustainability constraints.
[3] The EU uses the term "biogenic emissions" instead of "biospheric emissions."

Nevertheless, the use of bioenergy is expected to increase and play an important role in the EU. EU climate change policy aims to build a low-carbon economy and reach a reduction in GHG emissions by 80% to 95% by 2050 compared to 1990 levels (EC, 2011), with renewable energy making up at least 55% of the gross final energy consumption. A transition toward a bio-economy—where biomass substitutes for fossil fuels and GHG-intensive materials—could make a significant contribution to the transition to a low-carbon economy (Scarlat et al., 2015). This transition will require a sustainable and cost-efficient mobilization of feedstock resources.

A better understanding of the climate consequences of using bioenergy and the effects on other ecosystem services would facilitate the development of science-based policies for bioenergy that prevent negative impacts while promoting positive ones (Robledo-Abad et al., 2017). This thesis consists of five papers that contribute to this better understanding. The first part of the thesis (**Papers I-III**) investigates the contribution of forest biomass to climate change mitigation, i.e., to reducing emissions and increasing sequestration. The focus is on carbon balances associated with biomass production and use, and carbon stock changes in the Swedish forest, but the results and associated discussions have wider relevance. The second part of the thesis (**Papers IV** and **V**) investigates biomass supply-and-demand patterns (biomass includes forest and agricultural residues, and lignocellulosic crops) in the EU and interactions with LU, LUC, and other selected environmental aspects.

1.1   Aim and Scope

The aim of this thesis is to advance current knowledge about the effects of bioenergy on land use, climate change, and other environmental impacts in the context of a low-carbon economy. More specifically, the purpose is to: (i) bring together different methodological perspectives to improve the assessment and understanding of how increased demand for bioenergy will affect land use, biomass production and forest carbon balances, and how this in turn influences the contribution of forest bioenergy to climate change mitigation; and to (ii) develop a methodology framework for matching localized biomass supply and demand, and to estimate associated costs, CO_2 savings, LU, and LUC. The questions addressed in this thesis are:

1. To what extent can methodological choices and assumptions about critical parameters affect the outcome in assessments of land use, (forest biomass) carbon balances, and climate effects, and how should they be considered? (**Papers I-III**)
   - o How does the choice of spatial scale in analyses affect results and conclusions concerning forest carbon balances of forest bioenergy, and what scale is most relevant in a specific context? (**Papers I** and **II**)

   - o To what extent can market dynamics/demand for bioenergy and other forest products affect the carbon balances of forest bioenergy? (**Papers I** and **II**)

3

o How do different temporal scales and metrics capture the climate effects associated with forest bioenergy? (**Papers I** and **III**)

2. To what extent can biomass demand in the EU (including Norway and Switzerland) be met based on biomass resources within the same region, and how may environmental impacts in current agriculture be mitigated if part of the biomass supply comes from dedicated cultivation of lignocellulosic crops on existing cropland? (**Papers IV** and **V**)

   o What is the size and geographic distribution of biomass demand for energy if suitable coal power plants in the EU are used for biomass co-firing with coal or converted into biomass-dedicated power plants? (**Paper IV** and **V**)

   o What is the size and geographic distribution of biomass demand for energy if sites used for coal power are converted into biomass-dedicated plants producing bio-oil? (**Paper V**)

   o How much of the biomass demand can be met based on sourcing forest and agriculture biomass within certain distances? How could it affect land use in the surrounding areas? (**Papers IV** and **V**)

   o How may environmental impacts of current agriculture land use be affected if part of the supply comes from dedicated cultivation of lignocellulosic crops on current cropland? (**Paper V**)

More specifically, the content of each paper can be described as (Figure 1):

Papers I and **II** evaluate the land use, carbon balances, and GHG-mediated climate effect associated with forest-based energy and products from long-rotation managed forest in Sweden by using different spatial (stand and landscape in Figure 1) and temporal system boundaries and by including market mechanisms.

Paper III analyzes the potential role of the Swedish forest sector in scenarios for meeting Sweden's climate goals for 2030 and 2050 and quantifies the associated GHG balances. Additionally, the scenarios are placed in the context of the 2-degree target by allocating a CO_2 emissions budget to Sweden.

Paper IV presents a geographical information system (GIS) modeling framework (1,000 m resolution) to assess and analyze the availability and cost of forest and agricultural residues in relation to localized biomass demand for co-firing with coal in the EU (Figure 1).

Paper V extends the modeling framework used in **Paper IV** to include energy crops and potential associated environmental consequences in an assessment of biomass availability and cost, in relation to bio-electricity or bio-refining in the EU.

1.2   Outline of the thesis

This thesis consists of an extended summary with five papers appended. The extended summary is divided into eight chapters. Chapter 2 provides a general background on the role of biomass in climate mitigation and on biomass availability and associated critical issues. Chapter 3 is a literature review addressing (i) spatial and temporal system boundaries in studies of carbon balances of bioenergy systems, and (ii) biomass availability and associated sustainability issues. Chapter 4 describes the design of the analyses and the methods used for (i) quantifying carbon balances associated with forest products at different scales and using different climate metrics and (ii) geo-spatial matching of biomass supply and demand. Chapter 5 presents key findings and discusses them in relation to each research question. Chapter 6 discusses the methods and methodological choices, the role of bioenergy in a low-carbon economy, and implications for decision makers. Conclusions are presented in Chapter 7, and propositions for further work are presented in Chapter 8.
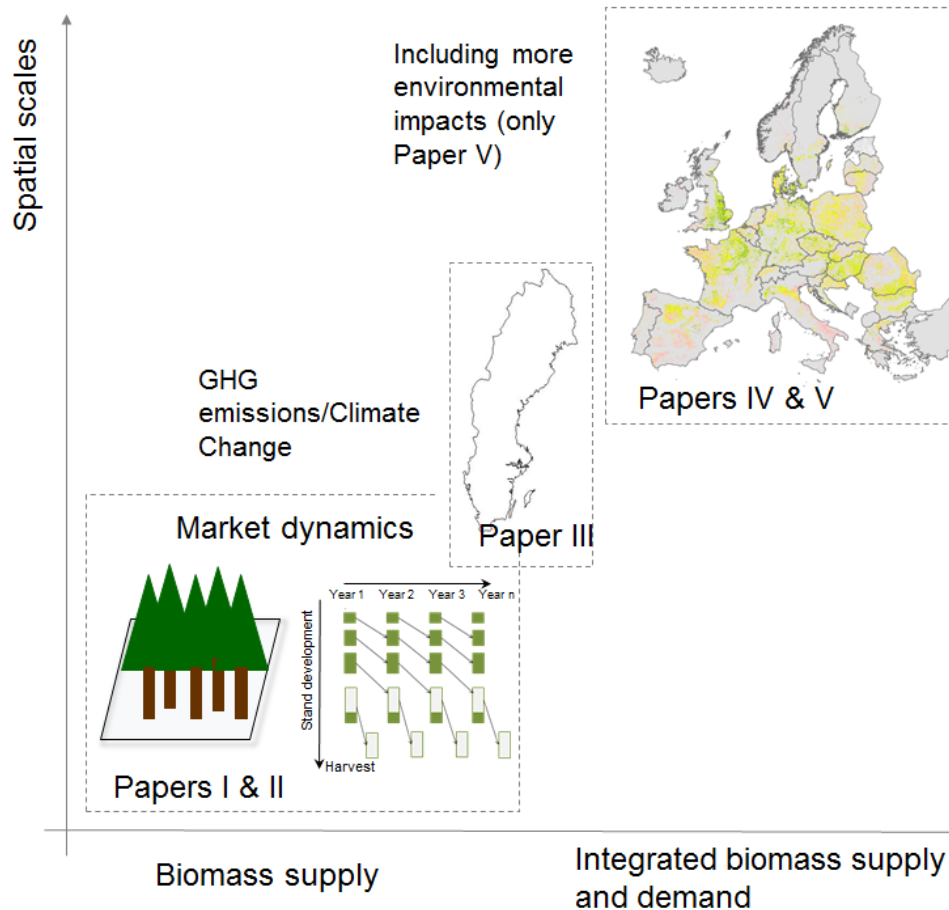

Figure 1: Scope of the different papers included in the thesis.

2 -   Background

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2.1   The role of bioenergy in climate mitigation

Biomass production through photosynthesis is part of the carbon cycle. In Figure 2 (based on IEA Bioenergy, 2010), the biosphere, consisting of the terrestrial biotic pool and the soil organic carbon (SOC) pool, exchanges CO_2 with the atmosphere. Atmospheric CO_2 can be assimilated into the biosphere via photosynthesis. Biospheric carbon can be released back into the atmosphere via plant respiration or converted into SOC. SOC can be released to the atmosphere by soil respiration. In contrast to this cycling between the biosphere and atmosphere, burning fossil fuels increases the amount of CO_2 in the atmosphere by releasing carbon that has been stored underground for millions of years.
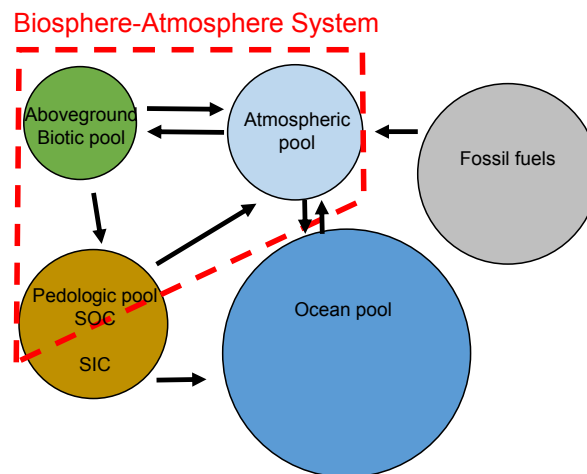
Figure 2: The carbon cycle. The five principal carbon pools and fluxes between them, based on IEA Bioenergy (2010). SOC = soil organic carbon pool, and SIC = inorganic carbon pool.

Land use and biomass extraction for the purpose of providing bio-based products affect the biospheric carbon stock, temporarily perturbing the balance between the atmosphere and biosphere, but they do not increase the total amount of carbon stored in the biosphere-atmosphere 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. Studies have often neglected this carbon imbalance and assumed that bioenergy systems are CO_2-neutral. The "carbon neutrality" assumption is based on the carbon released from biomass combustion previously having 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 LUC 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 whereby these emissions are reported as changes in carbon stock in the forest and placed in the LUC 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 lignocellulosic bioenergy (i.e., forest and agricultural residues, and lignocellulosic crops, which are the focus of this thesis) (JRC, 2013) make bioenergy seem like an attractive option for displacing fossil fuels in energy systems. Nevertheless, there is concern that promotion of bioenergy by policy interventions that do not consider the biospheric carbon fluxes could lead to the overexploitation of biomass resources, including biomass from long-rotation forestry[4] (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 determining 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 effects of bioenergy are often presented by comparing biosphere/atmosphere carbon fluxes with fossil fuel emissions. Some of these studies find that the carbon benefits of using forest biomass for bioenergy will only arise after several decades and that bioenergy implementation will (temporarily) contribute to increased warming (e.g., Sterman et al., 2018). In fact, a review by Bentsen (2017) reveals that the point in time when bioenergy brings climate benefits can vary by up to 200 years among the reported studies that lend themselves to comparisons. To summarize, there is a need to better understand the role of forest bioenergy in the climate change context and the reasons why studies arrive at different conclusions.

2.2   Biomass availability and impacts associated with biomass mobilization

Ecosystems provide multiple services, including not only biomass production and carbon storage, but also habitats for a range of species supporting biodiversity conservation, water purification, and soil stabilization, among other services. An increase in biomass production and extraction to meet an increasing demand for bioenergy will generate conflicts among different ecosystem services, and the conflicts need to be considered when promoting bioenergy. The extent to which biomass will contribute to energy supply

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[4] In this thesis, long-rotation forestry refers to trees that need 80 or more years to grow before harvest.

will be determined by what society can accept from an environmental and socioeconomic point of view with regard to the impact on ecosystems.

The potential contribution from residues (from forest and agricultural activities[5]) depends on existing and anticipated economic activities, i.e., demand for timber and food (Slade et al., 2014), and sustainability constraints for residue removals (Batidzirai et al., 2012; Dornburg et al., 2010). Residue removals could lead to nutrient loss, soil degradation, and other disturbances, which affect ecosystem services in different ways. Negative effects on water quality and biodiversity are sometimes an extension of the effect caused by timber and food production (cf. Berg et al., 1994; Pang, 2017; Thompson et al., 2011), while the effects on soil quality and future wood and crop production are directly associated with residue extraction (Egnell, 2017; Persson & Egnell, 2018). There are, however, ways to compensate for the negative impacts of removing residues, for instance, by ash recycling or fertilization, or by restricting extraction by quality type and site conditions (Ranius et al., 2018).

The potential contribution from energy crops is more uncertain and mainly depends on land availability and crop yields (Batidzirai et al., 2012; Berndes et al., 2003; Marland & Obersteiner, 2008; Slade et al., 2014). Land availability for energy crops is influenced by land requirements for meeting current and future demand for food, feed, and bio-based materials (e.g., pulp and paper, timber, bio-chemicals), as well as the need to protect land for conservation. There is high agreement that increasing land productivity (e.g., increasing food crop yields or intensifying grazing density) would result in a greater potential for energy crops. Similarly, the possibility of planting energy crops on land that is less suitable for food crops would increase the energy potential (Batidzirai et al., 2012; Nijsen et al., 2012). Planting perennial lignocellulosic crops (e.g., miscanthus, switchgrass, willow, and poplar) on low-productive land (i.e., degraded and marginal land[6]) has been proven to be economically viable (Dees et al., 2017). Thereby, emissions associated with food and feed production reoccurring in new locations, a form of indirect land use change (iLUC), may be reduced.

The introduction of lignocellulosic crop production on existing cropland can reduce negative environmental impacts from current agricultural activities (e.g., reduce soil erosion and flooding risk and improve potential carbon storage and water quality (e.g., Holland et al., 2015; Smeets et al., 2009) or even increase other ecosystem services (enhance biodiversity). Additionally, lignocellulosic energy crops are associated with lower GHG emissions (JRC, 2013). On the negative side, as with other types of crops, water scarcity can limit the expansion of lignocellulosic crops and restrict the types of crops possible to cultivate (Jans et al., 2018).

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[5] Other organic waste and residues, such as dung and food industry waste, are not considered in this thesis.
[6] Degraded land: land with long-term reduction in ecosystem services due to disturbances that cannot recover unaided. Marginal lands: land that is not cost-effective for food and feed production under current conditions. (Wicke , 2011)

3 - Overview of related research

This chapter is divided in three parts. The first covers literature on the climate consequences of establishing bioenergy systems, specifically focusing on carbon balances and land use. The second presents studies on estimating biomass availability and consequences of mobilizing biomass. The final section explains the contribution of the thesis to the current literature.

3.1 Evaluating the climate effects of forest bioenergy: Methodological options

The carbon balances and GHG-mediated climate effects of land use for forest bioenergy can be evaluated using different methodological approaches, including different spatial (see Table 1) and temporal system boundaries. Below, it is shown how quantifications of carbon balances can differ depending on the methodological approach used.

3.1.1 Spatial system boundaries

Studies of forest-based products can either focus on specific products or the forest system itself. 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. Following this logic, forest losses due to harvesting of biomass need to be attributed to the use of a particular forest product. This can be interpreted as an attempt to identify products with their localized impacts and specific forest operations and typically relies on 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), instead typically relying on landscape assessments.

Carbon balances associated with land use for establishing bioenergy systems (in forests managed for productive purposes) are commonly investigated using assessments at the stand or landscape (for an overview, see Berndes et al., 2013; Lamers and Junginger, 2013), and with different scopes (e.g., market mechanisms may or may not be included). The scale of analysis (see Table 1) affects assessments of carbon balances, as further discussed in Sections 5.1.1 and 5.1.2. Below, the different spatial scales are discussed.

Table 1: Spatial system boundaries for forests managed for productive purposes.

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 • **Conceptual Landscape** • **Real landscape**	A mosaic of forest stands managed coordinately to supply a continuous flow of wood. • A landscape generated by combining identical stands of varying age, i.e., with homogeneous site quality and uniform age distribution. • A landscape generated by using data from all the stands within that landscape, i.e., with unequal distribution of stand sizes, ages, species, and natural conditions

Studies that use the stand scale in determining the timing of bioenergy benefits (e.g., Cherubini et al., 2011; Helin et al., 2013; Holtsmark, 2013) acknowledge the carbon neutrality of the rotation period taken as a whole. However, when neutrality is considered at 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, see e.g., Cherubini et al., 2011; Holtsmark, 2013). The authors argue that even though bioenergy from long-rotation forest can be *carbon* neutral, when the stand is managed as it has been historically, it is not *climate* neutral due to the temporal carbon imbalance. These studies often focus on biomass extraction from a single intervention (final felling or thinning) to investigate its effect on the different carbon pools (e.g., trees, soil-and-litter, forest products). Some assessments consider 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., Holtsmark, 2012; 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), taking into consideration the net growth in the forest. Such studies investigate the interrelation between carbon dynamics at the stand level and the effect 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. In landscape assessments, the forest carbon stock will be relatively stable, and the climate effect of a forest system will depend on, e.g., harvest intensity and non-wood products being displaced (see Section 5.1.2).

However, conceptual landscapes are simplifications of real landscapes, which generally have an unequal distribution of age classes and stands of different sizes. Real landscape assessments could present a variety of forest management types to support bioenergy systems with different climate effects 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). Studies that 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 (Lauri et al., 2012; Moiseyev et al., 2011), 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 toward more intensive forest management in order to increase forest production in the long run (Miner et al., 2014). Verkerk et al. (2014) found that an increasing demand for energy and materials in the EU will increase the pressure on protective areas. Forest expansion or competition with other wood products can also lead to displacing products elsewhere (i.e., indirect LUC, iLUC, cf. Agostini et al., 2013).

Another type of study presents 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). These studies can be used to provide information about how different forest management systems can contribute to national targets. They typically capture the long-term mitigation effect of the carbon stored in long-lived products that were harvested earlier. However, the effect of specific interventions or products on the different carbon pools becomes less clear in such studies, along with their interconnections.

3.1.2   Temporal system boundaries and climate metrics

The climate impact associated with forest bioenergy can be assessed by using different metrics that can represent different temporal system boundaries. The choice of metric and time horizon depends on the objective of the study and can affect conclusions on the climate effects of bioenergy systems, cf. Sedjo (2011), as further discussed in Section 5.1.3. Below, different metrics are discussed.

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 and typically including at least one rotation period. Other studies, instead of including full rotation periods, have focused on estimating the point in time when a bioenergy system delivers carbon benefits relative to fossil fuels, cf. "carbon debt" (Fargione et al., 2008), "carbon payback time" (Gibbs et al., 2008; Madsen & Bentsen, 2018), and "carbon parity point" (e.g., Agostini et al., 2013; Nabuurs et al., 2017).

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) over a certain time period 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 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 used for the accounting under the Kyoto protocol. However, the GWP has been criticized as arbitrary and lacking a meaningful climate impact representation (Fuglestvedt & Berntsen, 2013; Peters et al., 2011).

Some studies avoid the arbitrary time frame and uncertain climate impact representation by using other metrics that can be expressed over time and evaluate cumulative warming or temperature increase, which can be directly linked to temperature targets. 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; Hammar et al. (2015); Ortiz et al. (2016) use global mean surface temperature change (ΔT) for the same purpose; and Ericsson et al. (2017) and Porsö and Hansson (2014) use ΔT to evaluate willow-based energy systems. 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. These metrics (Cherubini et al. 2011; Cherubini et al. 2013a) are derived using specific pulse emissions representing distinct bioenergy systems instead of using pulse emission for CO_2; therefore, they are only relevant for the bioenergy systems for which they were defined, limiting their use.

The previous metrics can be used for different geographical scopes and do not consider the need to stay within a certain climate limit, but others, such as the carbon budget, caps emissions at global or national scales. A cumulative global "carbon budget" in line with the 2-degree limit has been proposed to be more robust and easier to implement as a policy target than emissions-rate or concentration targets (Allen et al., 2009). The global carbon budget concept is based on that peak warming appears to be insensitive to the CO_2 emissions pathway. In other words, from the perspective of temperature targets, the exact timing of the CO_2 emissions is not so important; the cumulative CO_2 emissions are what matter (Allen et al., 2009; Knutti & Rogelj, 2015; MacDougall et al., 2015; Matthews et al., 2009; Meinshausen et al., 2009; Zickfeld et al., 2009). How the CO_2 budget should be distributed among countries is subject to debate and different arguments have been proposed, e.g., equal per-capita emissions (cf. Raupach et al., 2014). Questions regarding how to allocate the global budget, and the difficulties for governments in controlling their nation's share, present challenges. For instance, a cumulative budget does not map directly onto short-term emissions targets (Victor, 2009). Some studies have compared allocated budgets with national fossil emissions (e.g. Gignac and Matthews, 2015; Peters

et al., 2015). Others have considered LU and LUC emissions to evaluate how the forest sector contributes to achieving certain targets, or even how different forest strategies can contribute to national emissions targets (Burschel et al., 1993; Kallio et al., 2016; Lobianco et al., 2016). The latter studies, however, were not designed to comply with the global carbon budget nor to align with the 2-degree target.

The metrics described above are employed to assess long-term temperature targets and give equal weight to emissions regardless of the time of emission. In addition to long-term climate consequences, there are critical thresholds, so-called tipping points, which, if crossed, would lead to irreversible consequences (Galaz et al., 2016; Lenton et al., 2008; Nuttall, 2012; Russill, 2015), e.g., disappearance of the arctic summer sea ice or dieback of the boreal forest (Lenton et al., 2008). The likelihood of passing a tipping point is mainly linked to cumulative warming (Kirschbaum, 2014). For instance, Jørgensen et al. (2014) applied the Climate Tipping Potential (CTP) metric to bio-based products to assess their mitigation potential considering the urgency of not exceeding certain climate limits. The CTP expresses the cumulative impact of a marginal GHG emission from the time of emission to the time of reaching the limit, with the impact increasing as the limit is approached. However, there are many uncertainties associated with tipping points, and it is difficult to confidently derive probabilities of crossing them (Kirschbaum, 2014). They have therefore not been included in the thesis.

3.2 Evaluating biomass availability and consequences of biomass mobilization for energy: methodological choice

Biomass availability depends on sustainability aspects that are typically considered by defining constraints. Studies use different methods and approaches for this, with varying scopes, level of sophistication, assumptions, and system boundaries, all of which affect the results.

Resource-focused (bottom-up) assessments generally investigate biomass availability considering bio-physical and environmental constraints as well as competition among biomass resources and other land uses (Batidzirai et al., 2012; Berndes et al., 2003). Such studies use statistical analysis of empirical or modeled data, which can be combined with spatially explicit data to account for land use and site specific environmental and social constraints (Batidzirai et al., 2012). Examples of non-spatially-explicit studies in Europe include, for instance, Verkerk et al. (2011)'s estimate of woody biomass potential and Fischer et al. (2010)'s quantification of land availability for energy crops. Geographic information system (GIS) studies include biomass potentials from agricultural residues (see e.g., Haase et al., 2016; Monforti et al., 2013; Monforti et al., 2015 at 1000 m resolution); forest residues (e.g., Díaz-Yáñez et al., 2013 at the NUTS2 level), or the potential supply from energy crops (e.g., Schueler et al., 2013 at 2 min resolution).

Other types of GIS-based studies analyze biomass supply in relation to biomass demand to investigate the cost of mobilizing biomass. Some of these studies estimate biomass potentials from a ranges of sources at a rather coarse resolution (NUTS 2/ NUTS3 level),

in combination with techno-economic models to consider the entire potential biomass demand in the EU (Böttcher et al., 2013; Elbersen et al., 2013; Lamers et al., 2014; Ramirez-Almeyda et al., 2017). Assessments at higher resolution, including the location of end-use facilities and transport networks, can provide a more comprehensive understanding of to what extent available biomass is accessible and profitable for energy production. These studies, rather than focusing on the entire biomass demand, typically evaluate supply chains associated with specific biomass conversion pathways/sectors (e.g., Nord-Larsen and Talbot, 2004; Wetterlund et al., 2012). Some studies use existing infrastructure for biomass conversion (e.g., Nord-Larsen and Talbot, 2004), while others site new biomass conversion plants based on where resources are more densely located (see e.g., Monforti et al., 2013; Monforti et al., 2015 at 1000 m) and transportation is cost-optimal (e.g., Gonzales and Searcy, 2017, at 1 mile, de Jong et al., 2017b and Wetterlund et al., 2012 both at a resolution of half a degree). Still, the higher-resolution analyses found in the current literature did not account for biomass supplies from different land-use alternatives nor include supply-side responses (e.g., introducing energy crops) as a result of an increasing demand for bioenergy.

Some of the above-mentioned studies limit the extraction of residues by defining geographically explicit ecological constraints, based on, e.g., soil organic carbon (see e.g., Monforti et al., 2015) and risk of soil erosion (Di Fulvio et al., 2016; Haase et al., 2016), while others assume a fixed rate of residue extraction (cf. de Jong et al., 2017a). For establishing energy crops, some studies restrict suitable areas based on, e.g., RED: avoiding areas with high biodiversity value or high carbon stock (Ramirez-Almeyda et al., 2017); reducing direct GHG emissions from carbon stock changes (e.g., Schueler et al., 2013); and/or emissions from iLUC (from forest or grassland to agricultural lands for rotational arable corps) (Elbersen et al., 2013; Böttcher et al., 2013). Additionally, the selection of crops is often based on suitability aspects, for instance, climate and soil conditions (e.g., Ramirez-Almeyda et al., 2017).

Considering not only constraints to avoid negative impacts but also opportunities to mitigate current environmental impacts or even to provide benefits, is equally important (Dauber et al., 2012). The consequences of establishing energy crops for biodiversity and other ecosystem services mainly depend on the type of energy crop and the previous land use (Pedroli et al., 2013). Some studies have identified environmental benefits when converting from intensive cultivated crop to perennials (Berndes et al., 2008; Dauber & Miyake, 2016; Holland et al., 2015; Milner et al., 2016; Pedroli et al., 2013). Others have mapped negative impacts on soils (e.g. Lugato et al., 2017) or the possibility of potential improvements on agricultural land (e.g. Lugato et al., 2014a; Lugato et al., 2014b). These studies can be used as a basis for evaluating opportunities for improving ecosystem services associated with planting energy crops. Few studies were found that combine spatially explicit mapping of biomass demand sources with mapping of opportunities for establishing energy crops in ways that help reduce existing environmental impacts. Examples include explorative studies that apply relatively coarse geographical resolution or restricted geographical scope (e.g., Berndes et al., 2004). Linking this data with

biomass supply-and-demand modeling will benefit assessments of lignocellulosic energy crop expansion and bridge the literature on negative and positive associated impacts (Robledo-Abad et al., 2017).

3.3   Contribution of the thesis

This thesis contributes to the existing literature in three main ways:

Choice of methodology strongly influences the divergent conclusions reached by studies that assess carbon balances associated with forest-based fuels. In **Papers I-III**, we bring together approaches and perspectives from different fields to bridge the gaps among methodological choices in order to improve the 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 investigate 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, providing a proof of concept for forest bioenergy assessment based on carbon budgets (**Papers I** and **III**).

The literature includes studies carried out at the national level to understand the role of forests and forest products in achieving national climate targets. In this context, **Paper III** contributes by highlighting the relevance of forest management and by placing Sweden's emissions in the context of a global carbon budget and the 2-degree limit.

The literature review shows that studies have been conducted to match biomass supply and demand at the EU level, although typically at a fairly coarse resolution and only including one supply option (forest residues or agricultural residues), and excluding the potential LUC associated with introducing energy crops. There is a need for assessments to consider different feedstock supply options and associated impacts. In **Papers IV** and **V**, we present and demonstrate a methodology for matching supply and demand at a resolution of 1000 m, providing geographically explicit information on (i) plant-gate supply cost; (ii) CO_2 savings; and (iii) LU, LUC, and potential mitigation effects resulting from the introduction of energy crops on cropland.

4 -   Method and design of analyses

Table 2 provides an overview of the modeling framework and design of each of the studies included in this thesis. Two modeling frameworks are used to investigate the research questions (see Section 1.1). **Papers I-III** use various modeling approaches to quantify carbon balances and net GHG savings of using biomass products to displace fossil fuels. **Papers IV** and **V** develop a spatially explicit modeling framework to assess and balance biomass supply and demand. Both forestry/agricultural residues (**Papers IV** and **V**) and lignocellulosic crops (**Paper V**) are considered and plant-gate supply costs estimated.

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

Paper	Aim (short version)	Spatial scope	Temporal scope	Model focus	Approach	Indicator for environmental impact	Output
I	Describes how methodological choices and assumptions influence the climate effects of Swedish forest bioenergy	-Forest stand -Conceptual forest landscape -Real landscape in Sweden	300 years	Carbon balances including carbon stock changes, end of life of forest products, and avoided fossil carbon emissions.	- Bottom-up resource-focused (Stand and conceptual landscapes) - Bottom up + economic optimization of forest management + Forest products	Carbon balances and GHG emissions	Carbon stock changes, cumulative radiative forcing, global temperature change
II	Assesses carbon dynamics at the stand and landscape level, and for landscapes with varying market developments for forest products	-Forest stand -Conceptual forest landscape -Real landscape in Sweden	Present-2100	Carbon balances including carbon stock changes, end of life of forest products, and avoided fossil carbon emissions.	- Bottom-up resource-focused (Stand and conceptual landscapes) - Bottom up + economic optimization of forest management + Forest products	Carbon balances and GHG emissions	Cumulative carbon emissions
III	Evaluates the role of the Swedish forest in low-carbon scenarios	Swedish National Forest Landscape	Present-2100	GHG emissions associated with different forest management and energy scenarios	- Bottom up + economic optimization of forest management + Forest products	Carbon balances and GHG emissions	GHG emissions, global temperature potential, Swedish carbon budget
IV	Matches (availability and cost) forest and agricultural residue supplies with demand for co-firing in the EU	EU + Norway and Switzerland (1000 m resolution)	Present-2040 (demand)	Matching forest and agricultural residues with localized demand for co-firing	Bottom-up spatially explicit analysis integrated with localized demand	CO_2 emissions	Biomass demand being met, supply cost (at the plant gate), and CO_2 savings
V	Matches (availability and cost) forest and agricultural residues as well as lignocellulosic energy crops with demand for bio-electricity and biofuels	EU + Norway and Switzerland (1000 m resolution)	-	Matching forest and agricultural residues as well as lignocellulosic energy crops with localized demand for bio-electricity and biofuels	Bottom-up spatially explicit analysis integrated with localized demand	-Soil erosion -SOC -Diffuse N -CO_2 emissions	Biomass demand being met, supply cost (at the plant gate), and CO_2 savings

4.1 Climate effect of bioenergy

Figure 3 describes the modeling framework 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 product 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.
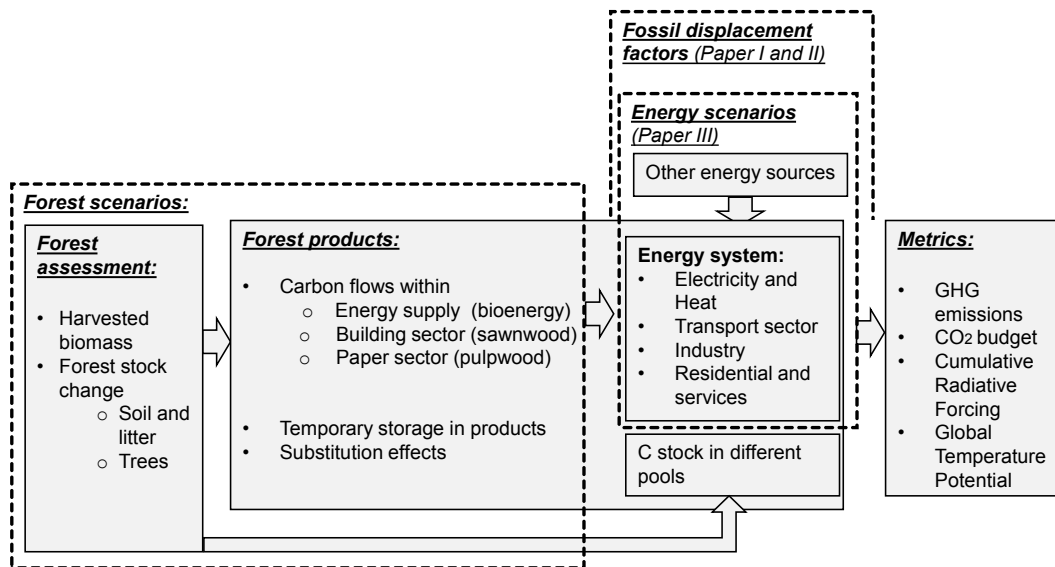

Figure 3: Modeling framework description. Forest assessments are performed with the Q model and Heureka or Hugin. Forest products assessments are performed with CAfBio 1.0 or CAfBio 2.0 (adapted from Figure 1 in Papers I and III).

The modeling framework is used to assess scenarios with respect to forest management and harvest intensity. For each scenario, the forest bioenergy supply and the associated carbon stock changes in forest pools (tress and soil-and-litter) and forest products are quantified on an annual basis (Figure 3). In **Papers I** and **II**, forest bioenergy is assumed to displace fossil fuels, whereas in **Paper III**, the forest bioenergy supply is modeled to meet bioenergy demand in national energy scenarios, and the displacement effect is inherent in each scenario. **Papers I** and **II** consider the emissions associated with avoided fossil fuels, and **Paper III** considers emissions from the entire energy system.

In **Papers I** and **II**, results are presented in terms of net effects—comparing a reference with a bioenergy scenario—in order to show the consequences of establishing bioenergy systems. In **Paper III**, results are presented in absolute terms to describe the role of the forest sector in national scenarios that comply with energy and climate policy goals. Results are 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 an estimated national carbon budget.

4.1.1 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 1). 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 were used (for more information see the appended papers):

i The Q model for assessments of forest stands and conceptual landscapes. 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 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 (see Figure 4).
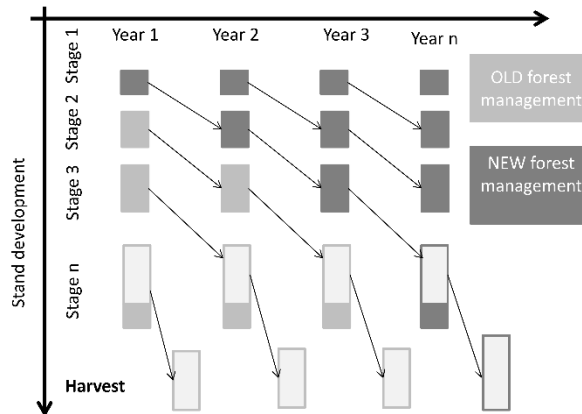

Figure 4: Conversion from one forest management regime to a new one in the forest landscape (adapted from Figure 2 in Paper I). The forest landscape is built by combining time-shifted single stands to obtain a uniform age distribution at the landscape level. The landscape is assumed to have a homogeneous 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. 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.

ii The PlanWise model for assessments of real forest landscapes in Sweden. The Heureka PlanWise software (Wikström et al., 2011) is used in **Papers I** and **II** to quantify the carbon balances of landscapes subject to different management planning depending on different demands for forest products. 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).

iii The HUGIN model for national landscape assessments. HUGIN (the old version of PlanWise) (Lundström & Söderberg, 1996) is used in **Paper III** to quantify forest carbon stock changes and volume of harvested biomass for different levels of sustainable harvesting at the national level. 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 for a wide range of management alternatives.

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.

4.1.2   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. 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 was 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 were 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 was 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.

4.1.3 Climate metrics

(1) Cumulative radiative forcing and absolute global temperature potential

Results in **Paper I** are presented in terms of CRF and AGTP. These were 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.

(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., for addressing 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 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 5a 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 global emissions per capita by using the global population prospects by DeSA (2013) (see Figure 5b 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 are distributed proportionally per capita (see Figure 5b 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 5a 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.

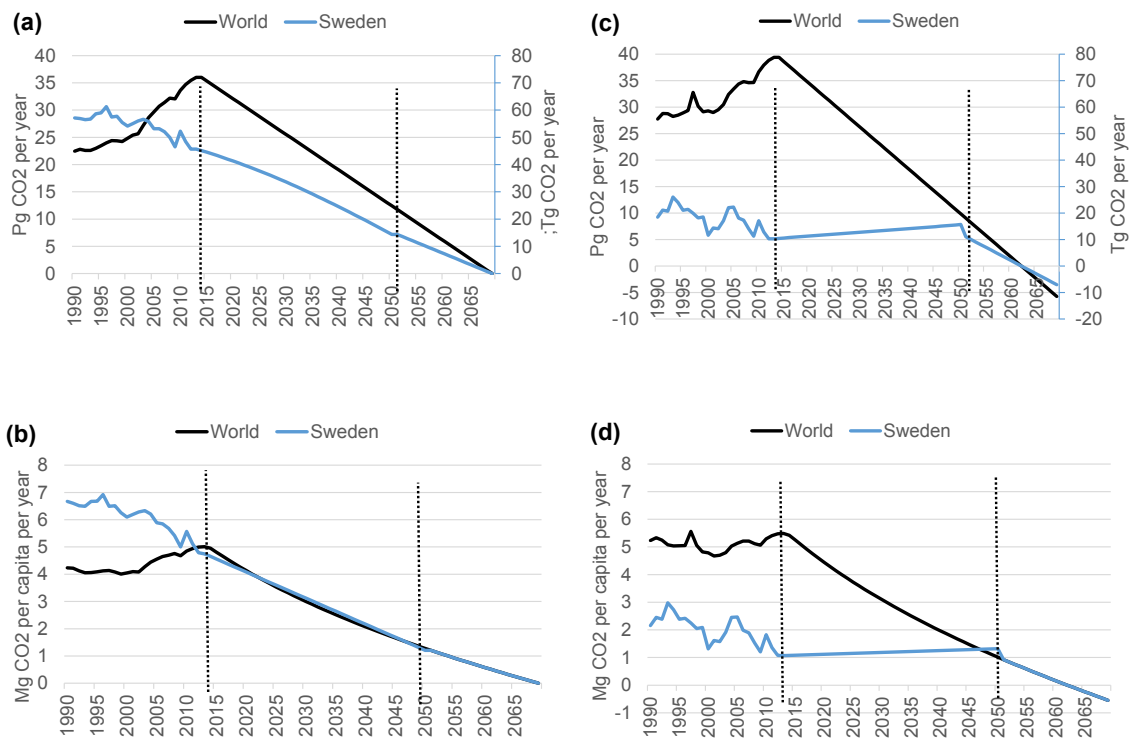Figure 5: Global and Swedish emissions following a linear decrease to zero and a convergence year (to reach equal per capita emissions) in 2050 when considering a) total fossil CO_2 emissions; b) per capita fossil CO_2 emissions; c) total CO_2 emissions from fossil fuels, forest management, and LUC; and d) per capita CO_2 emissions from fossil fuels, forest management, and LUC. Based on Gignac and Matthews (2015).

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 are distributed proportionally based on country population size and equal per-capita emissions (Neumayer, 2000) (see differences between the global and Swedish per capita emissions in Figure 5).

The resulting CO_2 budgets are presented in **Paper III**. 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 5b. 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, which significantly reduces Swedish emissions per capita to below the world's average emissions per capita, see Figure 5d.

4.2 Geospatial supply-demand modeling of lignocellulosic biomass for bioenergy in the EU

4.2.1 GIS-based analytical framework for biomass supply-demand modeling

Figure 6 shows the geographically explicit modeling framework developed and used in **Papers IV** and **V** to assess the availability and cost of lignocellulosic biomass in relation to specific localized biomass demands in the EU-28, Norway, and Switzerland. The framework combines a biomass demand module, a biomass supply module, and an integration module in which biomass supply and demand are matched at the lowest supply cost.

The **biomass demand module** provides estimates for different bioenergy development pathways, bioenergy output and associated demand for biomass, as well as the CO_2 emissions saved by displacing fossil fuels. In all pathways, biomass is assumed to be converted in coal power plants: either as biomass co-firing with coal (**Paper IV**), conversion from coal-based to bio-based electricity production or transformation from coal-power plants to bio-oil units to produce feedstock for refineries (**Paper V**). Coal power plant data are taken from the Chalmers Power Plant Database for Europe (CPPD) (Kjärstad & Johnsson, 2007), which is continuously updated and includes data on e.g., geographic coordinates, net power capacity, construction date, fuel type, and boiler type.
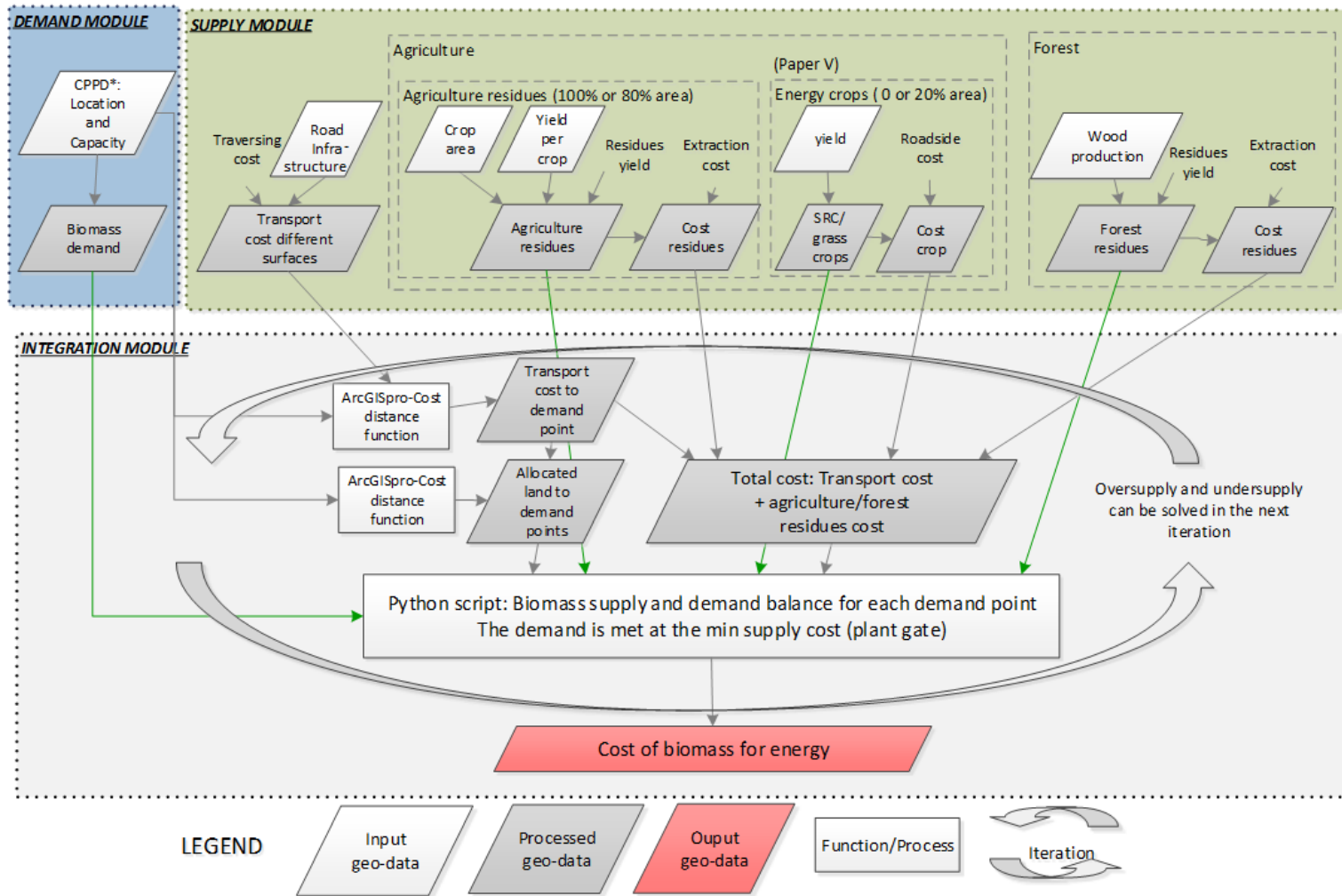
Figure 6: Modeling framework used in Paper IV and V.

The **biomass supply module** covers forest and agricultural residues (**Paper IV**), and cultivation of lignocellulosic energy crops on agricultural lands (**Paper V**), along with the roadside supply cost, which includes costs for extraction, collection, treatment, and transport to the roadside.

Total and harvestable volumes of forest and agricultural residues, and the amounts available for energy after considering competing use ("residue supply potential"), are estimated. Agricultural residues include residues from the major cereals (wheat, rye, barley, and maize), root crops (sugar beets), and oil plants (rapeseed and sunflower). The agricultural residue supply potential is estimated using geographically varying generation rates for residues and extraction rates (depending on topsoil and based on Haase et al., 2016), and deducting the amount needed for other purposes (straw for bedding based on Einarsson & Persson, 2017; Haase et al., 2016). Forest residues consist of tops and branches from forest thinning and final felling. Stumps and forest industry byproducts are not considered. The forest residue supply potential is estimated using geographically varying residue generation rates (Daioglou et al., 2016; Verkerk et al., 2015) and assuming that 28% of tops and branches can be extracted, based on de Jong et al. (2017a). The roadside supply costs are calculated at the country level using country-specific conversion factors based on labor costs and price indices, see **Paper IV** for further details.

Total biomass supply from energy crops is calculated based on the assumption that the crops can be established on up to 20% of the cropland cell. Two different types of energy crops are included: short rotation coppice (SRC, characterized using the properties of willow and poplar) and generic grass crops (characterized based on switchgrass and miscanthus). Biomass supply potentials from energy crops are estimated using geographically varying yield and roadside cost data (Ramirez-Almeyda et al., 2017), see **Paper V** for further details.

Emissions from carbon stock changes are not included in the analyses (see **Paper IV** for further explanation), and only GHG emissions associated with the supply chain of energy crops, mainly associated with the use of fertilizers in the cultivation phase, are considered.

The **integration module** models the biomass supply within certain transport distances (maximum 300 km) to match the biomass demand in the individual power plants, at the lowest supply cost, taking into account the costs of harvesting, treating, and transporting biomass to the power plant gate. This process is repeated for each plant and iterated as long as there are plants with unmet demand and local sources with unutilized supply. The transport cost is optimized in each iteration. In **Paper V**, which allows energy crops, the use of residues is prioritized over dedicated energy feedstock. The current land use is prioritized so residues, if sufficient within the allocated area to meet the demand for that plant, are used first; otherwise, energy crops are assumed to be established on 20% of each of the allocated cropland cells, so they could be used to meet the demand.

4.2.2 Mitigation of current negative land-use impacts

The prospects for mitigation of selected environmental impacts through introduction of perennial lignocellulosic bioenergy plantations in agricultural landscapes is investigated based on the results from the biomass supply-demand matching in those areas where bioenergy feedstock cultivation is needed as a complement to residues to meet the demand. The information on the locations of the required energy crops is combined with GIS-based mapping illustrating four levels of expected effectiveness in mitigating negative environmental impacts by introducing perennial lignocellulosic bioenergy plantations, taking into account both the severity of environmental impacts and the extent of annual crop cultivation in the landscape (annual crop density) (Englund et al., 2018). The following impact categories are considered: (i) soil loss due to water and wind erosion; (ii) diffuse nitrogen emissions to water; (iii) declining soil organic matter (soil organic carbon, SOC, status); and (iv) impacts associated with recurring floods, see (Englund et al., 2018).

5 -   Results and discussion

The results presented and discussed in this section are based on **Papers I-V**. They are described and organized according to each research question; some results are taken directly from the papers while other results are only presented in this introductory essay.

5.1   Land use and carbon balances

Research question 1: To what extent can methodological choices and assumptions about critical parameters affect the outcome in assessments of land use, (forest biomass) carbon balances, and climate effects, and how should they be considered?

5.1.1   Land use and carbon balances at different forest scales

How does the choice of spatial scale in analyses affect results and conclusions concerning forest carbon balances of forest bioenergy, and what scale is most relevant in a specific context?

Papers I and **II** find that the scale chosen for the carbon balance assessment affects the assessment output, contrary to the conclusion in Cherubini et al. (2013b) that different scales yield the same results.

<u>At the stand level</u>, the carbon emission dynamics are given by a pulse of emissions at the time biomass is harvested and used for bioenergy. Emissions increase as more biomass is harvested and used for energy, when the carbon in forest biomass is 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 7a). Meanwhile, <u>at the landscape level</u>, carbon dynamics typically reflect a trend of increasing, decreasing, or relatively stable carbon stocks. The drastic variations in carbon stocks shown at the stand level do not appear at the landscape level because carbon sequestration in some stands balances carbon losses in other stands (Figure 7b).

Figure 7 shows two forest states that can be observed at the landscape level. In a *steady-state* situation, carbon in harvested biomass will be equal to the carbon captured and stored in the forest in the same year. This is illustrated in REF, in which forest carbon pools are stable (Figure 7b). Net carbon fluxes between the biosphere and the atmosphere will be zero if the carbon in the products is released immediately after harvest (see Figure 8a and **Paper II**). The emissions can also be delayed if harvested biomass is used in long-lived products. Figure 7b 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 in harvested biomass from a managed forest *in transition* (i.e., a new harvest level is gradually introduced in the forest landscape, in BIO1) is greater than the carbon added to forest carbon pools the same year as the biomass is harvested. Carbon is transferred from the soil-and-litter pool to the harvested biomass pool (see Figure 7b). Hence, if the only change is that more biomass is extracted and used for bioenergy, there will be an initial period with net carbon losses (compared to REF).
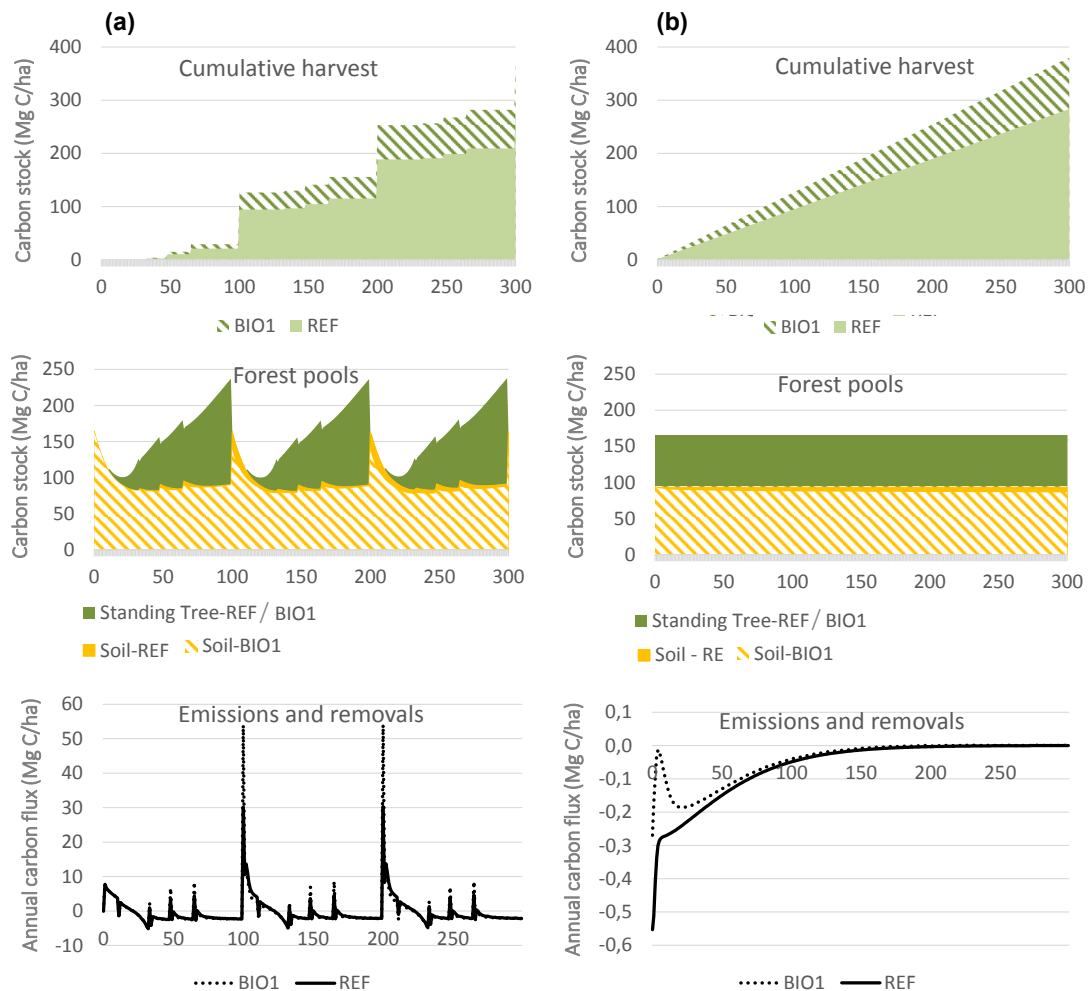

Figure 7: Carbon stock changes and carbon emissions and removals for two scenarios: REF (with only sawnwood and pulpwood production) and BIO1 (as REF, but 80% of the slash is removed to be used as bioenergy) for two forest scales: (a) stand and (b) landscape.

Figure 8 illustrates forest carbon fluxes associated with landscape- and stand-related approaches (e.g., Cherubini et al., 2013b; Holtsmark, 2012; Zetterberg and Chen, 2014). It shows that forest carbon dynamics for the same bioenergy system can differ depending on the approach used. Results from stand approaches can be misleading when they are generalized to represent a constant supply of bioenergy at the landscape level, because they do not capture all the carbon fluxes between atmosphere and biosphere during the whole accounting period (the stand level carbon profile is introduced every year, see **Paper II**). Additionally, when carbon accounting is commenced when biomass is extracted from a forest stand, and it assumes that a new stand is ready to be harvested

every year, there will per definition be an initial carbon loss (i.e., carbon emission). Landscape assessments can also show initial carbon losses (in a transition state, see Figure 8), but these are much lower than the ones that appear at the stand level (for the same amount of harvested biomass).

(a) Reference scenario (steady state)

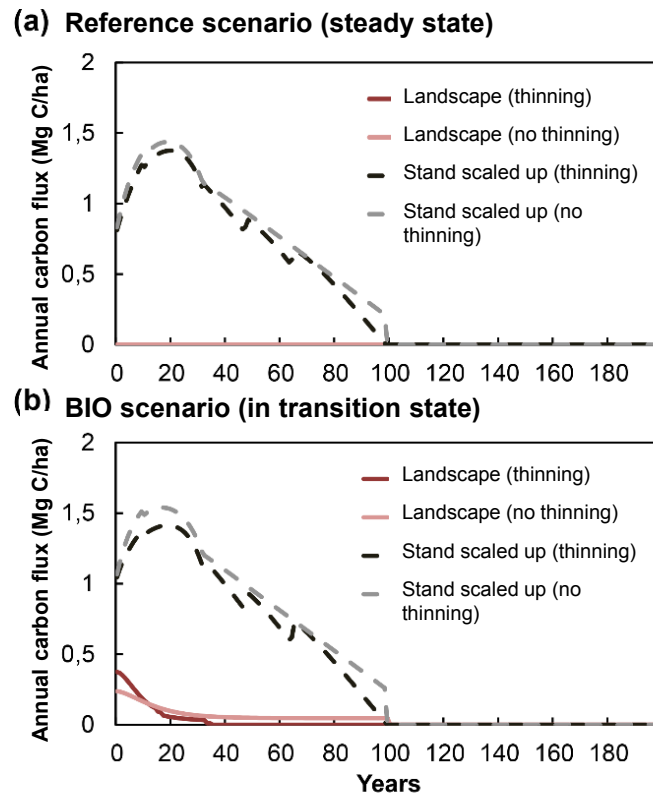**(b) BIO scenario (in transition state)**

Figure 8: Annual carbon flux (carbon emissions less sequestration) using landscape and stand-related approaches, referred to as expanding landscape in Figure 7 in Paper II. The latter represents a situation when a constant supply of forest products is modeled by scaling up the stand pattern, i.e., every year a mature new stand is brought into the system. Reference: theoretical situation in which stemwood is used for bioenergy. BIO: as Reference but 80% of the slash is removed to be used as bioenergy. These scenarios are used to facilitate analyses of the differences between landscape and stand-approaches but they do not reflect the reality in Sweden today.

In contrast, the landscape assessment can capture all carbon flows in the forest landscape throughout the accounting 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; similarly, it can identify unsustainable practices. While stand-level assessments are useful to understand the dynamics between the different forest pools (trees and soil-and-litter) and the effect of distinct operations on these pools (Lundmark et al., 2016; Sathre et al., 2010), the results cannot simply 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 consequences of LUC to produce forest biomass for bioenergy in addition to other forest products.

5.1.2 Conceptual vs. real landscapes and market dynamics considerations

To what extent can market dynamics/demand for bioenergy and other forest products affect the carbon balances of forest bioenergy?

An anticipated increase in demand for bioenergy and/or other forest products can incentivize investments in forest management for increased forest production, which could result in higher or lower carbon stock. The carbon balance effect associated with market dynamics for forest products is analyzed using conceptual and real landscapes (**Papers I-III**) and by comparing bioenergy systems with a baseline reference system for land use and energy production.

Figure 9 shows the difference between several bioenergy systems and a reference system in conceptual landscapes. The carbon balances are shown as stable lines that may generate carbon savings depending on several factors, including the displacement factor (coal and natural gas are reference fuels) and types of harvest residues removed (slash in BIO1 and stumps BIO2). Furthermore, it is important to consider that forest owners, in addition to extracting slash for energy (BIO1), could invest in measures to enhance forest growth (BIO+ scenarios). As shown in the figure, in this modeling such a scenario brings net carbon savings slightly earlier. The carbon savings, which are determined by the pace of implementation of growth-enhancing measures, also increase faster.
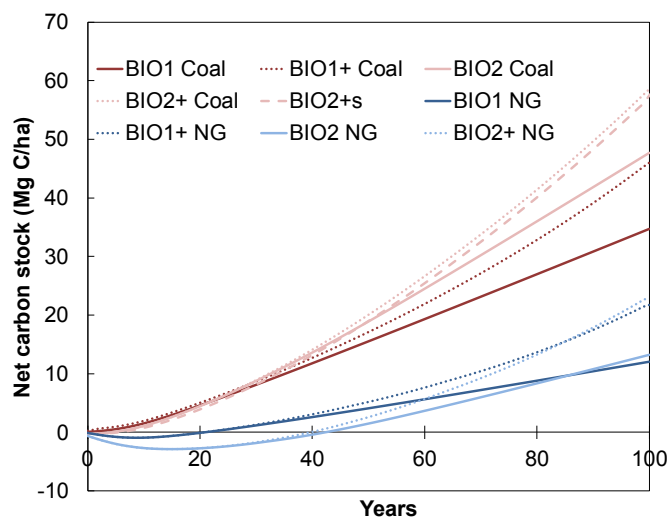
Figure 9: Net carbon stock (BIO-REF) comparison for the forest scenarios, for natural gas (NG) and coal scenarios at the conceptual landscape level (cf. zoom in Figure 5 in Paper I). Each line represents the net difference between the bioenergy-adapted scenario and the reference scenario, BIO1: 80% slash 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.

Real landscapes have an unequal distribution of stand sizes, age classes, species, and natural conditions. Figure 10 shows how the net carbon stock for two different bioenergy systems in the same real landscape depends on the size of the bioenergy demand increase

(given as price signals) and forest owners' responses to such increases in demand. This is in line with Abt et al. (2010); Blennow et al. (2014); Conrad et al. (2011); Philip Davies et al. (2013). In BIO+, a more intensive forestry including higher fertilization[7] and the use of genetically improved seedlings is implemented in response to high prices for bioenergy (higher than in BIO). The forest carbon stock loss due to an increased harvest level (Figure 10a) is outweighed by the combined effect of the extra sawnwood and bioenergy output, so that immediate carbon savings are obtained (Figure 10b).
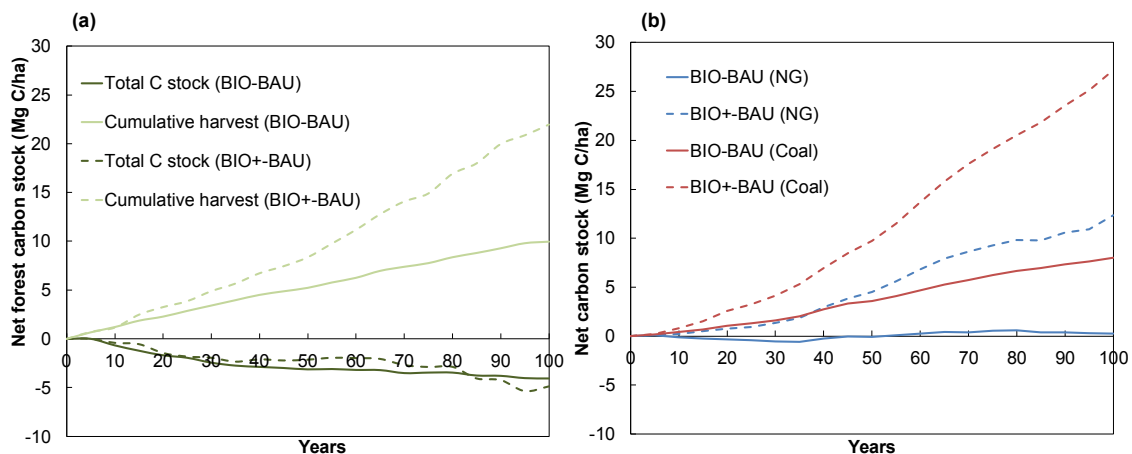

Figure 10: a) Net forest carbon stock (difference between BIOs and BAU) over time in forest pools and cumulatively in the harvested biomass at the real landscape level (adapted from Figure 9 in Paper II); b) Net carbon stock (difference between BIOs and BAU over time, when natural gas is displaced and when coal is displaced (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 all forest products (not only bioenergy) can affect carbon balances. Forest owners adapt forest management planning to current and anticipated markets to maximize their expected economic benefit 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.

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 11b). A slightly decreasing future demand in sawnwood together with an increasing demand in bioenergy will instead result in longer rotation periods and more thinning residues for bioenergy with higher forest carbon stock (**Paper I** and Figure 11a). Ultimately, the net carbon effects depend on the context and

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

nature of price drivers, e.g., whether bioenergy competes due to strong policy support or due to declining pulpwood/sawnwood prices, and, if the latter, whether prices are dropping due to reduction in paper demand or due to competition from other supply regions.
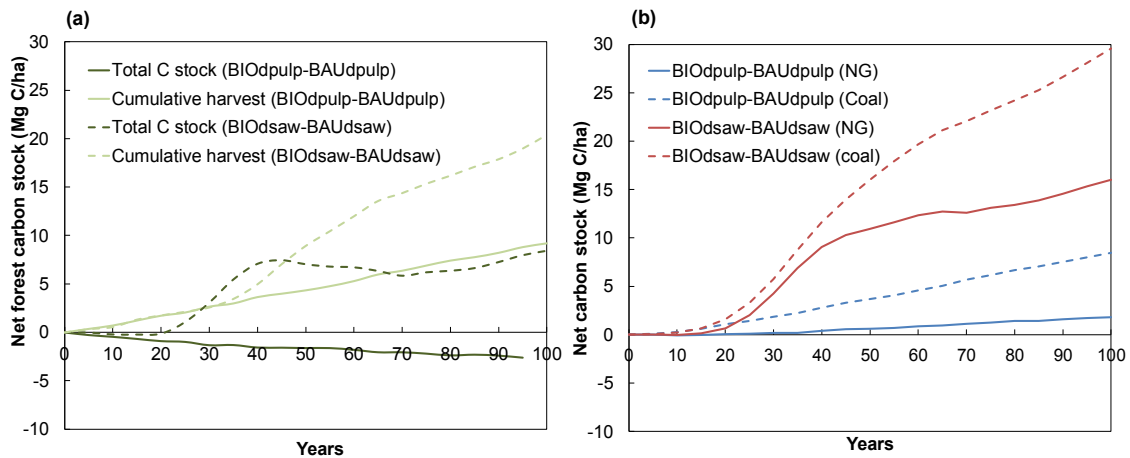

Figure 11: a) Net forest carbon stock (difference between BIOs and BAU) over time in forest pools and cumulatively in the harvested biomass at real landscape level (adapted from and Figure 6 in Paper I and Figure 9 in Paper II); b) Total net carbon stock (difference between BIOs and BAU) over time, when natural gas or coal is displaced (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.

Paper III also shows how market prospects for forest products can induce changes in forest management, affecting carbon balances. All forest landscapes in Sweden are evaluated for different forest management systems. BIO2 illustrates a situation in which the demand for sawnwood products increases, driving forest owners to invest on a more intensive forest management, including increased fertilization and genetically improved plant materials. In such a scenario, the forest biomass supply for bioenergy could cover the total estimated bioenergy demand in Sweden while still enhancing carbon sequestration in the forest—due to increased forest growth and carbon stored in the extra sawnwood products that will take many years before it is released back into the atmosphere (BIO2 vs BIO1 in Figure 11b). BIO2 could also provide biomass available for export or for additional domestic consumption (see Figure 11a, BIO2 forest supply exceeds demand).
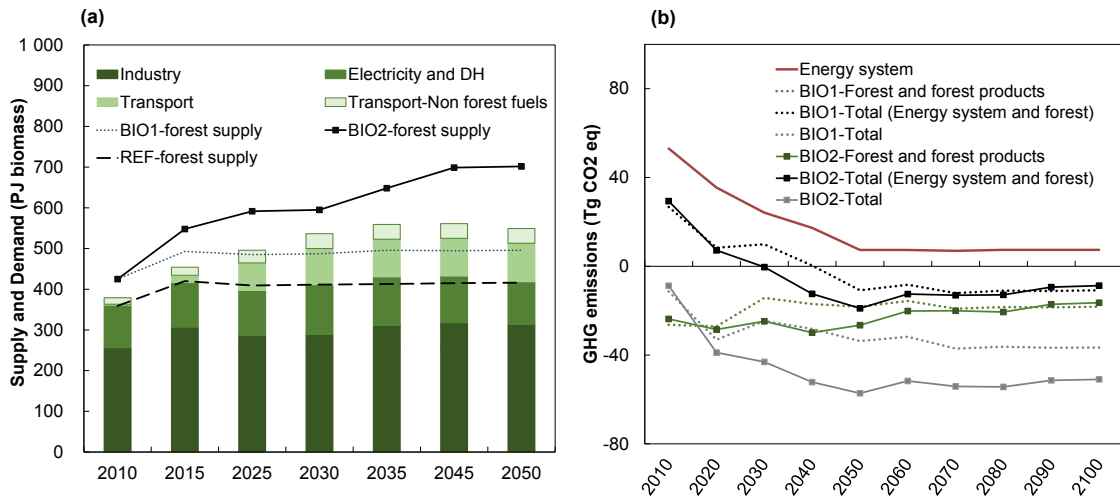
Figure 12: a) Comparison between forest biomass supply (black lines) REF, BIO1, and BIO2 and biomass demand for energy (cf. Figure 5 in Paper III), and b) Net GHG emissions in Sweden with and without considering displacement effects of exported forest products (adapted from Figure 10 in Paper III). Fossil 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; BIO1 as REF but 20% of stumps and 35% slash removal; BIO2: as BIO1 with measures to enhance growth.

All in all, changes in demand for forest bioenergy and other forest products affect land use and carbon balances. Therefore, assessments of bioenergy systems should consider all forest products, all changes in forest management that might occur simultaneously at the landscape level, and total carbon balances (including displacement effects). It is not sufficient to only consider forest stock changes (Lippke et al., 2011, Smyth et al 2017a, 2017b). Furthermore, bioenergy assessments should be complemented with alternative reference scenarios considering market effects for other forest-based products (Buchholz et al., 2014).

These findings highlight that the initial emissions, the so-called carbon debt (Fargione et al., 2008), attributed to establishing forest bioenergy systems and shown in conceptual landscape assessments (Figure 9) can either be present or not (Figure 10 and Figure 11). The carbon debt, rather than being inherent to forest bioenergy, depends on local conditions and forest management choices, among other factors. The carbon-balance difference between conceptual and real landscapes when growth-enhancing measures are implemented can be explained by lower slash extraction rates or faster landscape-wide implementation in real landscapes that results in net carbon savings obtained sooner.

5.1.3 Time dynamics and climate metrics

How do different temporal scales and metrics capture the climate effects associated with forest bioenergy?

In **Paper I**, the climate effect of forest bioenergy is captured by using different climate metrics and how they vary over time, while in **Paper III**, we analyze the role of Swedish forest management in achieving national climate targets and apply the carbon budget concept to place Sweden in the context of the 2-degree limit. With the carbon budget concept, the focus shifts from the timing of carbon sequestration and emissions to whether the scenario complies with a long-term climate target.

In **Paper I**, we find 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 (e.g., displacement factors or the level of harvest residues removed). However, if the results show climate warming effects, these are only temporary and, in most cases, the systems provide good climate mitigation benefits in the medium term (Figure 13). Our results are consistent with those reported by e.g., Hammar et al. (2015); Haus et al. (2014); Ortiz et al. (2016); Sathre and Gustavsson (2011). The mitigation effect of bioenergy increases with long time horizons. The CRF and ΔT figures show earlier benefits of bioenergy use than the carbon stock figure (Figure 9), since other GHGs mainly associated with the upfront emissions of fossil fuels 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. The metrics illustrate the interaction between the different carbon pools (see Figure 2) and the complexity of carbon dynamics that are ignored when GWP with an arbitrary fixed time horizon is used instead (Porsö, 2017). These metrics could also be relevant when including other climate forcings, such as albedo, to allow them to be compared on the same scale.
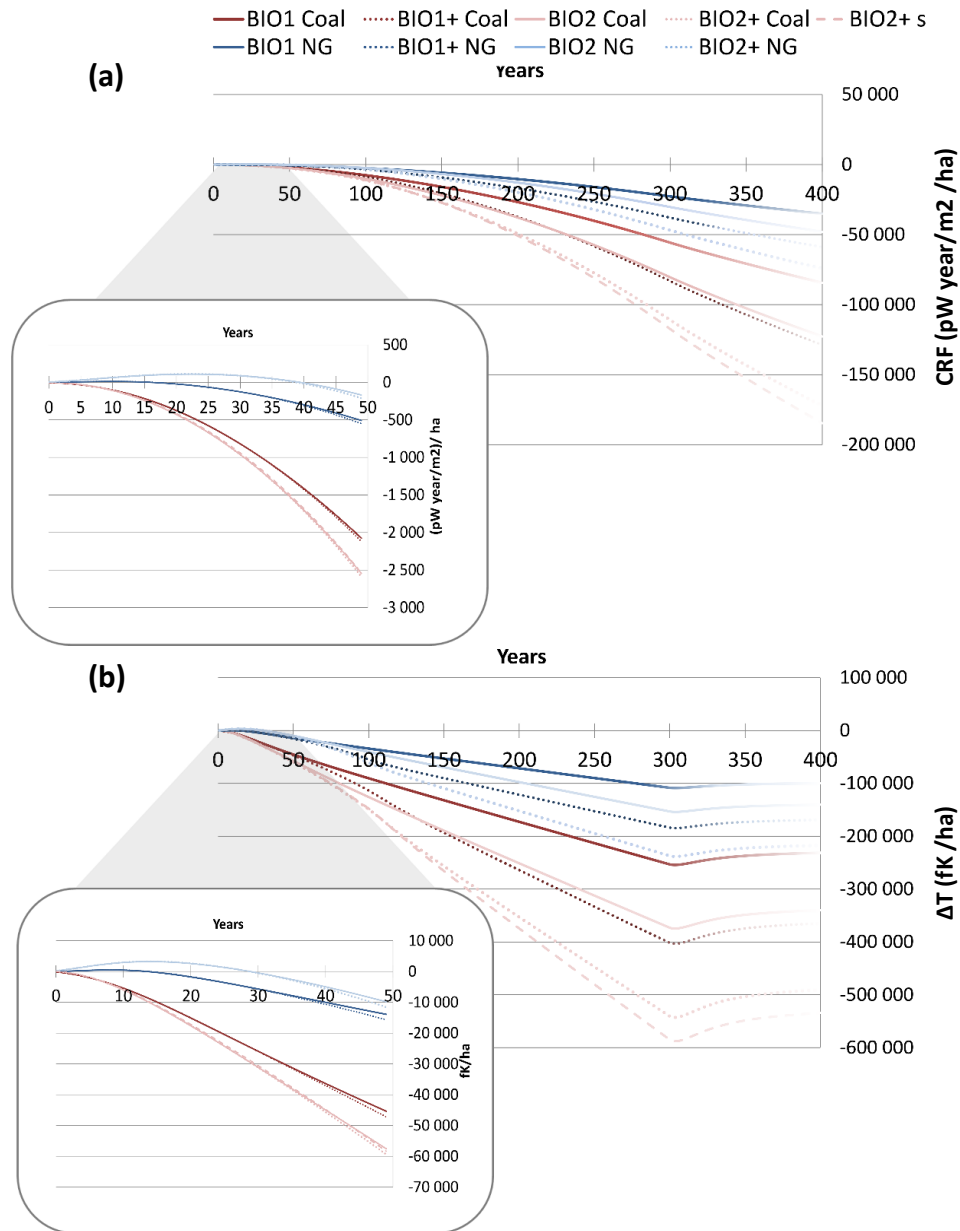
Figure 13: Net climate effects of the fossil and biomass-based systems implemented in a 300-year period at the landscape level. a) Net cumulative radiative forcing (CRF) in picowatt per hectare; b) Net change in temperature (ΔT) in femto Kelvin per hectare (cf. Figure 8 in Paper I). Negative values correspond to cooling. Each line represents the net difference between the bioenergy scenarios and the reference scenario. 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.

In **Paper III**, we estimate the climate effect of different types of Swedish forest management and energy scenarios and place them in the context of the 2-degree limit. In Figure 14, the net CO_2 emissions of each scenario are compared with the net CO_2 budget allocated to Sweden to evaluate whether the scenarios comply with the long-term climate target. The net CO_2 budget includes both fossil fuel emissions and emissions associated with forest management and LUC. The resulting emissions from the business-as-usual scenario (BAU in Figure 11b) claim the net CO_2 budget (see Figure 14 where the resulting

emissions exceed the allocated budget) and therefore it does not comply with the 2-degree global target. In contrast, the scenarios in line with the Swedish political targets (BIO 1 and BIO2 in Figure 11) will not claim the budget during the period covered by the scenarios and instead create more CO_2 emissions space (in effect increasing the net budget, see Figure 14). 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 (see GHG emissions in Figure 11b). Then, the scenarios in line with the Swedish target (BIO1 and BIO2) are also in line with the 2 degree target, and the unused budget can be used by other countries for emitting and therefore having more time to implement measures to reduce CO_2 emissions (see **Paper III**), or, if not compensated for elsewhere, can be used to increase the likelihood of staying below the 2-degree limit.

Conclusions on whether the scenarios are in line with the 2-degree target depend on the size of the carbon budget allocated to Sweden. If historical responsibility for emissions is considered, i.e., if we use an equal-per-capita emissions trajectory (from 1990) to address emissions inequalities among countries (Gignac and Matthews, 2015) not considered in the contraction and convergence framework, the emissions budget allocated to Sweden would be even larger (see Section 4.1.3). This budget would also be unused when it is combined with the Swedish target scenarios (BIO1 and BIO2). On the other hand, the allocation of a net carbon budget to Sweden is done considering a budget for both positive and negative emissions from fossil sources and LU and LUC. A recent study (Peters et al, 2018) calculated separate budgets for positive and negative emissions. This approach could require to comply with both budgets so that Sweden might need to abate fossil CO_2 emissions beyond the reduction in the Swedish target scenarios to comply with the positive budget. The purpose of using the carbon budget in **Paper III** is to offer a proof of concept for applying a carbon budget approach, and the results should not be seen as estimates of the actual carbon budget for Sweden.

The carbon budget concept is used as a complement to other time-dependent indicators to place national emissions in a context with regard to long-term climate targets. As discussed above, some of the bioenergy systems are associated with initial net emissions, which in most of the cases revert over time (Figure 13). This fact raises the question whether the size of the initial emissions are within a safe level, or allowed budget, i.e., whether those emissions are acceptable in order to provide further savings in the long term. Leaving behind fossil fuels and transforming the energy sector is not exempt from emissions. Ramping-up low-emission energy systems, e.g., solar, wind, carbon capture and storage, or electric vehicles, is also associated with emissions and warming. There is energy embodied in the extraction, construction, and operation of these technologies, which might come from fossil fuels (e.g., Myhrvold and Caldeira, 2012; Pehl et al., 2017). This does not mean the transition toward low carbon intensive energy systems can wait but rather that establishing this technology and infrastructure will have associated emissions and that trade-offs between short-term and long-term effects are required. It is equally important to find a balance between the objectives of maintaining forest carbon

stock and leaving fossil fuels underground. Mitigation efforts during the coming decades will determine whether the long-term target will be accomplished. All the employed metrics assess long-term climate impacts, but short-term climate effects and tipping points should not be overlooked.
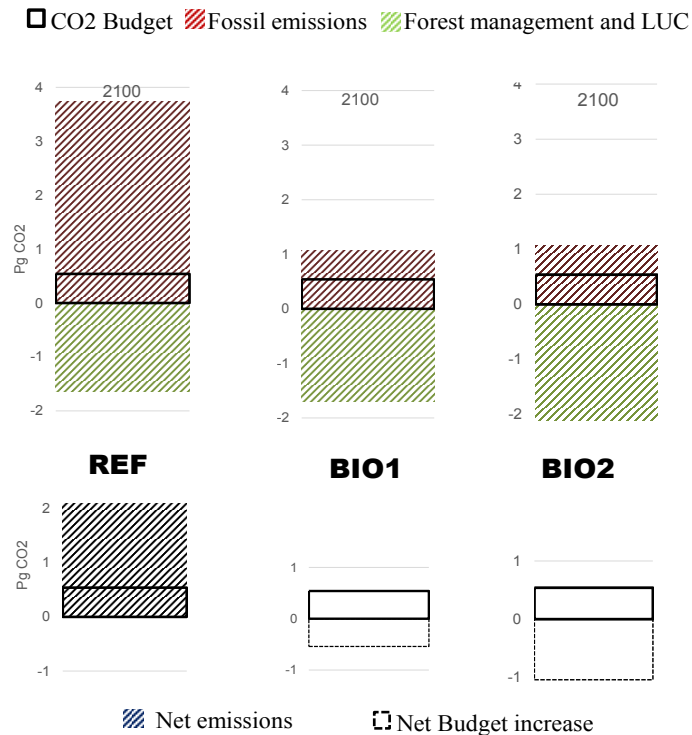

Figure 14: Comparison between the net CO_2 budget for Sweden and the cumulative emissions (fossil and LUC emissions in Pg CO_2) for the different scenario combinations (cf. Figure 11 in Paper III). REF: conventional forest management with 15% slash removal; BIO1: as REF but 20% of stumps and 35% slash removal; BIO2: as BIO1 with measures to enhance growth.

5.2 Geospatial supply-demand modeling of lignocellulosic biomass for bioenergy in the EU

Research question 2: To what extent can biomass demand in the EU (including Norway and Switzerland) be met based on biomass resources within the same region, and how may environmental impacts in current agriculture be mitigated if part of the biomass supply comes from dedicated cultivation of lignocellulosic crops on existing cropland?

The extent to which biomass demand can be met is strongly influenced by the nature of the demand (technical requirement for biomass quality) and the willingness to pay for biomass (as seen also in Section 5.1.2). In **Papers IV** and **V** we investigate possibilities for greening the existing fossil infrastructure in the EU, specifically coal power plants and refineries, and how this in turn can help to build out supply chains for biomass.

First, co-firing is evaluated as a near-term option to stimulate bioenergy markets and the build-up of the biomass supply infrastructure that can facilitate implementation of other bioenergy options once those technologies are commercially available. Second, a complete conversion to biomass-dedicated plants is investigated, following the UK

experience where economic incentives encouraged the full conversion of three co-firing coal power plants to biomass-dedicated plants (IEA Bioenergy, 2016; Roni et al., 2017). Finally, we also investigate a situation in which existing refineries[8] shift away from crude oil to bio-based oil. Bio-oil is assumed to be produced in pyrolysis units located in former coal power plant sites to make use of the existing logistics infrastructure and knowledge.

5.2.1 Matching biomass supply and demand at the EU level: availability, supply cost, and CO_2 emissions saving

What is the size and geographic distribution of biomass demand for energy if suitable coal power plants in the EU are used for biomass co-firing with coal or converted into biomass-dedicated plants producing electricity? What is the size and geographic distribution of biomass demand for energy if sites used for coal power are converted into biomass-dedicated plants producing bio-oil?

The total biomass demand is estimated at 184 PJ biomass if suitable coal power plants in the EU are used for biomass co-firing with coal[9]; 2133 PJ if all the those plants and the ones that already use co-firing are converted to use only biomass as fuel; and 1493 PJ (to produce 970 PJ of bio-oil) if 100-MW bio-oil plants are built on all the existing coal power plant sites.

Coal power plants in the EU are mainly located in Germany, Poland, and the Czech Republic, representing 75% of the total assessed demand for co-firing and bioelectricity and 60% of the assessed demand for pyrolysis in the EU. The selected results presented below concern these countries where the identified demand for biomass is concentrated (see **Papers IV** and **V** for the rest of the countries in the EU28 +). If biomass demand in other locations (existing industries and/or new green field sites) and/or other transport options (train and ships) and bioenergy pathways were considered, a larger part of the biomass resources would be available and supply-side responses might enhance supplies. The geographic distribution of the demand for the selected countries is illustrated in Figure 15.

How much of the biomass demand can be met based on sourcing forest and agriculture biomass within certain distances? How could it affect land use in the surrounding area?

Figure 15 provides geographically explicit information about the location and the feedstock used to meet demands for co-firing (a and b), bioelectricity (c), and bio-oil (d), when the sourcing areas are restricted to short distances (here considered a maximum of 300 km). If, due to technical reasons, only forest residues are suitable for co-firing, a lower demand can be met than if agricultural residues are also considered (see Figure 16). Meeting the co-firing demand with only forest residues will affect a larger area and require longer transport distances since the density of forest residues is significantly lower

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[8] Refineries with hydrocrackers, corresponding to category type three and four in Johansson et al. (2012)
[9] The co-firing fraction is set to 10% or 15% depending on the boiler type, see **Paper IV**

than agricultural residues (see Figure 15). This also leads to considerably higher total supply costs than when agricultural residues are also used (see Figure 16).

A full conversion of coal-based power plants to bio-based will more likely be associated with higher willingness to pay for biomass, which could stimulate land owners to establish energy crops. In that case, the amount of available biomass for bioenergy will increase significantly. Forest residues and short rotation coppice (SRC) on 20% of the cropland could meet the entire demand for biomass in the Czech Republic and Poland and half the demand in Germany (25 Mha for forest residues and 4.5 Mha with SRC). Alternatively, we assume that all coal power plants are converted to bio-oil units to produce bio-oil for refineries, and that agricultural residues are also suitable and prioritized over energy crops (we prioritize current land use). Biomass for bio-oil could meet the entire demand for biomass in the Czech Republic and around 80-83% of the demand in Poland and in Germany (56 Mha for residues and 1 Mha with SRC). A lower amount of biomass can be used to meet the demand for bio-oil (affecting a larger area) than for bioelectricity. This is explained by the fact that bio-oil is mainly produced from agricultural residues (when available they are prioritized in the model), while bio-electricity uses more energy crops (more geographically concentrated than residues). Biomass concentration also improves logistics for energy crops and decreases their transport cost; however, energy crops have higher road-side costs because of the cost of growing them. As a result, biomass demand in the bio-oil scenario can be met at a lower cost than in the bioelectricity scenario. Figure 16 also shows that using bioenergy for electricity is more effective for mitigating climate change than producing bio-oil to substitute for crude oil.
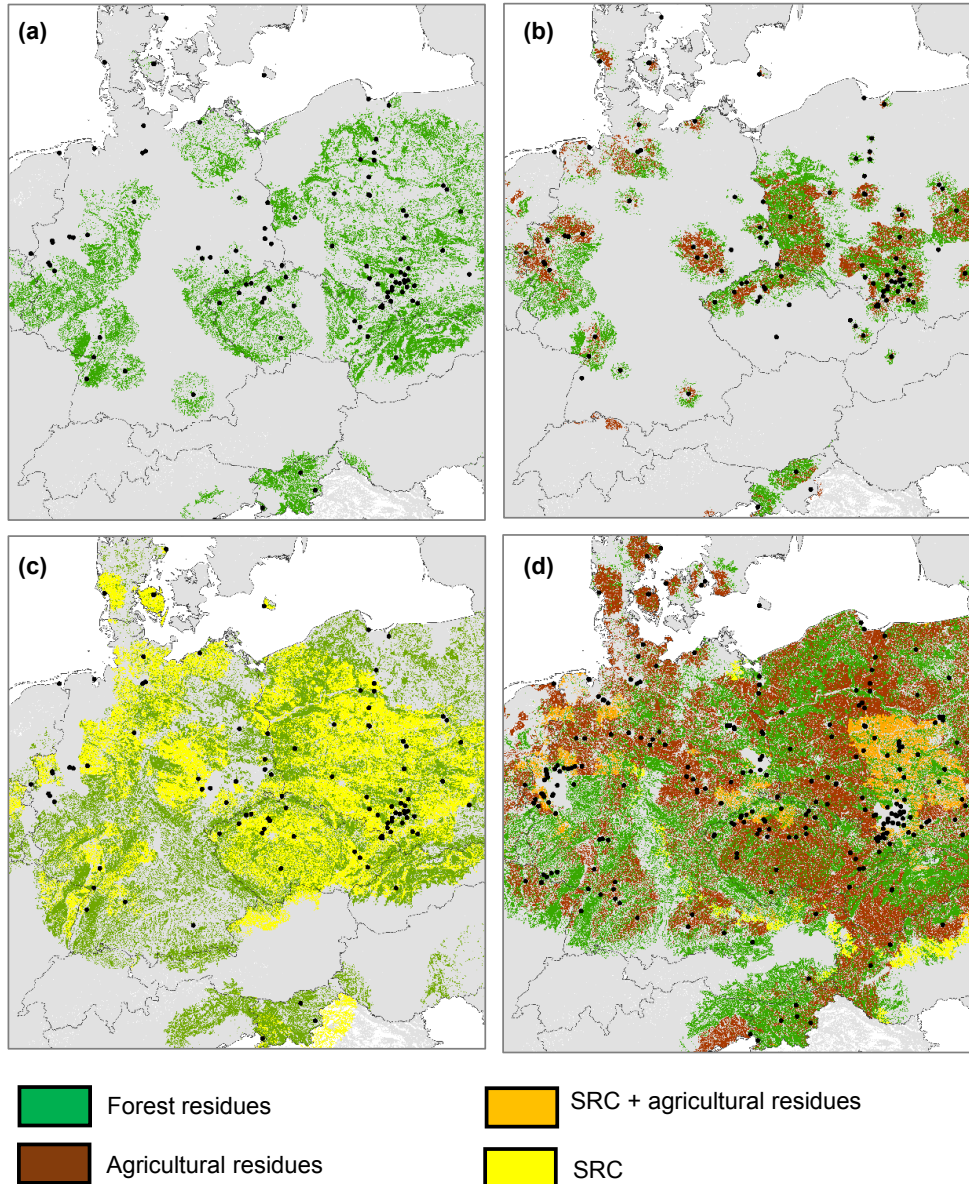
Figure 15: Feedstock used to meet the demand at 300 km for (a) co-firing with forest residues; (b) co-firing with agricultural and forest residues; (c) bioelectricity production from forest residues and energy crops; and (d) bio-oil production from forest and agricultural residues and energy crops. Dots represent demand points. Zoom-in of Germany, Poland, and the Czech Republic.
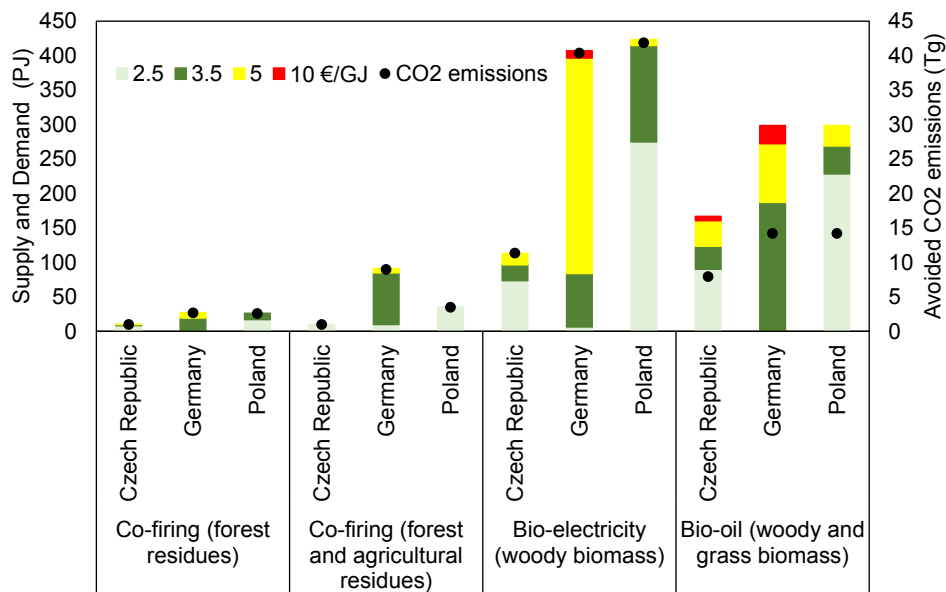
Figure 16: Biomass demand being met at different cost intervals and avoided CO_2 emissions for the different scenarios: co-firing, bioelectricity, and bio-oil at 300 km.

5.2.2 Potential environmental benefits associated with energy crops

How may environmental impacts of current agriculture land use be affected if part of the supply comes from dedicated cultivation of lignocellulosic crops on current cropland?

Figure 17 shows the expected effectiveness in mitigating soil erosion, flooding risk, diffuse nitrogen loads, as well as enhancing SOC when introducing SRC into agricultural land (**Paper V**). The mitigation effect is greater when the risk of a certain environmental problem is greater and the annual crops density in the sub-catchment where the land use change occurs is greater. In the three investigated countries, the expected contribution to improving SOC is rather high, while the effectiveness in mitigating soil erosion and diffuse nitrogen loads from agriculture activity goes from low to medium and varies from low to high for flooding. The expectation for mitigation of environmental impacts is greater in the bioelectricity scenario than in bio-oil because the former requires more area covered with lignocellulosic crops. In the bio-oil scenario, we have assumed that agricultural residues are prioritized over energy crops. In reality, land-owners could decide to introduce lignocellulosic energy crops based on local conditions, e.g., to improve some SOC or soil erosion, instead of extracting agricultural residues which could affect soil quality even more negatively.
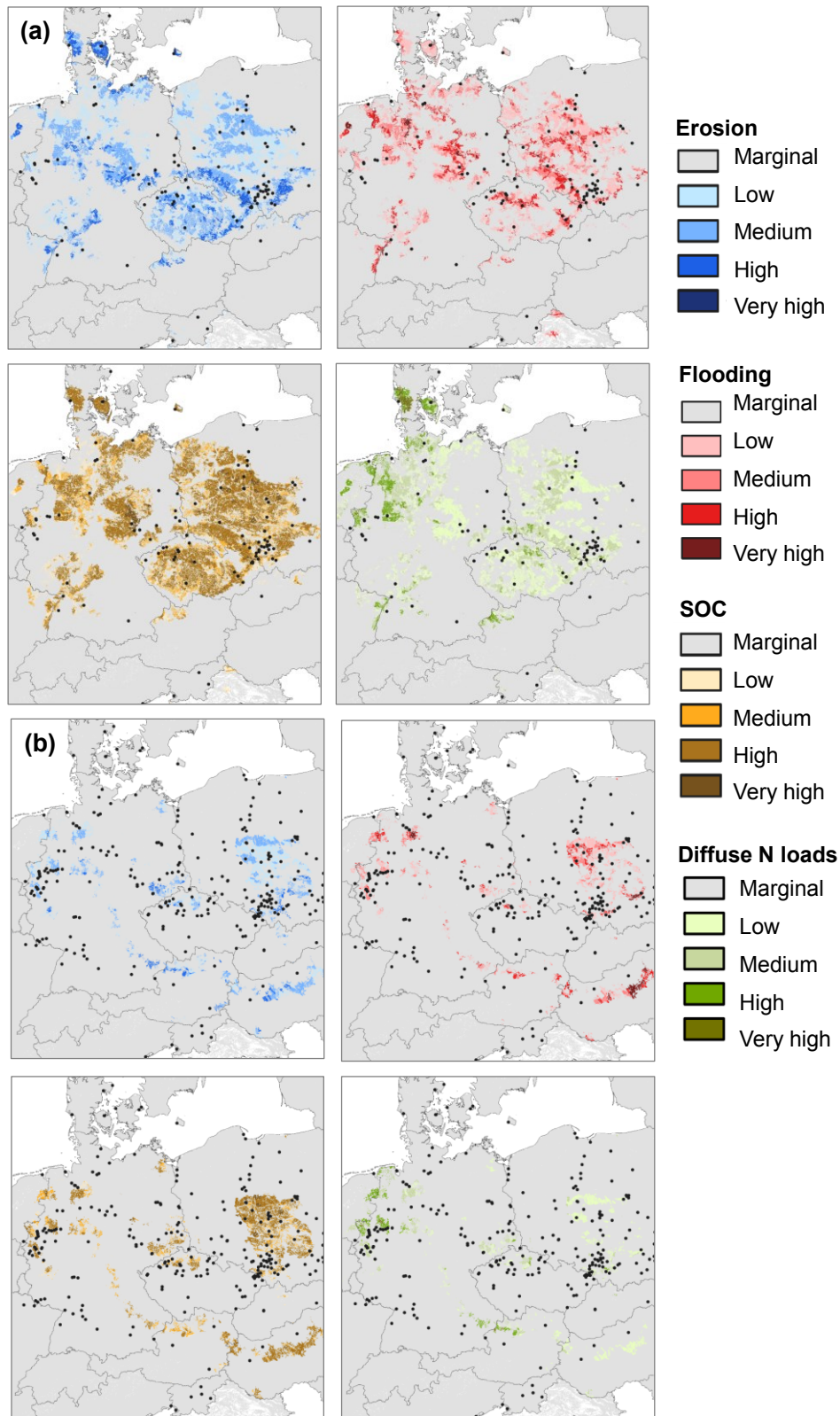
Figure 17: Indication of effectiveness in mitigation of selected environmental impacts for the case in which SRC can be sourced up to 300 km from the point of biomass demand for (a) bioelectricity production from forest residues and SRC, and (b) bio-oil production from forest and agricultural residues and SRC. Dots represent demand points. Zoom-in of Germany, Poland, and the Czech Republic.

The production of lignocellulosic biomass is associated with low GHG emissions (JRC, 2013) and can, in combination with the improvement of SOC, enhance this climate mitigation effect even further. The planting of energy crops may cause iLUC emissions due to displacing previous land use. Specific options have been identified for expanding energy crops to reduce the risk of causing iLUC: (i) planting on degraded/marginal lands that can be found in many parts of the world (Wicke et al., 2012; Wicke, 2011); (ii) planting on "surplus" cropland that is not needed (or not economically competitive) for production of food and other agriculture products. Some so-called "low iLUC projects" link the planting of energy crops with initiatives to boost land-use productivity in a region so that the amount of food crops produced in the region does not decrease. Illustrative of the scope for such a strategy, Kluts et al. (2017) estimated possible annual increase in crops yields at 0.2-0.5% in Western Europe and 2-2.6% in Eastern Europe by 2030; or/and (iii) integrated biomass land-use systems that simultaneously provide fuel, feed, and food (e.g., Dale et al., 2010; Egeskog et al., 2011; Wicke et al., 2012). Integrating perennials and annual food crops can help increase water use efficiency and water infiltration recharging groundwater levels (Basche & Edelson, 2017). Nevertheless, the effects on biodiversity conditions and ecosystem services other than biomass provision need to be carefully considered in evaluations of the effect of an expansion of energy crops.

6 - General discussion

6.1 Methodological choices and limitations

The methods used in the different papers are mainly determined by the scope of the analyses, but also by data availability and computational resources. Below, we discuss some methodological choices and the associated limitations.

6.1.1 Climate change effect of bioenergy systems

In **Papers I-III**, different methods are used to evaluate carbon balances and GHG-mediated climate effects associated with forest-based energy. The purpose is to understand the effect of different methodological choices and assumptions on the results rather than derive exact numbers for how biomass use for energy influences net carbon emissions over time. Below, methodological assumptions and modeling limitations are discussed. Other uncertainties associated with parameter assumptions, e.g., decay factors for slash and stumps, are acknowledged but not included in this discussion.

Different impact metrics can be used for evaluating the climate effect of forest-based energy. In **Papers I** and **II**, most of the analysis uses "hectare of forest" as a basis. **Paper I** also uses climate impact per unit of bioenergy output. GHG emissions per unit of energy output is a common basis, which facilitates the comparison of emission factors among energy sources, as for instance in JRC (2013). One challenge is that numerical results may be determined by complex interactions that are not made explicit through the use of such metrics. For example, as has been discussed throughout the thesis, the climate impact of bioenergy depends partly on the forest management and how it is influenced by the bioenergy market and also other forest product markets; this could possibly be made more explicit by using hectare as a basis. It is important to not only present results as single emission factors but to show how the outcome depends on interactions within studied systems and how climate impacts vary over time.

The consequences of using bioenergy are commonly investigated by comparing the bioenergy system with a reference system, which includes the forest system (without bioenergy) and a reference energy system. The definition of the reference system is crucial for the conclusions (Buchholz et al., 2014; Peñaloza et al., 2017; Parish et al., 2017; Soimakallio et al., 2015) and should be consistent with the objective of the study. In **Papers I** and **II**, the chosen forest reference system (i.e., baseline land use) represents the current land use and production of forest products to investigate the effect of bioenergy incentives relative to the present situation. Other studies (Soimakallio et al., 2015) argue that using a forest system under natural conditions as a reference would result in the "real"(i.e., human-induced land-use) impact of bioenergy, although no clear guidance in selecting the reference system with regard to the objective of the study is

provided (Koponen et al., 2018). In case a natural forest is used as the reference when estimating climate impacts of bioenergy, alternatives to current Swedish forest products (either sawnwood and pulp and paper from forests elsewhere, or other products that are substitutes for these forest products) need to be considered in the assessment. Another uncertainty is that the effect of events such as storms, wildfires, or insect outbreaks is different on natural and managed forests (Kurz et at., 2008). This adds uncertainty and complexity into the analysis as carbon balances are significantly affected by how a reference forest is modeled. Using natural forest as a reference land use has also been criticized as not realistic in the EU (Nabuurs, 2017).

The reference systems used in **Papers I** and **II** also considered fossil displacement factors for bio-based products (e.g., emission savings by substituting fossil fuels and cement products), which are set to be constant over time. This assumption might lead to an overestimation of the displaced fossil emissions because, in reality, the emission intensity of these products could decrease over time. For instance, emissions from cement production are expected to drop by 32% by 2050 due to efficiency measures and fuel shifting (IEA-CSI, 2018). In **Papers I-II**, it is assumed that all the extra sawnwood production in BIO+ scenarios (with regard to the reference scenario) is used to displace concrete but might in reality displace a variety of products (such as steel, linoleum, plastics, see, e.g., Smyth et at., 2017b; Lundmark et al., 2014). This assumption would affect the pace at which climate benefits are obtained. In **Paper III**, instead of using specific displacement factors, effects were quantified based on scenarios where bio-based products were assumed to meet future demand in all economic sectors where forest products will be used. In this case, the transformations in the energy system were reflected, but a full integration between bio-based product supply and demand is still needed to understand which products are being displaced and their GHG mitigation effect over time.

The real landscape scenarios in **Papers I-III** are generated with linear optimization models. Here, we have assumed that all forest owners have perfect information and 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 overestimated.

The analyses performed in this thesis consider a constant forest area. As observed in **Papers II** and **III**, an increased demand for bioenergy in Sweden could affect the production of other forest products, leading to product competition (also found by e.g., Moiseyev et al., 2011; Lauri et al., 2012; Moiseyev et al., 2013), which may also influence land use in other regions. For instance, an increase in demand for biofuels could drive conversion of protected areas into forest managed for productive proposes (Verkerk et al., 2014). Nevertheless, analyses of how bioenergy incentives cause competition for land

and 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 and land uses (as done in **Papers IV** and **V**).

6.1.2   Geospatial supply-demand modeling

The modeling framework developed in **Papers IV** and **V** is used to understand supply-demand patterns associated with specific bioenergy options. The model is not used to predict how these sectors will develop but rather to gain insights about connections between biomass supply and demand and the resulting influence on LU and LUC in the neighboring area. Modeling limitations as well as data availability are discussed below.

In **Papers IV** and **V**, we perform geographically explicit analyses at 1000 m. The spatial resolution is chosen as a trade-off between the resolution of input data, level of details, and computational time (on average 8 hours). This resolution provides a more comprehensive assessment of supply and demand patterns in Europe than previous studies with similar geographical scope (e.g., Hansson et al., 2009; Bertrand et al., 2014), and it is also sufficiently detailed to be helpful in capturing transport cost and environmental impacts. Nevertheless, a meaningful assessment on how/where to introduce energy crops in the landscape to provide environmental benefits, will require further assessments at higher resolution, even at the catchment level (Berndes, 2008), requiring large computational resources.

Computational time is also a limiting factor for matching biomass demand with the supply. For each power plant, the least costly biomass supply is determined by claiming the least costly biomass available in the area that is allocated to the plant. All cells with the same cost are used to meet the demand even if the sum of supplies in these cells exceeds the demand. This leads to an oversupply. In **Papers IV** and **V,** the average oversupply is 8-10%, which could be reduced by increasing the number of iterations. However, this will require longer computational time and/or more powerful computer resources. The estimated oversupply resulted in a larger area required to meet the demand but still did not influence the supply of the other plants. We run the scenarios with double the time to check that the results were rather similar, i.e., the same amount of plants could meet their demands but using slightly less land.

To reduce complexity, the analyses do not include possible changes over time of some critical factors. For example, we did not consider potential changes in crop yields (due to technology development or climate effect (DaMatta et al., 2010) or costs (decrease over time due to learning, or increase due to certain input factors becoming costlier), which may affect biomass availability and supply costs over time.

In addition, both land management and the availability of biomass for bioenergy are affected by the interactions with future demand for food and materials, and by other land uses such as planting of forests and expansion of societal infrastructure, e.g., roads and buildings. The assessments presented in this thesis do not consider these factors. Other

studies use socio-economic models/data to provide complementary insights. For instance, Elbersen et al. (2013) used a partial equilibrum model for agriculture (CAPRI) to estimate energy crop supplies considering future demand for food, feed, and processing; Fischer et al. (2010) used statistical data for current land use and future food demand for the same purpose; and Daioglou et al. (2016) used an integrated assessment model (IMAGE) to estimate future residue availability. Nevertheless, the total supply potentials used in the modeling are within the ranges reported in the review of bioenergy potential studies for Europe by Bentsen and Feldby (2012).

In a similar way, competition for biomass among different energy sectors is not explicitly considered in our analyses. We limit biomass availability for the specific bioenergy pathway to areas within a certain distance from the power plants; thus, biomass outside these areas could be used for other purposes. In reality, other biomass uses might be prioritized based on, e.g., willingness to pay for biomass. Some studies combine bottom-up biomass supply models with energy-economic modeling (e.g., Hoefnagels et al., 2014) to consider the bioenergy options that are most cost-effective in achieving certain climate targets. There is a high agreement that bioenergy will contribute significantly to the energy supply in order to reach the climate targets (biofuels will be required in the transport sector as well as BECCS in the industry and/or electricity to achieve negative emissions, (IEA, 2017); however, there is great uncertainty about technological development and costs over time.

Data availability is a limitation for estimating the spatial distribution of residue production. As seen throughout **Papers I** and **II**, the availability of forest residues depends on site conditions (e.g., soil and climate conditions). We did not find comprehensive inventories/databases containing spatially explicit information on possible residue extraction rates, and therefore we adopted a constant extraction percentage (based on de Jong et al., 2017a) and used it for all countries in Europe. Other studies employ forest models (e.g., G4M by Di Fulvio et al., 2016) to estimate geographical explicit residue availability, obtaining a more accurate distributed forest residues availability than the one estimated in our study. In a similar way, our estimates of agricultural residue availability only consider average European values for the residue-to-product-ratio (RPR) for most of the countries, and country-specific RPR for a few of them, when information was available. The RPR varies geographically and can affect residue availability significantly (Scarlat et al., 2010). To address the lack of regional specificity, studies included sensitivity analysis (Thorenz et al., 2018) or present biomass availability as ranges (Scarlat et al., 2010).

The environmental consequences of introducing energy crops are not in focus in **Papers IV** and **V** although selected environmental aspects are addressed in **Paper V**. Studies present data and information about impact of energy crops on ecosystem services as well as impacts on water quality, soil quality, and biodiversity (e.g.,. Ferrarini et al., 2017). Such data, in combination with elaborate high resolution inventories/databases on the state of ecosystem services in agricultural landscapes can be used in studies investigating

environmental trade-offs associated with energy crops expansion. For instance, water-footprint analyses of energy crops combined with water availability mapping can be useful for selecting crops and siting plantations (Dauber et al., 2012; Gerberns-Leenes et al., 2009). Also, spatially explicit information on location of degraded/marginal land will also guide the localization of new energy crop plantations.

6.2 Potential contribution of bioenergy and bio-based products to a low carbon economy

This thesis shows that bioenergy and bio-based products can contribute positively to climate change mitigation by providing CO_2 savings. But it emphasizes that there are modeling limitations and inherent uncertainties concerning development of critical factors, which make it difficult to determine how large this contribution can be.

Our results show that Swedish forest products already make an important contribution to a low-carbon economy by displacing fossil-based products, but also by promoting forest management to maintain or enhance forest production and carbon storage in vegetation and soils (in line with Gustavsson et al. 2017; Iordan et al. 2018; Lundmark et al., 2014). The harvested stemwood is currently used by sawmill and pulp and paper industries, and slash is used for bioenergy. Biomass used in long-lived products (sawnwood) has an extra benefit in that the carbon in the products is stored for many years and in that they can substitute for GHG-intensive materials (e.g., Gustavsson et al. 2017, Smyth et al. 2017b).

Results from **Papers I-III** show that the use of forest residues as well as pulpwood (under certain conditions) for bioenergy can bring significant climate benefits. While there is a quite wide agreement that the use of forest residues for energy leads to climate benefits (unless residues were to decay very slowly if left in the forest) (e.g., Hammar et al., 2015; Ortiz et al., 2016; Sathre and Gustavsson, 2011); there are studies (e.g., Holtsmark, 2013; McKechnie el al., 2010; Searchinger et al., 2018) reporting that the use of stemwood for energy leads to a negative climate impact. We found, however, that the outcome depends on the market conditions as well as the forest management in place. As shown, declining pulp demand (leading to lower thinning intensity) could impact sawnwood production, total forest production, and carbon balances negatively, but the possibility to use thinning wood for bioenergy can counteract this negative effect. In a similar way, the increased production of wood pellets in southeastern US partially occurs in parallel with a decline in pulp and paper production (Goh et al., 2013). A lack of market for wood products could lead to unhealthy, unmanaged forest or forest conversion to other uses (Parish et al., 2017), by, for instance, removing economic incentives for fire prevention management. Regardless of the biomass fraction being used for energy, our results show that using bioenergy to substitute for coal will lead to earlier carbon savings than substituting for natural gas (**Papers I** and **II**) or transport fuels (**Paper V**).

In general, scenarios with intensified forest management in Sweden show the greatest climate benefits because more biomass production, carbon storage in long-lived products, and GHG savings from product substitution, can compensate for the forest carbon stock

losses caused by higher harvest intensity. This is in line with Lundmark et al. (2014). Gustavsson et al. 2017, in addition, found that an intensive forest management with high harvest levels and efficient use of forest products will be better from a climate perspective than setting aside forest to store more carbon. However, trade-offs with other ecosystem services, as well as economic aspects, need to be further investigated. Increasing biomass production and carbon stock through forest intensification, planting monocultures, fertilization, and application of shorter rotation periods may also negatively affect the capacity to support ecosystem services, biodiversity and recreational values (Pang, 2017). Fewer old trees and less dead wood in the forest, simplification of forest structure, and reduced habitat size are all negative from a biodiversity point of view (cf. Berg et al., 1994; Pang, 2017; Thompson et al., 2011; Hanski, 2011; Ranius & Roberge, 2011).

The carbon balances associated with bioenergy systems are site specific, and results from Swedish forests cannot be extrapolated to represent other forests/bioenergy systems. However, the identified forest dynamics and discussions are relevant to forests managed for productive proposes elsewhere.

At the EU, the total availability of agricultural residues is estimated at 2.5 EJ and forest residues at 0.4 EJ (Paper IV). Furthermore, an extra 5 EJ could be available if energy crops were to be introduced on 20% of the agricultural land (**Paper V**). This can be compared with the review by Bentsen and Feldby (2012), reporting ranges for the lignocellulosic bioenergy potential for 2030 of 0.9-3.1 EJ/yr agricultural residues, 0.8-6.0 EJ/yr forest biomass, and 4.3-6.0 EJ/yr energy crops. Estimates of the availability of forest residues (in **Papers IV** and **V**) only consider current forest management and a constant percentage of forest residue extraction, excluding stumps, changes in forest management, and forest industry residues (bark, sawdust and woodchips from sawmills and pulp and paper). As estimated in **Papers I-III** and reported in Díaz-Yáñez et al. (2013), these excluded biomass sources represent a significant part of the total volume of forest sector residues (up to 75% of the total potential) .

The estimated biomass supply can be employed in different applications in a low carbon economy. **Papers IV** and **V** investigate biomass supply with regard to a localized demand to produce bioelectricity or bio-oil under specific conditions. The use of bioenergy could be prioritized to ensure the highest climate benefits, for instance, for electricity production (see Figure 15) (Suttles et al., 2014). Alternatively, in a low carbon economy, the importance of different biomass uses can be affected by the technology development for both the bio-based options and for other alternatives to fossil fuels and GHG-intensive materials. For instance, when evaluating alternative energy options it is important to recognize that these can both compete with, and be complementary to, each other. In an energy system with large amounts of variable renewable power such as wind and solar PV, dispatchable biomass power can be a valuable complement to balance power, provided that it meets the requirements of low net GHG emissions. In addition, electrification of transport systems is considered an important step toward more climate friendly transport. But it takes time to transform the current transport systems, and

biofuels can, especially in the coming decades, make an important contribution to achieving rapid and deep reduction in fossil fuel use in the transport sector. In the longer-term, biofuels may primarily be used in applications where substitution away from carbon-based fuels is difficult, such as aviation. Regardless of which uses will dominate in the longer term, options that are available in the near term are important for stimulating the build-up of biomass supply infrastructures that provide access to the biomass resources. Early options, e.g., co-firing of biomass in existing coal power plants, pave the way for later options such as biofuels for aviation or bio-chemicals.

6.3 Implications for decision makers

Our results show the relevance of land management. Our findings suggest that focusing on forest management and stocks rather than on quantifying carbon fluxes of specific forest products can be more efficient from a policy point of view. This is in line with, e.g., Böttcher et al. (2013) who concluded that GHG emissions can be controlled more efficiently by land-use policies than by bioenergy sustainability criteria. The design of the accounting framework strongly influences estimates of carbon flows (Bentsen, 2017).

Incentives targeting individual products rather than the land management, including all the associated products, can have unexpected consequences. For instance, some studies claim that the use of harvested products for raw materials should be prioritized over use for energy, the so-called cascading effect, in order to enable long-term sustained carbon sequestration (e.g., Böttcher et al., 2012) or that bioenergy should be restricted to residues and waste (Beddington et al., 2018). Ensuring that wood is first used to stored carbon and efficiently recycled afterwards, would bring positive effects (Mehr et al., 2017), but constraining energy sources to only recycled wood products would certainly reduce opportunities for improving carbon balances. As discussed earlier, this constraint might disincentivize the removal of thinning biomass, reducing sawnwood production (**Papers I-III**), or the removal of dead wood and thinning biomass for fire prevention (Parish et al., 2017).

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. Immediate net carbon savings may be possible if the increase in demand is anticipated by forest owners. Nevertheless, some bioenergy systems present initial carbon losses (emissions) that could be greater than the achieved fossil carbon savings during some years but will bring important carbon savings in the long run. Therefore, it is important that results from these assessments consider short-term versus 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 might rather focus on expanding low-carbon energy technology, for instance by promoting sustainable forest management.

Assessments need to consider trade-offs between biomass production and climate change, and among other ecosystem services, too, including opportunities to provide benefits when introducing energy crops. For instance, targeting marginal or degraded land for establishing lignocellulosic energy crops seems to be associated with positive carbon stocks and other environmental and social benefits. A broader sustainability perspective, considering other forest ecosystem services, such as air quality improvement, water purification, soil stabilization, biodiversity conservation, and social services, should also be considered when designing bioenergy policy incentives.

In short, shifting attention from an assessment of flows of individual products to an assessment of maintaining carbon stock in the landscape to deliver ecosystem services— including forest and agricultural products—could capture potential impacts associated with bio-based products while also being simpler to perform.

7 -   Summary and conclusions

The role of bioenergy will remain controversial until uncertainties associated with large-scale implementation of bioenergy systems are unresolved. The work presented in this thesis focuses on methodology development to better understand land use, climate effects, and other consequences associated with bioenergy systems. The questions addressed are:

To what extent can methodological choices and assumptions about critical parameters affect the outcome in assessments of land use, (forest biomass) carbon balances, and climate effects, and how should they be considered?

The carbon dynamics associated with bioenergy systems are rather complex. There are studies that quantify a "carbon payback time," concluding that bioenergy systems can only bring net GHG savings after some years. Other studies show that bioenergy systems deliver immediate reductions in GHG emissions. The conclusions are mainly determined by the forest structure, spatial scale of the assessment, type of bioenergy feedstock, forest product portfolio (including displacement factors), market prospects for all forest products, ownership structure, and land management responses to market incentives for bioenergy and other forest products.

Based on the findings in this thesis we recommend that:

- Studies of how forest carbon stocks and sinks are affected by forest management be made at the landscape level to take full account of all types of forest management operations that occur across the landscape. Landscape-level approaches can account for all carbon flows between biosphere and atmosphere throughout the accounting time period. It is also the appropriate scale for assessing how bioenergy incentives and increased demand for bioenergy affect forest management and in turn the forest carbon stock.

- Studies should consider both short-term and long-term effects to clarify how the studied systems contribute to climate change mitigation on different time scales. Some systems may contribute less in the near term, due to initial carbon losses from soils and biomass, but then make a stronger contribution in the longer term thanks to achieving high biomass yields and/or to the cumulative effect of displacing fossil-based products. Other systems can make a positive contribution in the initial years, due to carbon sequestration into biomass and soils, but may contribute less in the longer term due to low yields.

- Effects on parallel industries (wood products, feed, food, and energy) need to be considered. Our assessments showed the relevance of considering supply-side responses to increasing demand for bioenergy and other wood products, e.g.,

changed silviculture operations and crop choices in agriculture. Different types of management affect ecosystem services differently.

- Complementary studies need to be made to clarify how different bioenergy options contribute to the transformation of the energy sector. This includes energy modeling studies and studies that specifically investigate actor behavior and learning effects associated with specific technologies.

- Results should be presented so as to reflect that the outcome depends on the assumptions and methodological choices made (e.g., selection of reference system and the development of future market for forest products). For the results to be relevant and correctly interpreted, stakeholders could be involved, for instance, when designing the goal and the scope of assessments.

To what extent can biomass demand in the EU (including Norway and Switzerland) be met based on biomass resources within the same region, and how may environmental impacts in current agriculture be mitigated if part of the biomass supply comes from dedicated cultivation of lignocellulosic crops on existing cropland?

A new modeling framework was developed to investigate interactions between biomass supply and a localized demand, and to evaluate supply costs, CO_2 savings, and potential LUC, considering also opportunities for introducing lignocellulosic crops to address current land use impacts. **Papers IV** and **V** investigate lowest-cost biomass supply systems with regard to a localized demand and specific scenarios and conditions. If all suitable coal based power plants were converted to instead use biomass sourced from distances within 300 km, an estimated 150 TWh of biomass derived electricity would be produced (4.5 % of electricity use in the EU28+), using 18% of the total estimated supply and assuming unchanged capacity and conversion efficiency. If all existing coal power sites are used for bio-oil production in 100-MW pyrolysis units, about 820 PJ of bio-oil could be produced, corresponding to 7% of crude oil use in suitable EU refineries (i.e., refineries equipped with hydro crackers), and using 17 % of the total supply.

Paper V also shows that lignocellulosic crops can be a complement to forest and agricultural residues, which can help mitigate environmental impacts in agriculture. The effects on SOC status indicate possible positive effects in most of the analyzed countries. Besides improvements in soil productivity, the carbon sequestration in soils would enhance the climate benefits of fossil fuel displacement with biomass. Concerning soil erosion, flooding, and eutrophication, mitigation opportunities range from high to marginal depending on location. The results motivate more comprehensive assessments including additional environmental aspects associated with lignocellulosic crops. This can help to avoid/reduce negative impacts and identify expansion routes that generate additional environmental benefits.

8 - Future work

The work presented in this thesis opens up several routes of exploration to better understand the consequences and trade-offs associated with bioenergy systems.

The consequences of using bioenergy on other climate forcers, such as albedo and aerosols, need to be understood alongside assessments of carbon balances and other GHGs in order to provide a fuller understanding of bioenergy's contribution to climate change mitigation.

More studies evaluating the consequences of different management and harvesting regimes for carbon balances and other ecosystem services are required for different regions and countries since forests and forest product portfolios in associated industries differ. The environmental consequences associated with the establishment of bioenergy systems are site-specific, indicating that generalizations from individual studies are not suitable. Studies conducted at both the stand and landscape level are needed because of the different insights these can provide (see Ranius et al., 2018). This will help in understanding trade-offs between forest management, biomass production, and other ecosystem services and in producing geographically explicit information that can be used for regional models employed for policy design/assessment.

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 is the method that dominates in Sweden. However, other approaches to forest management, such as continuous-cover forestry, need further investigation (see, e.g., Lundmark et al., 2016).

Future work will further address different forest management strategies and how these affect the development of energy, transport, and industry systems. For instance, bioenergy implementation to displace fossil fuels may in some instances not lead to equally high net GHG savings as the strategy to leave forests unharvested to sequester carbon. However, the bioenergy implementation may to a greater degree stimulate energy system change with faster phasing-out of technologies and infrastructures that rely on fossil fuels. Trade-offs between different land-use alternatives need to be analyzed for scenarios depicting different energy system pathways. This will help the development of energy and climate policies and provide new insights concerning bioenergy implementation relative to the trade-off between short-term GHG targets and longer-term goals such as the 2-degree limit.

The modeling framework used in **Papers IV** and **V** can be improved in the following ways. The assessment of the supply and demand sources can be extended to consider, for instance: (i) time dynamics of biomass supply systems, including carbon balances

associated with establishing bioenergy systems; (ii) extension of biomass demand sources, e.g., existing industries that might shift to bio-based feedstock ; (iii) extension of the forest supply database to include industrial residue flows from the sawmill and pulp and paper industry as well as changes in forest management; and (iv) extension of the potential effects of introducing dedicated energy crops, e.g., changed hydrological flows and biodiversity effects. Taking a step further, the modeling framework in combination with energy modeling (including biomass demand from different energy sectors) and policy scenarios can be used to better inform how different energy and climate policy instruments may affect development in the forestry and agriculture sectors, and how this in turn influences LU and LUC with associated impacts.

As a practical example, the role of large-scale deployment of BECCS in the European context can be investigated. BECCS has received a lot of attention, including in the last IPCC report (IPCC, 2014), as an option for achieving negative emissions to help keep warming below 2 degrees. For that, spatially explicit assessments of potential storage sites for captured CO_2 can be combined with the above-mentioned study for Europe.

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