Deparment of Mathematics and Systems Analysis

Climate impacts of bioenergy from forest harvest residues

Anna Repo

Aalto University

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Climate impacts of bioenergy from forest harvest residues

Anna Repo

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Abstract

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Abstract

Climate change mitigation requires substantial cuts in greenhouse gas emissions in the next decades. One option to reduce these emissions is to replace fossil fuels with low-carbon alternatives. Bioenergy from forest harvest residues has been considered as a carbon neutral source of energy, and therefore it has been regarded as an effective means to reduce the emissions. However, an increase in the extraction of forest harvest residues decreases the carbon stock, and the carbon sink capacity of forests. This effect can lessen the greenhouse gas emission savings and undermine the climate change mitigation potential of this bioenergy source. This dissertation examines the climate impacts of bioenergy produced from forest harvest residues. In this dissertation, an approach was developed to quantify the greenhouse gas emissions and the consequent warming climate impact of bioenergy from forest harvest residues. In addition, this dissertation suggests cost-effective ways to compensate for the carbon loss resulting from residue harvesting, and thus improve the climate impacts of this form of bioenergy. The dissertation illustrates the importance of accounting for reductions in the forest carbon stock in order to estimate the efficiency of bioenergy in reducing CO_2 emissions reliably. The findings of this dissertation have implications for renewable energy and climate policies, and forest management. The results presented provide guidance on how to choose and plan bioenergy production practices that deliver the largest climate benefits. The approaches presented in this dissertation can be applied in the development of new forest management, which maximizes climate benefits of bioenergy from forest harvest residues with a low cost to the forest owner and the end-user of bioenergy.

Keywords carbon neutrality, climate change mitigation, forest carbon, soil, sustainability

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Tiivistelmä

Ilmastonmuutoksen hillintä edellyttää kasvihuonekaasupäästöjen nopeita vähennyksiä. Päästövähennyksiä voidaan saavuttaa esimerkiksi korvaamalla fossiilisia polttoaineita vähähiilisillä vaihtoehdoilla. Hakkuutähteitä on aikaisemmin pidetty hiilineutraalina energianlähteenä ja näin ollen tehokkaana keinona vähentää päästöjä. Lisääntyvä hakkuutähteiden korjuu pienentää kuitenkin metsien hiilivarastoa ja -nielua. Tämä puolestaan vähentää hakkuutähteiden energiakäytöllä saavutettavia päästövähennyksiä. Tässä väitöskirjassa tarkastellaan hakkuutähteiden energiankäytön ilmastovaikutuksia. Työssä esitetään menetelmä hakkuutähteiden energiankäytön kasvihuonekaasupäästöjen ja lämmittävän ilmastovaikutuksen arvioimiseksi. Väitöskirjassa tarkastellaan myös päästöjen suuruuteen vaikuttavia tekijöitä. Lisäksi väitöskirjassa esitetään kustannustehokkaita keinoja pienentää hakkutähteiden korjuun seurauksena syntyvää hiilivajetta ja parantaa tämän metsäbiomassan energiankäytön ilmastovaikutusta. Väitöskirjassa osoitetaan, että hiilivarastomuutosten huomioiminen on ensiarvoisen tärkeää arvioitaessa bioenergian tehokkuutta keinona hillitä ilmastonmuutosta. Väitöskirjan tuloksia voidaan hyödyntää energia- ja ilmastopolitiikassa sekä metsänhoidon suunnittelussa. Tulosten perusteella metsäenergian tuotantoa voidaan suunnata sellaisiin kohteisiin ja käytäntöihin, jotka auttavat hillitsemään ilmastonmuutosta mahdollisimman tehokkaasti. Esitettyjä menetelmiä voidaan soveltaa kehitettäessä metsänhoitoa suuntaan, joka maksimoi bioenergialla saavutettavat ilmastohyödyt mahdollisimman pienin kustannuksin metsänomistajalle ja bioenergian loppukäyttäjälle.

Avainsanat hiilineutraalisuus, ilmastonmuutoksen hillintä, metsien hiilivarastot, maaperä, kestävyys

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Helsinki, April 14, 2015
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Contents

List of Publications

This doctoral dissertation consists of a summary and the following five original publications:

I. Repo A, Tuomi M, Liski J. 2011. Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *Global Change Biology Bioenergy* 3 (2), 107–115.

II. Repo A, Känkänen R, Tuovinen J-P, Antikainen R, Tuomi M, Vanhala P, Liski J. 2012. Forest bioenergy climate impact can be improved by allocating forest residue removal. *Global Change Biology Bioenergy* 4 (2), 202–212.

III. Repo A, Böttcher H, Kindermann G, Liski J. 2014. Sustainability of forest bioenergy in Europe: land-use-related carbon dioxide emissions of forest harvest residues. *Global Change Biology Bioenergy*. Forthcoming.

IV. Repo A, Tuovinen J-P, Liski J. 2015. Can we produce carbon and climate neutral forest bioenergy? *Global Change Biology Bioenergy* 7 (2), 253-262.

V. Repo A, Ahtikoski A, Liski J. 2015. Cost of turning forest residue bioenergy to carbon neutral. *Forest Policy and Economics*. Forthcoming.

Author's Contribution

Paper I: Repo is the lead author. Liski proposed the research topic of this paper. Repo designed the study together with Tuomi and Liski, established the results and wrote the paper.

Paper II: Repo is the lead author. The concept for the analysis was planned by all authors. Repo carried out radiative forcing calculations, analysed the results and wrote the paper. Känkänen simulated the litter decomposition and Antikainen computed the production chain emissions. Tuovinen, Tuomi, Vanhala and Liski provided comments on the paper.

Paper III: Repo is the lead author. She proposed the research topic of the paper and developed the modelling framework that linked two existing models together with Kindermann. Repo carried out the simulations, analysed the results and wrote the paper. Liski and Böttcher provided comments on the paper.

Paper IV: Repo is the lead author. She proposed the research topic based on initial suggestions by Professor Salo. Repo and Liski designed the study. Repo carried out the simulations, analysed the results and wrote the paper. Tuovinen provided comments on the paper.

Paper IV: Repo is the lead author. She and Liski planned the concept and developed the idea for the paper. Repo developed the optimization model together with Ahtikoski. Repo carried out the analysis and wrote the paper.

1. Introduction

Bioenergy can be used to replace fossil fuels in the energy sector in order to reduce greenhouse gas (GHG) emissions and mitigate climate change (IPCC, 2001). Bioenergy has been regarded as a carbon neutral energy source meaning that it does not cause any net carbon dioxide (CO_2) emissions to the atmosphere. This assumption is based on reasoning that the amount of CO_2 released in the combustion process is taken up again by the next generation of growing plants (Chum et al., 2011). The assumption of carbon neutrality is one of the reasons why bioenergy has an important role in national plans for achieving the climate and energy policy targets agreed, for example, in the European Union (2009/28/EC, 2009; Beurskens & Hekkenberg, 2011; Szabó et al., 2011). Consequently, the annual demand for bioenergy is expected to increase from the level of 5.7 EJ to 10 EJ in the EU by 2020. Biomass is the major contributor to renewable energy projections of the EU, and it is expected to account for over half of the renewable energy supply by 2020 (Bentsen & Felby, 2012).

Recently, the assumption of carbon neutrality of bioenergy has been questioned because of land-use-related emissions (Fargione et al., 2008; Searchinger et al., 2008, 2009; Melillo et al., 2009). These emissions occur when bioenergy production reduces the carbon stocks of biomass or soil, for example, when forests are converted to energy crop cultivations. These reductions in the carbon stocks lessen significantly the emission savings achievable by bioenergy (Fargione et al., 2008; Searchinger et al., 2008, 2009).

The reductions in the carbon stocks and the resulting land-use-related emissions are not limited to situations of land-use change, but may also occur within the same land-use. This is the case in the intensification of biomass harvests from forests (Schlamadinger et al., 1995; Schulze et al., 2012). Forest harvest residues, such as branches, unmerchantable tops, stumps and other residual biomass left behind in logging operations, are an important potential source of bioenergy from northern temperate and boreal forests, (Mantau et al., 2010; Díaz-Yáñez et al., 2013; Fritsche et al., 2013; Scarlat et al., 2013). However, increasing the extraction of forest harvest residues decreases carbon input to the carbon pools of dead wood, litter and soil, and consequently results in a forest carbon loss (Schlamadinger et al., 1995). This carbon loss associated with the extraction of forest harvest residues has been demonstrated in empirical and modelling studies of forest stands

(Schlamadinger et al., 1995; Palosuo et al., 2001; Ågren & Hyvönen, 2003; Hope, 2007; Strömgren et al., 2013), forest landscapes (McKechnie et al., 2011; Domke et al., 2012), and entire countries (Kallio et al., 2013; Sievänen et al., 2014). Nevertheless, the significance of this carbon loss for the climate change mitigation potential of forest bioenergy is still only partly understood (McKechnie et al., 2011).

The use of forest harvest residues for energy is increasing rapidly. For example, in Finland the annual consumption of forest harvest residues in heating and power plants has risen from 5 PJ in the year 2000 to 55 PJ in the year 2012. During the same time period, the share of forest chips in renewable energy consumption has increased from 2% to 17% (Finnish Statistical Yearbook of Forestry, 2013). Finland aims to increase the use of forest harvest residues for energy to 97 PJ yr $^{-1}$ by 2020 (Ministry of Employment and the Economy, 2010). In Europe, the estimates of energy potential in forest harvest residues range from 0.4 to 2.3 EJ yr $^{-1}$, and additional fellings may expand the upper end of this range to 10.6 EJ yr $^{-1}$ (EEA, 2006, 2007; Ericsson & Nilsson, 2006; Alakangas et al., 2007; Asikainen et al., 2008; UNECE, 2008; Anttila et al., 2009; Haberl et al., 2010; de Wit & Faaij, 2010; Bentsen & Felby, 2012).

Energy and climate policies, and carbon accounting rules that ignore changes in the carbon stocks of forests may prove ineffective at reducing emissions (Searchinger et al., 2009). This may also pose risks to business opportunities related to bioenergy, and to the overall acceptability of bioenergy. Therefore, quantitative information on the climate impact of bioenergy from forest harvest residues is needed. In addition, information on means to improve this impact is crucial to maximize the climate benefits from using this renewable resource.

This dissertation examines the climate impacts of bioenergy produced from forest harvest residues. The aims of this dissertation were to quantify the GHG emissions and the consequent climate impact of forest residue bioenergy, introduce ways to improve the climate impact and to estimate the cost of these improvements. In particular, this dissertation had the following objectives

1) to develop an approach to estimate GHG emissions and consequent climate impacts associated with the bioenergy production from forest harvest residues (Papers I, II),
2) to assess the variation in the climate impact within a country, and determine the significant factors that affect the magnitude of the climate impact (Paper II),
3) to estimate CO_2 emission reductions achievable by sustainable levels of forest harvest residue extraction for bioenergy in different EU countries (Paper III),
4) to investigate changes in forest management and forest residue harvesting practices that improve the climate impacts of forest residue bioenergy (Papers II, IV, V),
5) to estimate the financial cost of improvements in the climate impacts and the cost of carbon neutrality (Paper V).

This dissertation proceeds from the quantification of GHG emissions and the climate impacts of bioenergy from forest harvest residues to research on means to improve these climate impacts cost-effectively. Paper I provides the methodological basis for the other papers by introducing an approach to estimate the emissions of bioenergy production from forest harvest residues. Paper II combines the method for GHG emission calculations in Paper I with a climate impact assessment applying radiative forcing metrics. Paper II studies the variation of emissions and consequent climate impacts of forest harvest residue bioenergy in Finland. Paper III uses a spatially explicit modelling framework to estimate the changes in the European litter and soil carbon stocks, assuming that a sustainable bioenergy potential of forest harvest residues is adopted. Specifically, it applies the approach of Paper I to establish estimates of the CO_2 emission savings from forest harvest residue bioenergy compared to fossil fuel alternative in different EU countries. The findings are discussed in the context of sustainability of bioenergy production and EU climate and energy policies. Paper IV builds on Papers I and II and analyses which changes in the forest carbon cycle would compensate for the carbon loss resulting from forest harvest residue removal within the forest rotation period, so that bioenergy from forest harvest residues could be justifiably claimed as carbon neutral, and discusses the probability of these changes. Paper V further develops the ideas presented in Paper IV by analysing which changes in forest management and forest residue harvesting, or combinations of these two, would be financially viable to compensate for the carbon loss resulting from forest harvest residue extraction, and thus also improve the climate impacts of this form of bioenergy.

2. Background

2.1 Carbon neutrality of bioenergy

The carbon neutrality of bioenergy is based on the assumption that CO_2 emissions from bioenergy use are balanced by plant growth (Chum et al., 2011). This assumption of carbon neutrality derives from a misinterpretation of the guidelines for the national greenhouse gas inventories of the United Nations Framework Convention on Climate Change (UNFCCC) (Smith et al. 2014). In the inventory reports, the emissions from biomass combustion are not reported under the energy sector. This is to avoid double counting because CO_2 emissions from the use of biomass for energy are accounted for as a land-use emission (IPCC, 2006). However, this does not mean that the IPCC would consider bioenergy as carbon neutral. According to the IPCC, this approach of not including the emissions in the energy sector should not be interpreted as a conclusion about the sustainability or carbon neutrality of bioenergy (IPCC, 2014a). Nevertheless, for example, in the European policy framework biogenic CO_2 emissions from the combustion of biomass for energy are set to zero (Agostini, et al., 2013). Recent studies have pointed out this loophole in climate and energy policies (e.g. Fargione et al., 2008; Pingoud et al. 2010; Searchinger et al., 2009; Haberl et al., 2012). The problem of incomplete accounting for the emissions of bioenergy in the policy context derives from the incomplete geographic coverage of the Kyoto Protocol, the optional inclusion of forest management in the first commitment period of the protocol, and limited inclusion in the second commitment period due to the forest reference level approach (Bird et al., 2010;Marland, 2010).

The carbon neutrality of bioenergy from forest harvest residues is questioned for several reasons because i) land management, harvest and bioenergy processing require fossil fuels; ii) there is a delay between biomass combustion and tree growth; iii) intensifying forest biomass removal reduces the carbon stock or the carbon sink capacity of forests (Schlamadinger et al., 1995; Haberl et al., 2010; Walker et al., 2010; Holtsmark, 2012; Zanchi et al., 2011; Schulze et al., 2012). The use of forest harvest residues for energy decreases the carbon sink capacity of forests if with bioenergy production the forest carbon stock increases at a slower rate than it would have increased in the absence of the bioenergy production (Cowie et al,. 2013). These aspects have an effect on the potential to reduce GHG emissions with this form of renewable energy. On the one hand, forest harvest residues, as well as other biomass sources for renewable energy, may replace fossil fuels. On the other hand, deployment of bioenergy can alter the carbon cycle (Schlamadinger et al. 1997). For example, there is a risk of reduction in the carbon stocks, which may offset the obtained emission savings compared to fossil fuels (Cowie et al. 2006; Chum et al. 2011). Biomass is different from other renewable energy sources, because only biomass is also part of the global carbon cycle (Schlamadinger et al., 1995; Berndes et al., 2013).

2.2 Forest carbon cycle

Forests are important in the global carbon cycle because they recycle and store carbon, and control the development of atmospheric concentrations of CO_2 (Canadell & Raupach, 2008; Pan et al., 2011). First, terrestrial ecosystems remove nearly one fourth of anthropogenic CO_2 emissions from fossil fuel burning and land-use change annually (GCP, 2014). A large share of these emissions is absorbed by forests (Pan et al., 2011). Second, forests store carbon temporarily in biomass and soil (Malhi et al., 1999). The size of the forest biomass carbon stock is determined by biomass growth and drain. Currently in Europe, fellings are below increment and increasing forest biomass stock acts as a sink (State of Europe's Forests 2011). However, in some parts of Western Europe this sink seem to have become saturated likely as a result from reaching a dynamic equilibrium with the current intensity of management, tree species and age-class distribution (Nabuurs et al. 2013). The size of carbon stocks of dead wood, litter and soil are controlled by carbon inputs from living trees, harvests and natural mortality together with the decomposition rate of organic matter, erosion and leaching (Cowie et al., 2006). Over half world's forest carbon is stored in the soil and litter carbon pool, and in boreal forests soils contain three times more carbon than biomass (Pan et al., 2011). Therefore, even small changes in this large carbon pool may have significant effects on the global carbon budget (Peng et al., 2008; Pan et al., 2011). Nevertheless, little information on the development of non-biomass carbon stocks is available compared to that on biomass (State of Europe's Forests 2011). Forestry influences the atmospheric concentration of CO_2 through changes in carbon storage in forests and forest products, substitution of energy intensive materials with wood products and displacement of fossil fuels with bioenergy (Nabuurs et al., 2007).

Bioenergy production from forest harvest residues changes the carbon cycle. Increasing forest harvest residue extraction decreases litter input to the carbon pools of dead wood, litter and soil, and consequently reduces forest carbon stocks (Schlamadinger et al., 1995; Palosuo et al., 2001; Ågren & Hyvönen, 2003; Hope, 2007; Strömgren et al., 2013). Combustion of harvested residues releases the carbon of the residues at once unlike slow decomposition in the forest. Therefore, carbon loss from the forest results in emissions to the atmosphere and increases the CO_2 concentration in the atmosphere.

The magnitude of carbon loss resulting from forest harvest residue extraction depends crucially on the decomposition rate of the residues in the forest. Factors that affect the decomposition rate include litter chemical composition, climate, nutrient availability, decomposer organisms and site-specific factors (Swift et al., 1979; Berg & McClaugherty, 2003). In addition, the diameter affects the decomposition of woody litter (Harmon et al., 2000; Tuomi et al., 2011a). Recently published extensive datasets of litter and dead wood decomposition measurements (Tarasov & Birdsey, 2001; Palviainen et al., 2004; Mäkinen et al., 2006; Vávrová et al., 2009) combined with advanced mathematical methods (Tuomi et al., 2009, 2011a) make it possible to estimate the decay rate of forest harvest residues more reliably than before. In turn, this makes it possible to estimate the carbon loss resulting from forest harvest residue extraction and energy use more accurately than before.

Forest management practices affect forest carbon budget (Jandl et al., 2007). For example, a conversion to shorter forest rotation periods decreases carbon stocks (Marland & Schlamadinger, 1995), whereas extending rotation lengths (Cooper, 1983; Liski et al., 2001; Kaipainen et al., 2004) and forest fertilization (Johnson, 1992) increase carbon stocks. The changes in forest management that increase carbon sequestration may offer means to compensate for the carbon loss resulting from forest harvest residue extraction.

2.3 Climate impact assessment

Various indicators are used to assess climate impacts of bioenergy. These indicators include, for example, GHG emissions from bioenergy systems, relative GHG savings describing the percentage of emission reduction with respect to the fossil alternative, and radiative forcing (RF) (Chum et al., 2011). RF is defined as the change in the net irradiance at the troposphere following, for example, an increase in a GHG concentration (Shine et al., 2003; IPCC, 2007). GHGs absorb the outgoing infrared radiation from the Earth. The chemical characteristics of a gas determine the wavelength it absorbs. The absorbed radiation is reradiated, and this process increases the temperature of the lower layers of the atmosphere. The longer the atmospheric lifetime of a GHG is, the longer the gas will stay in the atmosphere and affect radiative balance (Holmgren et al., 2007). A positive RF warms the surface of the Earth, whereas negative RF cools the surface.

Bioenergy production from forest harvest residues influences the atmospheric concentrations of GHGs through emissions related to changes in the carbon stocks and emissions from the bioenergy production chain (Chum et al., 2011). However, many previous studies estimating the GHG emissions of bioenergy from forest harvest residues have focused only on the emissions of the production chain (Gustavsson et al., 1995; Börjesson & Gustavsson, 1996; Börjesson, 2000; Forsberg, 2000; Wihersaari, 2005). To estimate the net reduction in the GHG emissions through the use of bioenergy both emission pathways should be accounted for (Schlamadinger et al., 1995).

Simulation models are useful tools to assess the changes in the carbon stocks and fluxes associated with increased forest harvest residue extraction (Sathre & Gustavsson, 2011; Zanchi et al., 2011; Domke et al., 2012; Routa et al., 2012; Alam et al., 2013). Some of these studies have considered dynamic changes in the forest carbon stocks, whereas others have not accounted for the timing of emissions and carbon sequestration. However, from the point of view of climate change mitigation, the timing of emissions matters. A pulse of CO_2 emitted to the atmosphere through biomass combustion stays in the atmosphere for decades (IPCC, 2007). Dynamic modelling of forest carbon stocks follows changes in the forest carbon stocks and fluxes from year to year, and offers an approach to investigate the timing of emissions and carbon sequestration. RF takes into account the atmospheric residence times, warming capacity and background concentrations of GHGs, providing a more comprehensive metric for climate impact assessment than the GHG emission calculations alone (IPCC, 2007). Together with dynamic modelling, radiative forcing provides a comprehensive metric of climate impact, because this approach takes into account both the time-dependence of GHG fluxes and atmospheric residence times of the GHGs (e.g. Kirkinen et al., 2008; Sathre & Gustavsson, 2011).

3. Materials and methods

In this dissertation, an approach for assessing climate impacts of bioenergy from forest harvest residues was developed. This approach was applied to quantify GHG emissions and climate impacts of forest residue bioenergy, to study ways to improve the climate impacts through management changes, and to estimate the costs of these changes. The approach consisted of an estimation of land-use-related emissions, an estimation of production chain GHG emissions and an assessment of climate impact (Papers I-IV). Land-use-related emissions resulted from changes in the forest carbon stocks, whereas production chain emissions derived from the biomass procurement chain and from the combustion at the power plant (Figure 1). Paper V introduces an approach that includes financial analyses in the framework. This approach combined established, tested and widely used simulation models from the scientific literature.

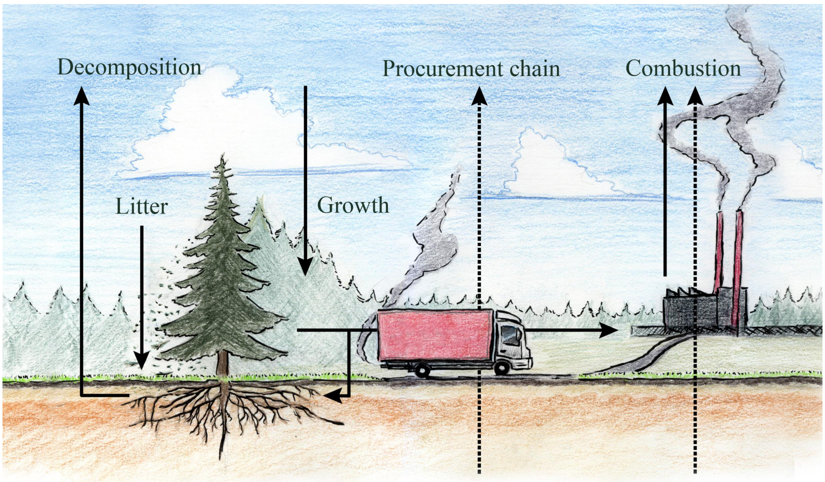

Figure 1. Overview of the estimation of GHG emissions. Solid lines represent flows of biogenic carbon and dashed lines flows of fossil carbon.

This dissertation focused on bioenergy production from forest harvest residues. These residues were collected from final fellings in addition to saw logs and pulpwood. Needles were assumed to be left in the forest to avoid nutrient losses (Papers I, III-V). Thinning wood was collected for energy from young stand thinnings, either as whole-tree or stem only harvest (Paper II). The residues were combusted for bioenergy immediately after collection in the harvesting year. Waste and residues from wood processing industries and stem wood are important sources of bioenergy (e.g. Finnish Statistical Yearbook of Forestry, 2013), but were excluded from this study.

The GHG emission estimates covered land-use-related emissions (Papers I-IV) and production chain emissions (Papers I-II). To estimate the land-use-related emission per energy unit, first the carbon loss resulting from forest residue harvesting was estimated, and second this carbon loss was proportionated to the energy produced from the harvested residues. The carbon loss was quantified by simulating the annual development of forest carbon stocks over the selected period, up to 120 years, with and without forest harvest residue extraction. In all papers, the reference case to forest harvest residue extraction and energy use was to leave the residues to decompose in the forest. The carbon loss was the difference between the forest harvest residue extraction case and the reference case. The emissions per energy unit in the year *t* we estimated by proportioning the cumulative carbon loss until year *t* with the cumulative primary energy (Papers I-II) or cumulative heat or electricity (Papers III-IV) obtained until year *t* from the harvested residues. To include the GHG emissions of the bioenergy production, the CO_2, CH_4 and N_2O emissions from the production chain were estimated based on the literature, and added to the land-use-related emissions. The production chain emissions originated from transport at the harvest site, chipping in intermediate storage, machine transfer, stump harvesting and, long-distance transport, and included GHG emissions other than CO_2 from combustion (Paper II).

In Papers I and II, the forest carbon loss was estimated based on the decomposition rate of the harvested residues. It was assumed that forest harvest residue extraction did not affect the growth of the next vegetation generation, and the growing stock absorbed and stored carbon similarly in the residue harvesting case and in the reference case. The only difference between these two cases was that in the bioenergy case the carbon of the residues was emitted to the atmosphere without delay through combustion, whereas in the reference case the emissions occurred gradually. Therefore, the carbon loss was the amount of carbon remaining in the residues if they were left to decompose in the forest. To estimate the emissions of continuous bioenergy production, the stand-level analyses of forest carbon stock changes were extended to landscapes (Papers I-II). Papers I and II give details of the approach.

The carbon loss was estimated by simulating the decomposition of the harvested residues with the dynamic litter and soil carbon model Yasso07 (Tuomi et al., 2009, 2011a, 2011b, 2011c).

The Yasso07 model was applied because it combines an extensive data set of measurements with advanced mathematical modelling. In the development of the Yasso07 model, in total over 12 000 measurements of nonwoody litter decomposition, woody litter decomposition and accumulation of soil organic carbon were used. Because of the measurements on the accumulation of soil organic carbon, the Yasso07 also covers the late phases of decomposition and the formation of humus. These two processes are not captured in negative exponential models that are fitted to measurements of woody litter mass remaining (e.g. Melin et al. 2009). An advantage of the Yasso07 compared to other soil models or plant-soil models is the low requirement for input data (Palosuo et al., 2012). To run the model, only information on the quantity and quality of the litter input and the climatic conditions are needed. In the Yasso07 model, the decomposition rate of different types of carbon inputs depends on the chemical composition of the input types and the climate conditions (Tuomi et al., 2009). The model divides nonwoody and woody litter into four chemically distinguishable fractions that decompose at their unique rates. The fractions are i) water soluble (W); ii) ethanol soluble (E); iii) acid hydrolysable (A); and iv) neither soluble nor hydrolysable (N). In addition, there is a humus (H) fraction consisting of more recalcitrant compounds formed of the decomposition products of the A, W, E, and N fractions. The decomposition rate of woody litter also depends on the diameter of the litter. An increase in the diameter of woody litter slows down the decomposition rate (Tuomi et al., 2011a). The parameter values of the Yass07 were estimated with Bayesian inference. The Bayesian model-selection was used in the development of the model to avoid overparameterization (Tuomi et al. 2009; Tuomi et al., 2011a). In addition, the validity of the Yasso07 model has been widely tested (Tuomi et al., 2009; Karhu et al., 2011; Thum et al,. 2011; Rantakari et al., 2012; Lu et al., 2013; Ortiz et al., 2013).

In Papers III-V, the forest carbon loss was determined by simulating development of forest carbon stocks with and without forest harvest residue extraction combined with changing climate and stem wood harvests (Paper III) and changes in forest management practices (Papers IV-V). To investigate the possible carbon loss from the European litter and soil carbon stocks, assuming that a sustainable bioenergy potential of forest harvest residues was adopted (Elbersen et al., 2011), a spatially explicit modelling framework was developed (Paper III). This framework linked the Global Forest Model G4M (Kindermann et al., 2008, 2013), which estimates the development of stem biomass and harvests in Europe under changing environmental conditions, with the Yasso07 model, which simulates the corresponding changes in the litter and soil carbon stocks (Paper III). The G4M is a spatially explicit (25 km x 25 km) model that simulates the stock and harvests of stem wood (Kindermann et al., 2008, 2013). These G4M estimates were converted to total tree biomass and litter input to the soil according to a calculation scheme presented in detail in Paper III. Papers IV and V investigated means to compensate for the carbon loss resulting from forest residue harvesting and the costs of compensation to the forest owner at stand-level in Finland. In these papers the development of forest carbon stocks was simulated with a combination CO2FIX model (Masera et al., 2003; Schelhaas et al., 2004), and the Yasso07 model (Papers IV-V). The CO2FIX model is a bookkeeping model that simulates the annual biomass carbon stocks and fluxes at hectare scale. In the CO2FIX simulations the values of current annual increment and the timing and the quantity of forest thinning were adopted from Kaipainen et al. (2004), because these values are based on Finnish growth and yield tables and are in line with the current good practice guidance for forestry (Äijälä et al. 2014). To estimate climate impacts of different bioenergy scenarios in Paper IV, stand-level analyses were utilized to simulate cases in which a forest landscape is taken into bioenergy production.

The climate impact was assessed in terms of radiative forcing (Papers II, IV). The emissions of forest harvest residue bioenergy increased the atmospheric concentrations of GHGs, and consequently changed RF. The changes in RF were estimated with the modified version (Lohila et al., 2010) of the REFUGE model (Monni et al., 2003). In this model, RF is estimated by integrating the response function related to the decay of a series of annual concentration pulses over a period of time, taking into account annual variation in the emissions and the uptake, as well as the background concentrations of the long-lived GHGs (CO_2, CH_4 and N_2O). Instantaneous RFs were calculated to follow yearly changes in RF, and cumulative RFs to account for the warming impact of the long-lived GHG of the emissions from the previous years, i.e. the accumulated energy. The variation in the climate impact within a country was studied by estimating the GHG emissions of forest harvest residues that varied in biomass diameter, species, climatic conditions of the harvest site and young stand thinning methods (whole tree or stem only) (Paper II).

The achievable emission savings from heating and electricity generation in different EU countries were estimated by comparing the emissions from bioenergy from forest harvest residues to fossil fuel alternatives (COM, 2010), including energy conversion losses in the calculations (Paper III). The comparator values represented fossil fuel mixes in the EU-27 countries (COM, 2010).

To find means to improve the climate impacts of forest harvest residue bioenergy, the first step was to determine significant factors affecting the magnitude of the GHG emissions (Paper II). Because Paper II showed that GHG emissions result mainly from changes in the forest carbon stocks, whereas the emissions from the production chain contribute only little to the total emissions, Papers III-V focused only on the forest carbon stocks. Thus, the second step was to identify changes in the forest carbon cycle that would compensate for the carbon loss resulting from forest residue removal over the forest rotation period following the residue extraction. In this case, bioenergy from forest harvest residues could be justifiably claimed as carbon neutral (Papers IV). In Paper IV the carbon loss was considered to be compensated, and bioenergy carbon neutral, when the average of the total forest carbon (biomass and soil) over a forest rotation period was equal to the corresponding value in the no-residue-removal scenario. Two theoretical approaches to compensate for the carbon loss from forest were identified, first an increase in the carbon input to the forest carbon stock, and second a decrease in the outflow from the stock. The inflow was raised in the simulations by increasing tree growth, lengthening the forest rotation period. The reduction in the outflow was a result of a decrease in the decomposition rate of the remaining organic matter (Paper IV). The changes in the forest carbon cycle were studied with a combination of two simulation models: CO2FIX and Yasso07. In addition, Paper IV discussed if these theoretical means for carbon loss compensation are likely to occur as result of forest residue harvesting, forest fertilization or changes in environmental conditions.

The cost of carbon loss compensation to the forest owner was estimated by comparing net present values (NPV) of alternative management regimes with the NPV of the no-residue-removal option (Paper V). A decrease in the NPV compared to the no-residue-removal option was taken as the financial cost for balancing the carbon loss. Alternative management regimes included different levels of forest fertilization, prolonged rotation periods, choice of the type of forest residues harvested, and leaving high stumps. The costs were studied at different time periods (20, 50, 100, 110, 120 years) and discount rates (2, 3, and 4%). The NPV calculations accounted for the income from pulpwood, logs, and forest residues and the costs of forest fertilization, site preparation and planting. Leaving high stumps reduced the income from pulp and saw wood. Prolongation of the forest rotation period postponed income from the final felling. The costs and incomes were discounted to the time of the first final felling, when the choice between forest management and residue harvesting regimes took place. In Paper V, the carbon loss was considered to be fully compensated for when both the total forest carbon stock and the soil carbon stock were equal to or larger than these stocks in the no forest residue harvesting scenario after the studied time period. This very strict requirement of carbon neutrality was applied to avoid a decrease in both biomass stock and soil carbon stock, because measures that compensate for the total carbon loss may not prevent soil carbon loss (Paper IV). Since it is debatable who the actual payer of the costs should be, the additional cost of carbon neutrality to the end-user of the forest residue-based electricity was also calculated. This additional cost was the change in the NPV compared to the no residue removal regime proportioned to the energy produced from the extracted forest harvest residues.

Nonlinear programming was used to calculate the optimal combination of alternative forest management and residue harvesting regimes for a hypothetical forest area so that the cost of carbon loss compensation would be minimized for the forest owner.

4. Main results

The extraction of forest harvest residues for bioenergy reduced the simulated litter and soil carbon stocks. The simulations carried out for the climatic conditions of southern Finland showed that if left to decompose in the forest, branches of Norway spruce had 30-55% and stumps 63-81% of their initial mass still remaining ten years after final felling, depending on the diameter of the residues. The decay rate slowed down over time, and after 100 years the branches had still 2-16% and the stumps 19-28% of their initial mass remaining (Paper I). Therefore, harvesting these residues for bioenergy reduced the carbon stocks of litter and soil compared to a situation in which these residues were left to decompose in the forest.

In European countries, the extraction of the sustainable amount of forest harvest residues reduced the simulated carbon stocks of litter and soil on average 3 tC ha^{-1} by the year 2100. There were large differences in the carbon loss between countries depending on the amount of residues extracted, the availability of forest land for the residue harvesting and the climatic conditions. Generally, the reduction was small compared to the size of the carbon stock, but significant when related to the energy produced from the residues (Paper III).

When the practice of forest harvest residue extraction and energy use was started, the total GHG emissions were equal to, or even larger than emission of fossil fuels (Papers I-III). A great majority (85-98%) of the total emissions resulted from the reduction in the carbon stock (Papers I, II). However, continuing bioenergy production decreased the emissions per energy unit over time because the residues gradually release CO_2 into the atmosphere if left to decompose in the forest. The rate of the emission decrease depended on the decomposition rate of the harvested residues. The faster the residues decomposed, the smaller the emissions from producing energy from these residues were. For example, producing bioenergy from Norway spruce branches in southern Finland for 20 years decreased the emissions from 105 to 47 g CO_2 eq. MJ^{-1}, whereas the corresponding emissions from stumps, which are more recalcitrant to decomposition, reduced from 105 to 92 g CO_2 eq. MJ^{-1}. Continuing bioenergy production for 100 years reduced the emissions of bioenergy from branches to 21 g CO_2 eq. MJ^{-1} and those of stumps to 56 g CO_2 eq. MJ^{-1} (Paper II). For comparison, the GHG emissions from the fossil fuel production chain and combustion were 110, 89 and 78 CO_2 eq. MJ^{-1} for coal, heavy fuel oil and natural gas respectively (Paper II).

The emissions and consequent climate impacts varied significantly within a country (Paper II). The variation followed the differences in the decomposition rate (Paper II). The most significant factors affecting the decomposition rate were the size of the harvested residues and the climatic conditions of the harvest area. Tree species or the harvesting method of young thinning wood (whole tree or stem-only) had a smaller effect on the magnitude of the emissions. In Finland, the lowest GHG emissions occurred when birch branches were harvested for energy from southern Finland and the highest when spruce stumps from northern Finland were used (Paper II). For example, after 20 years, the emissions of birch branch bioenergy were 42 g CO_2 eq. MJ^{-1} and those of spruce stump bioenergy over two times higher, 98 g CO_2 eq. MJ^{-1}. The relative difference between these bioenergy options increased over time. After 100 years, the corresponding emissions from the spruce stump bioenergy were three and half times as high as the emissions from the birch branch bioenergy (Paper II).

Because of the time-dependency of the emissions, bioenergy from forest harvest residues delivered climate benefits compared to fossil fuels with a delay (Papers I-III). The GHG emissions per unit of primary energy were lower than those of fossil fuels after only a few years when branches were harvested for bioenergy, whereas it took decades for the emissions from stumps to decrease below the emissions of fossil fuels (Papers I-II). In most European countries electricity generation from forest harvest residues would need to be continued for over 20 years to achieve any emission reductions compared with fossil fuels. The magnitude of emissions savings from fossil fuel substitution varied between the countries because of differences in the carbon loss. In order to reach the 60% CO_2 emission reduction target, which corresponds to the target set in the Renewable Energy Directive, in heat and power generation bioenergy production would need to be continued for 60-80 years in Europe (Paper III). In the short-term, forest residue bioenergy increased atmospheric concentration of GHGs, causing an increase in RF, in other words, a climate warming impact. In the longer term, the climate impact, measured with cumulative radiative forcing metrics, was smaller compared to fossil fuels (Paper II). Producing one unit of primary energy each year from forest harvest residues reduced cumulative radiative forcing by 29-77% compared to fossil fuels in 100 years (Paper II), depending on the used residues and reference fossil fuel.

Two approaches improved the climate impacts of forest harvest residue bioenergy. These approaches were the prioritization of quickly decomposing residues in forest residues harvesting (Papers I-II) and the increase of carbon sequestration through changes in forest management (Paper IV). Following the differences in the decomposition rate, the energy use of branches instead of stumps reduced the climate impact measured in terms of cumulative radiative forcing by 54% in 100 years. As the residues decay at a slower rate in the cool climatic conditions of northern Finland, collecting branches from southern Finland instead of stumps from northern Finland further reduced the climate impact by 5 percentage units in 100 years (Paper II).

Another means to improve the climate impacts was to compensate for the carbon loss with changes in the forest carbon cycle (Paper IV). To balance for the carbon loss resulting from forest residue harvesting for bioenergy, a 10% increase in tree growth or delaying the final felling for 20 years from 90 to 110 years was needed. However, these changes did not prevent litter and soil carbon loss. To maintain litter and soil carbon stock a 38% increase in tree growth or a 21% decrease in the decomposition rate of the remaining organic matter was required. Only with these changes in the carbon cycle, could bioenergy from forest harvest residues be justifiably claimed as carbon neutral. The carbon neutrality was achieved with a delay because the carbon loss occurred instantaneously, whereas the increase of carbon sequestration was a gradual process. In the simulated cases the carbon loss compensation took from 22 to 37 years depending on the change in carbon sequestration. As a result of this delay, all the alternatives studied had a climate warming impact for the study period of 100 years, except for the growth increase of 38%, which had a warming impact for the first 62 years and then a cooling impact. Due to the timing of the emissions and the slow removal of CO_2 from the atmosphere, even carbon neutral cases had a warming impact on climate, and thus were not climate neutral. Although carbon neutrality did not produce climate neutrality, the increases in the carbon sequestration resulted in 50% smaller climate impact or eventually even a cooling impact compared to the production of bioenergy without the compensation for the carbon loss. Based on previous studies, it appeared unlikely that forest residue harvesting would cause the additional carbon sequestration needed for the carbon loss compensation (Paper IV).

Some changes in forest management and harvesting practices provided cost-effective means to reduce carbon loss from forest and improve the climate impacts of bioenergy from forest harvest residues. Paper V presented combinations for forest management changes and residue harvesting regimes for carbon loss compensation. The costs to the forest owner from carbon loss compensation varied widely from 5 to 4000 € ha $^{-1}$ between the management options. Among the regimes that fully compensated for the carbon loss in all time periods studied, the most cost-effective one was to harvest only branches and adopt the least intensive fertilization regime. In these cases the cost to the forest owner was from 110 to 370 € ha $^{-1}$ depending on the interest rate and studied time period. The highest costs, from 310 to 1080 € ha $^{-1}$, resulted from branch harvesting with the most intensive fertilization regime. For the end-user of biomass-based electricity, the additional cost of carbon neutrality ranged from 0.2 to 3.0 Euro cent kWh $^{-1}$.

Optimization results indicated that combinations of changes in forest management and harvesting practices might enable simultaneous bioenergy production from forest residues, carbon loss compensation and even an increase in the NPV of the forest stand. The increase in the NPV resulted from additional income from timber. The optimal management combinations depended on the time period studied. The sooner the full carbon compensation was required, the more intensive and more expensive compensatory measures were needed. In addition, with the 50-year time period the combination of management regimes that minimized the costs of carbon loss compensation consisted of a large number of different regimes. With time periods of 90 years or longer, there were only two to three management regimes in the combination that minimized costs, although there were more alternatives that could compensate for carbon loss than in shorter time periods.

5. Discussion

5.1 Implications

Bioenergy from forest harvest residues delivered significant but delayed GHG emission savings compared to fossil fuels. The findings of this dissertation are consistent with other studies and show that this delay results from the time-dependency of the emissions and the atmospheric dynamics of GHGs (Holmgren et al., 2007; Kirkinen et al., 2008; McKechnie et al., 2011; Sathre & Gustavsson, 2011). This delay is problematic from the point of view of climate change mitigation, because limiting the global temperature rise to two degrees compared to pre-industrial levels requires substantial cuts in anthropogenic GHG emissions within the next decades (IPCC, 2014b). In this dissertation, the GHG emissions of bioenergy from forest harvest residues were of the same order of magnitude as fossil fuels when bioenergy production was started or increased. The emissions decreased over time because the residues would emit CO_2 through decomposition even if left in the forest. This dissertation and previous studies demonstrate the following: assuming that replacing fossil fuels with bioenergy from forest harvest residues delivers instantaneous and full GHG emission savings overestimates the climate change mitigation potential of this form of bioenergy (Kendall et al., 2009; Cherubini et al., 2011a).

Current energy and climate policies do not fully account for the carbon stock changes. In this dissertation, the decrease in the carbon stocks had a significant effect on the climate impacts of bioenergy from forest harvest residues. This decrease in the carbon stocks is even greater if the bioenergy is produced from biomass derived from additional fellings. This is because additional forest harvests cut the carbon sink of biomass and soil, whereas increasing the extraction of forest harvest residues reduces mainly litter and soil carbon stocks (Holtsmark, 2012; Sievänen et al. 2014). Other studies have shown the importance of accounting for carbon stock changes in climate impact assessment of bioenergy derived from additional fellings (Schulze et al., 2012; Kallio et al., 2013; Sievänen et al., 2014), and from systems involving a change in the land-use (Fargione et al., 2008; Searchinger et al., 2008, 2009; Melillo et al., 2009). Nevertheless, the European Renewable Energy Directive, for example, accounts for the changes in the carbon stocks only if they are associated with land-use change (2009/28/EC, 2009). In the Kyoto protocol, during the first commitment period, a party could choose not to report changes in the carbon pools if it could verifiably show that the pool is not a carbon source. In addition, a party could choose not to include forest management in the reporting (UNFCCC, 2006). During the second commitment period, reporting of the changes in the forest carbon stocks is mandatory, but the decrease in the carbon stock is not accounted for if the carbon sink of the forest remains above the margin of the set forest management reference level (UNFCCC, 2012). If increased levels of forest biomass harvesting are included in the forest management reference level, the reduction in the forest carbon sink resulting from these forest bioenergy policies is not accounted for. All these shortcomings in the climate and energy policies distort net emission calculations and may lead to the underestimation of measures to mitigate climate change efficiently. However, a GHG accounting system that includes these carbon stock changes already exists. Unlike the Kyoto protocol, the guidelines for reporting under UNFCCC include all emissions and removals from agriculture, forestry and other land-use sectors (previously land-use, land-use change and forestry sector) in the total emissions of a country (IPCC, 2006). Therefore, the problem is not in the carbon accounting or in the UNFCCC guidelines, but in the implementation of the carbon neutrality assumption in international policies.

If the changes in the forest carbon stocks were fully included in the climate change mitigation agreements, excessively ambitious emission saving requirements might impede the use of forest harvest residues for bioenergy. The European Renewable Energy Directive (RED) sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. In addition, the directive establishes sustainability criteria for biofuels and bioliquids (2009/28/EC 2009). The objective of the sustainability criteria is to ensure that bioenergy production delivers significant reductions in GHG emissions and does not lead to biodiversity loss (2009/28/EC 2009). The sustainability criteria of the directive mandates that GHG emission savings from the use of biofuels shall be at least 60% compared to use of fossil fuels from 2018 onwards. The calculation rules for showing the required emissions savings are also set in the sustainability criteria. Currently, the sustainability criteria of the RED are set for biofuels and bioliquids, but an extension of the criteria to solid and gaseous bioenergy is being planned (COM, 2010; Lamers et al., 2013; Fritsche et al., 2014). This dissertation demonstrates that if changes in the forest carbon stocks are fully accounted for, it is difficult to achieve the 60% emission reduction with forest harvest residues in heating and electricity generation. This finding is in agreement with studies on liquid biofuels (Holma et al., 2013; Koponen et al., 2013).

Regarding the mandatory emissions reduction targets, such as the 60% target, this dissertation also highlights an effort-sharing issue, how to define one target value for the emissions reduction when the achievable emissions cuts with forest harvest residue bioenergy differ significantly among the EU countries. Biofuels used for compliance with the national renewable energy targets are required to fulfil the sustainability criteria of the RED. If a source of energy does not meet the emission reduction target set in the sustainability criteria, it has to be replaced by another renewable energy source to reach the agreed renewable energy target (2009/28/EC, 2009; Agostini, et al., 2013). Therefore, the excessively ambitious emission reduction target may be problematic because bioenergy from forest harvest residues can pave the way for sustainable energy systems. This is because, in the longer term, the use of forest residues for energy delivers emissions savings and has a smaller climate impact compared to fossil fuels, which was shown in this dissertation. In addition, bioenergy from forest harvest residues may promote diversification of energy sources, energy independency without threatening food production, and rural development with creation of new jobs (Creutzig et al., 2014; Roach & Berch, 2014).

In some cases sustainable forest management and forest certification have been considered as a guarantee for sustainable bioenergy production from forest harvest residues (Stupak et al., 2011). This dissertation shows that otherwise sustainable levels of forest residue harvesting may cause soil carbon loss. In addition to climate impacts, this carbon loss may put important functions of the soil organic matter at risk, e.g. amendment of soil structure, water regulation, nutrient cycling, site fertility and biological activity (Schils et al., 2008; Agostini, et al., 2013). The reduction of site fertility (Luiro et al., 2009; Helmisaari et al., 2011) may further increase the net GHG emissions from bioenergy production (Cowie et al., 2006). Given that one of the incentives to increase the use of bioenergy is to reduce GHG emissions and mitigate climate change, it is logical to include emissions savings in the sustainability criteria (2009/28/EC, 2009). Nevertheless, sustainability of timber harvest levels does not yet ensure GHG emission savings or sustainability of forest harvest residue bioenergy (Haberl et al., 2012).

This dissertation and other studies demonstrate that forest harvest residues cannot be considered as a carbon or climate neutral source of energy (Savolainen et al. 1994; Walker et al., 2010; Lindholm et al., 2011; McKechnie et al., 2011; Sathre & Gustavsson, 2011; Zanchi et al., 2011; Domke et al., 2012). This does not imply that bioenergy from forest harvest residues should be excluded from the future renewable energy portfolio. However, efficient mitigation of climate change requires reliable and comprehensive estimates of the climate impacts of mitigation activities, including bioenergy. These estimates are needed to quantify the climate change mitigation potential of bioenergy and to determine adequate means for mitigation in the other sectors. The delay in the emission savings with bioenergy implies the need for even larger reductions in the emissions from other sectors in order to reach the emission pathway in which emissions start to decrease in the near future. The findings of this dissertation and other studies illustrate that it is crucial to include possible decrease in the carbon stocks in the assessment of GHG mitigation potential of bioenergy (e.g. Schlamadinger et al., 1997; Cowie & Gardner, 2007; Cherubini et al., 2009; Johnson, 2009; McKechnie et al., 2011).

Changes in current forest management and residue extraction practices may offer cost-effective ways to improve the climate impacts of bioenergy from forest harvest residues. This dissertation introduced two approaches to improve climate impacts, i) minimizing carbon loss by prioritizing forest residue removal, and ii) compensating for the carbon loss by increasing carbon sequestration. For example, producing bioenergy from Finnish branches instead of stumps reduced the total GHG emissions to one third and halved the climate impact compared to stumps in 100 years. Different combinations of residues collected together with forest fertilization or prolongation of rotation period resulted in truly carbon neutral bioenergy. Although the carbon neutrality does not guarantee climate neutrality because carbon loss and increased carbon sequestration do not occur simultaneously (Cherubini et al., 2011a, 2011b), all changes that bring the bioenergy system closer to carbon neutrality improve the climate impacts.

Practical forest management planning considers various aspects in addition to climate impacts of bioenergy from forest harvest residues. Forest fertilization may be a cost-effective means to compensate for the carbon loss resulting from the extraction of forest harvest residues. However, forest fertilization may affect wood quality and involves environmental concerns, e.g. changes in soil properties and flora and fauna, increased risk of nutrient leaching and abiotic and biotic damage, such as wind throws, insect damage, fungus damage and moose browsing (Nilsen, 2001; Saarsalmi & Mälkönen, 2001). In addition to fertilization and prolongation of forest rotation period, also changes in thinning regimes and stocking densities (Routa et al., 2012; Alam et al., 2013) increase carbon sequestration. Including forest carbon budget as one of the aspects in forest management planning may create new management regimes that consider climate impacts in addition to other aspects of sustainability.

5.2 Applicability of the results

The approach presented can be considered suitable for climate impact assessment because it has an appropriate reference case (Smith et al. 2014). In this dissertation, the climate impacts were studied comparing systems with and without bioenergy production. This comparison shows the climate impact of an activity (Helin et al., 2013; Creutzig et al., 2014, Smith et al. 2014). The reference case was to leave the residues to decompose in the forest. If the alternative to bioenergy use was simply to burn the residues on the roadside (Roach & Berch, 2014; Ter-Mikaelian et al., 2014), the energy use of the residues would deliver climate benefits sooner than estimated in this dissertation. Calculations that use zero carbon sink as a reference level and show that increasing forest harvest residue removal does not turn forests from carbon sinks to carbon sources may illustrate properties of a bioenergy system, but the relevance of such an approach for climate impact assessment is questionable (Helin et al., 2013). This is because the carbon sink capacity of forests is important for climate change mitigation (Pan et al., 2011; GCP, 2014, Smith et al. 2014). Without forests, climate change would be even more severe than it is. For example, in Finland the agriculture, forestry and other land-use sector offset from 20 to over 60% of the annual emissions from the other sectors during the period 1990–2012. Forests were the main contributor to the removals (NIR 2014). Because forests have an important role as sources for bioenergy as well as a carbon sink, quantitative information on the changes in the carbon stocks is needed to provide comprehensive estimates of the true climate impacts of bioenergy energy production.

The approach presented also accounts for the timing of the GHG emissions. In some modelling studies carbon emissions and uptake occurring during the studied time period, for example a forest rotation period, are summed up (Routa et al., 2012; Alam et al., 2013). However, this approach ignores the fact that emissions from biomass combustion and regrowth do not occur simultaneously, and consequently results in an overestimation of the climate change mitigation potential of bioenergy (Kendall et al., 2009; Cherubini et al., 2011a; Sathre & Gustavsson, 2011; Pingoud et al., 2012). In this dissertation the timing of the emissions and carbon sequestration were taken into account with dynamic forest carbon modelling and radiative forcing metrics.

The approach for estimating biogenic CO_2 emission from bioenergy in this dissertation is consistent with the UNFCCC guidelines. This approach even applies the same litter and soil carbon model that is used in some national greenhouse gas inventories for the UNFCCC (NIR, 2012a, 2012b, 2012c, 2012d). The same approach can be applied to estimate effects of different bioenergy policies on national net GHG emissions (Kallio et al., 2013).

The estimated GHG emissions and consequent climate impacts depend crucially on the decomposition rate of the forest harvest residues. The decay of the residues was simulated with the process-based Yasso07 model. The measurements for model development include an extensive data set of litter decomposition measurements of nonwoody litter across Europe and North and Central America, data sets on the decomposition of woody litter in Finland and neighbouring regions in Estonia and Russia, and measurements on the accumulation of soil organic carbon. Because the Yasso07 builds on the measurements on the accumulation of soil organic carbon, the model also covers the late phases of decomposition and the formation of humus. This large set of data covers spatially and temporally the cases simulated in this dissertation well. The validity of the Yasso07 model has been tested at global (Tuomi et al., 2009; Thum et al., 2011), national (Rantakari et al., 2012; Ortiz et al., 2013) and site scales (Karhu et al., 2011; Lu et al., 2013). Based on these studies the Yasso07 model is suitable for estimating the decomposition rate of litter, the carbon stocks of litter and soil, and changes in these stocks dealt with in this dissertation. The Yasso07 model can also account for the effect of climate change because it is driven by climate variables.

The approach presented in this dissertation shows the magnitude of GHG emissions and the climate impact of bioenergy from forest harvest residues. The assessment of climate impact in this dissertation focused only on GHG emissions, and the approach presented could be extended by including other climatic forcers, such as albedo and black carbon (Bright et al., 2011; Creutzig et al., 2014). This dissertation highlights which factors affect the magnitude of the emissions significantly. It shows that emissions result mainly from the reduction in forest carbon stock, whereas the emissions from the rest of the production chain contribute only a little to the total emissions. Other authors have drawn similar conclusions (e.g. Palosuo et al., 2001; Jäppinen et al., 2014). Consequently, the most efficient means to reduce total emissions are those that minimize the carbon loss from forest. This dissertation gives an indication of the dynamics of alternative measures for carbon loss compensation and an estimate of the costs of these measures. In addition, this dissertation presents estimates of CO_2 emission reductions with bioenergy from forest harvest residues in different EU countries. Comparisons with independent data in Paper III supported the adequacy of the approach. The quantitative estimates presented for individual countries involve uncertainty, but the general conclusions are not sensitive to these uncertainties.

The uncertainty of the quantitative estimates could be reduced with more detailed information about the relevant parameters applied in the approach. For example, the response to repeated fertilizations was estimated with a model based on empirical data, and it was in line with the current recommendations for forest fertilization (Kukkola & Saramäki, 1983; Äijälä et al., 2014). This model was considered to be the best available model for the Finnish conditions, but the fertilization response is always site-specific (Nilsen, 2001; Nohrstedt, 2001; Saarsalmi & Mälkönen, 2001). In this dissertation, the diameters of woody litter ranged from 1 to 35 cm. Because the diameter of the woody litter affects the decomposition rate in the model, better knowledge on the diameter distribution branches and stump-root systems would improve the accuracy of the presented results (Liski et al., 2014). The magnitude and duration of the possible CO_2 emissions resulting from soil disruption and duration of these emissions are still under investigation (Johansson, 1994; Walmsley & Godbold, 2010; Strömgren et al., 2012). Therefore, these emissions were not included in this dissertation. In addition, the increased energy consumption may offset partly the emission savings resulting from fossil fuel replacement (Agostini, et al., 2013). This effect is called the rebound effect, i.e. a reduction in expected gains because of behavioural or other systemic responses. In the longer term, the use of forest residues for energy may reduce GHG emissions per produced energy unit compared to fossil fuels. If the overall energy consumption increases simultaneously, it is possible that the total emissions do not decrease.

The means and the costs of carbon loss compensation were studied only in Finland, where tree growth and decomposition are slow because of cool climatic conditions. Consequently, the carbon loss resulting from forest residue harvesting and the additional carbon sequestration needed to balance for the loss would be smaller in warmer climate. However, the approach to calculate the cost of carbon loss compensation is applicable to other locations. The estimates of the costs of carbon loss compensation were established by adopting a very strict requirement for carbon neutrality, so that the carbon loss was considered to be fully compensated for when both the total forest carbon stock and the soil carbon stock were equal to or larger than these stocks in the scenario involving no forest residue harvesting. This requirement was applied to prevent permanent soil carbon loss. Compensating carbon loss by maintaining the average total carbon stock over a rotation period results in zero net emission to the atmosphere over the same time period. In that case, the required increase in the carbon sequestration for carbon loss compensation, and consequently the costs, would be smaller than in this dissertation. The additional cost of carbon neutrality was estimated for the end-user of electricity. If the residues were combusted with higher conversion efficiency, for example, in combined heat and power plants, the additional cost of carbon neutrality per energy unit would be smaller than in this study. Regardless of the cool climatic conditions in Finland, and the strict carbon neutrality requirement and low conversion efficiency, this dissertation identifies inexpensive means to compensate for the carbon loss. This indicates that it is possible to produce carbon neutral bioenergy from forest harvest residues cost-efficiently.

6. Conclusions

Bioenergy from forest harvest residues may deliver significant GHG emission savings compared to fossil fuels. However, these climate benefits come with a delay, and are smaller than has been previously thought based on the assumption of carbon neutrality of bioenergy. This is because increasing forest harvest residue extraction and energy use reduces forest carbon stock and carbon sink capacity. Therefore, transformation to an energy system using forest harvest residues may even increase GHG emissions to the atmosphere compared to fossil fuels. Quantitative estimates of the emissions of bioenergy from forest harvest residues are needed to prioritize those bioenergy options that deliver the greatest climate benefits and to ensure adequate emission cuts in other sectors. The inclusion of forest carbon stock changes in the estimation of the emissions is crucial for a comprehensive climate impact assessment. Changes in forest management and residue harvesting practices offer means to improve the climate impacts of bioenergy from forest harvest residues, and these changes may even be inexpensive for the forest owner and the end-user of bioenergy. However, this requires careful planning to minimize other possible environmental risks. Abandonment of the carbon neutrality assumption is an essential cornerstone in the planning of new forest management that maximizes the achievable climate benefits of bioenergy from forest harvest residues without jeopardizing other aspects of sustainability. The approaches presented in this dissertation can be applied in the development of sustainable bioenergy solutions.

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Errata

Paper II contains the following errors

i) The correct form of the end of the sentence on page 4 is : " … except for the late phases of decomposition for which the Yasso07 estimates of mass remaining are higher than those of Melin et al. (2009) and Palviainen et al. (2010)."

ii) In Figure 5 (MW/m^2) should be (mW/m^2).

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