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Sanni Väisänen

Greenhouse gas emissions from peat and biomass-derived fuels, electricity and heat —

Estimation of various production chains by using LCA methodology

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1381 at Lappeenranta University of Technology, Lappeenranta, Finland on the 7th of February, 2014, at noon.

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Abstract

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More discussion is required on how and which types of biomass should be used to achieve a significant reduction in the carbon load released into the atmosphere in the short term. The energy sector is one of the largest greenhouse gas (GHG) emitters and thus its role in climate change mitigation is important. Replacing fossil fuels with biomass has been a simple way to reduce carbon emissions because the carbon bonded to biomass is considered as carbon neutral. With this in mind, this thesis has the following objectives: (1) to study the significance of the different GHG emission sources related to energy production from peat and biomass, (2) to explore opportunities to develop more climate friendly biomass energy options and (3) to discuss the importance of biogenic emissions of biomass systems. The discussion on biogenic carbon and other GHG emissions comprises four case studies of which two consider peat utilization, one forest biomass and one cultivated biomasses. Various different biomass types (peat, pine logs and forest residues, palm oil, rapeseed oil and jatropha oil) are used as examples to demonstrate the importance of biogenic carbon to life cycle GHG emissions. The biogenic carbon emissions of biomass are defined as the difference in the carbon stock between the utilization and the non-utilization scenarios of biomass. Forestry-drained peatlands were studied by using the high emission values of the peatland types in question to discuss the emission reduction potential of the peatlands. The results are presented in terms of global warming potential (GWP) values. Based on the results, the climate impact of the peat production can be reduced by selecting high-emission-level peatlands for peat production. The comparison of the two different types of forest biomass in integrated ethanol production in pulp mill shows that the type of forest biomass impacts the biogenic carbon emissions of biofuel production. The assessment of cultivated biomasses demonstrates that several selections made in the production chain significantly affect the GHG emissions of biofuels. The emissions caused by biofuel can exceed the emissions from fossil-based fuels in the short term if biomass is in part consumed in the process itself and does not end up in the final product. Including biogenic carbon and other land use carbon emissions into the carbon footprint calculations of biofuel reveals the importance of the time frame and of the efficiency of biomass carbon content utilization.

As regards the climate impact of biomass energy use, the net impact on carbon stocks (in organic matter of soils and biomass), compared to the impact of the replaced energy source, is the key issue. Promoting renewable biomass regardless of biogenic GHG emissions can increase GHG emissions in the short term and also possibly in the long term.

Keywords: bioenergy, biomass, peat, forest stand, oil palm, rapeseed, jatropha, greenhouse gas, LCA, static LCA, dynamic LCA

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Sanni Väisänen
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I dedicate my dissertation to my family and many friends. I feel warm gratitude towards my loving parents, mother Eija and the memory of my father Hannu, for words of encouragement and push for tenacity. My sister Katri has always believed that I can do anything I want to. I dedicate this work and give special thanks to my husband Jani and my wonderful sons Nooa and Luukas for being there for me throughout the entire doctoral program. You all have been my best mentors.

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Publications

List of publications

This Thesis contains material from the following papers. The rights have been granted by publishers to include the material in dissertation.

I. Silvan, N., Silvan, K., Väisänen, S., Soukka, R., and Laine J. (2012). Excavation-drier method of energy-peat extraction reduces long-term climatic impact. *Boreal Env. Res.*, 17, pp. 263-276.

II. Väisänen, S., Silvan, N., Ihalainen A. and Soukka, R. (2013.). Peat production in high-emission level peatlands – key to reduce climatic impacts? *Energy and Environment*, 24 (5), pp. 757-778.

III. Väisänen, S., Valtonen, T., and Soukka, R. (2012). Biogenic carbon emissions of integrated ethanol production. *International Journal of Energy sector management*, 6(3), pp. 381-396.

IV. Uusitalo V., Väisänen S., Havukainen J., Havukainen M., Soukka R., Luoranen M. *(In press.)*. Carbon Footprint of Renewable Diesel from Palm Oil, Jatropha Oil and Rapeseed Oil. *Renewable Energy*.

Author's contribution

I am the principal author and investigator in papers II and III. In paper I, Dr. Niko Silvan was the corresponding author and I conducted the LCA calculations. In paper II, the Forest Inventory data was assembled by Mr. Antti Ihalainen. Heterotrophic respiration values of peatland soils in papers I and II was measured by Dr. Niko Silvan. In paper IV I actively took part in the writing and commenting of the article and delivered the chapter of land use’s relation to life cycle GHG emissions in the article.

Nomenclature

In the present work, variables and constants are denoted using *slanted style*, and abbreviations are denoted using regular style.

Latin alphabet

a	year	
C	carbon	kg
E	emission	kg

Greek alphabet

Δ	(capital delta)	usually used for change without slanting: Δ

Superscripts

-

Subscripts

Bio	biogenic
G	gain
i	year or gas component
L	loss
t	time (of assessment period)
net	net (impact)
x	proportion

Abbreviations

AGWP	The Absolute Global Warming Potential
AR4	IPCC Fourth Assessment Report (2007)
AR5	IPCC Fifth Assessment Report (2013)
C	Carbon
CO_2-eq.	Carbon Dioxide Equivalent Amount
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
ECCP	The European Climate Change Programme
EJ	Exajoules, 10^{18} Joules
EN 14214	CEN European standard for FAME
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWP_{bio}	Biogenic Global Warming Potential
ILUC	Indirect Land Use Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LUC	Land Use Change
LULUCF	Land Use, Land Use Change and Forestry
NFI	National Forest Inventory
OM	Organic Matter
PCF	Product Carbon Footprint
RD	Renewable Diesel (In this study: NExBTL)
RF	Radiative Forcing
RRFC	Relative Radiative Forcing Commitment
SETAC	Society of Environmental Toxicology and Chemistry
SOC	Soil Organic Carbon

SOM	Soil Organic Matter
UK	United Kingdom
UNEP	United Nations Environment Programme
USA	United States of America

1 Introduction

Climate change is one of the greatest challenges of mankind. Mitigation and adaptation to climate change require major changes in the way people are living, in terms of manufacturing, and especially in the selection of sustainable energy sources. Based on research, climate change will increase e.g. the risk of extreme weather, extinction, water scarcity in certain areas and famine, but when and how these impacts will take place is difficult to estimate (IPCC, 2007a; Wuebbles and Jain, 2001).

The impacts of climate change and their size are affected by the scale and speed with which GHG emission reductions are achieved (Wuebbles and Jain, 2001). The European Union has set the target to limit the average global temperature at most to 2℃ over the pre-industrial level (COM(2007) 354 final). Achieving even this target seems to be very challenging. This limitation to the average temperature means that the emissions need to be cut by 50% to 80% from the emission level of the year 2000 by the year 2050 (IPCC, 2007b).

The energy sector is one of the largest greenhouse gas (GHG) emitters, and thus its role in climate change mitigation is important. There does not exist one single approach for emission reduction in the energy sector. Instead, it is necessary to take all possible approaches, such as reducing energy consumption, improving energy efficiency, favoring fuels with low emission factors, nuclear power, increasing the use of renewable energy and carbon capture and storage (CCS) (COM(2006) 105 final). In the European Union, climate and energy policies are consolidated in one energy and climate package to reach the 20/20/20 targets of energy efficiency and the share of renewable energy sources for the purpose of GHG emission reduction.

Replacing fossil fuels with biomass reduces the rate of carbon transfer from geological reserves. The use of biomass as a fuel is considered to reduce the greenhouse gas emissions of the energy sector compared to the use of fossil fuels due to the decision that use of biofuels is considered carbon neutral (Directive 2009/28/EC, OJ L 140/16). The carbon neutrality of biomass used to produce fuels and other energy products is a long-established convention in GHG accounting, based on the assumption that the carbon emission that is released during biomass combustion is reabsorbed when new biomass is grown (Cherubini et al., 2011; OECD, 1991). The carbon released from biomass is, however, not included in the carbon emissions of heat, electricity or fuel production unit reporting. Although carbon stock changes due to land use are reported at national level under the sector “Land Use, Land Use Change and Forestry” (LULUCF), this GHG effect is not accounted for in the energy sector (IPCC, 2006a). Within these frames, the measured impact of the use of biomass for energy on the GHG emissions of electricity, heat and biofuel production lacks precision and could be misleading.

The types of renewable biomass include woody and non-woody biomass from sustainable managed forests, croplands or grasslands, biomass residues when their use does not involve a decrease in carbon pools and the biomass fraction of industrial or municipal waste (UNFCCC, 2012). In contrast, peat is counted as partially renewable or non-renewable biomass because of its relatively slow renewal (Finnish Academy of Science and Letters, 2010). Whereas agricultural biomass takes approximately a year and forest biomass decades to renew itself, peat may take millenniums (Finnish Academy of Science and Letters, 2010). As a consequence, emissions released from peat combustion are accounted for similarly to emissions from fossil fuels (IPCC, 2006b). Peat emissions are calculated on the basis of the carbon content and the heating value of peat. Emissions from the peat harvesting sites and peatland areas out of utilization and carbon accumulation in forests are reported in the land use sector (LULUCF).

The carbon neutrality of biofuels has lately been questioned because the cultivation of biomass has in some cases been noticed to release soil carbon (Searchinger et al., 2008). Soil and vegetation contains four times more carbon than the atmosphere (Sabine et al., 2003). When soil is prepared for cultivation, the decomposing soil organic matter and loss of below-ground and above-ground biomass releases emissions which might – in the worst case – exceed the emissions of the fossil fuel being replaced with the cultivated biomass in question (Fargione et al., 2008). Ignoring these emissions may thus give an overly optimistic picture of the GHG impacts of biomass use.

This thesis is the result of concern for the environmental consequences of biomass utilization for electricity, heat and biofuel production purposes and a motivation to improve the design of sustainable energy production systems for humankind. This study aims to demonstrate how great an impact the choice of production area, biomass source and production efficiency can have on the GHG emissions of biomass production.

1.1 Research problem and objectives

The aim of this thesis is to examine the amount of greenhouse gas produced in biomass-based fuel, heat and electricity production in the selected biomass-to-fuel chains. The thesis explores the significance of the different GHG emission sources related to electricity, heat and biofuel production from biomass and the opportunities to develop more climate friendly biomass energy options. The GHG balances of using biomass for electricity, heat and biofuel production are studied. The importance of biogenic emissions and ways to reduce the carbon emissions of biomass systems are discussed.

The following research questions were formulated:

1. What is the significance of the production area in GHG emissions of biomass-based fuel?
2. What is the significance of the production method and technology in GHG emissions of biomass-based fuel?
3. What methodological choices made in LCA have meaning for GHG emissions of biomass-based fuels?

1.2 Scope of the study

The thesis consists of four research papers. Whereas the first two papers concentrate on the peatland emissions and peat utilization for the production of heat energy, the third paper discusses the utilization and the carbon neutrality of forest biomasses as a biofuel. The fourth paper presents the production of renewable transportation fuel from cultivated biomasses.

The peatlands used as examples in this study were selected on the basis of the availability of published information on soil emissions. Soil emissions and carbon stocks are high in peatlands when compared to other soil types, and peatland utilization causes significant changes in the GHG balance and the carbon stored in the peatland (Joosten and Clarke, 2002). The selected peatlands are drained for forestry and their utilization for electricity, heat and biofuel production is in line with the Finnish mire and peatland strategy (Ministry of Agriculture and Forestry of Finland, 2011). Previously published studies have proved that the emissions from peat utilization from average forestry-drained peatland areas are nearly equal with the emissions from coal use in heat and electricity production (Kirkinen et al., 2007). In this study, the utilization of high-emission peatlands is studied to demonstrate the significance of the original peatland emission level for the GHG emissions and to estimate the maximal GHG benefit of the reference peatland area for peat fuel.

The biorefinery pulp mill and the utilization of forest biomass were chosen as other examples owing to the trend to increasingly use forest biomass in biofuel production. The impact on forest carbon stock formation differs significantly depending on whether pine logs or forest residues are used as raw material in biofuel production. The use of pine logs serves as a demonstration of the impact of carbon debt on the carbon stock and thus biogenic GHG emissions.

The cultivated biomasses presented in paper IV were selected on the basis of the suitability for renewable diesel fuel production and represent comparable utilization chains based on material and local differentiation. The fourth paper serves as a demonstration of different selections made over the production chains and their impacts on biofuel production GHG emissions. The production of cultivated biomasses also includes the risk of land use change (LUC), and paper IV discusses the GHG emission risk of LUC.

Biomasses considered in this thesis can be divided into three main groups based on the feedstock sources. Accounting for the carbon content of biomass has been presented through three different examples: peat, forest and cultivated biomass based fuel production. Peat is classified as a slowly renewable biomass source. This is based on the assumption that the carbon released from biomass combustion is not bound back to growing biomass over a reasonable time. All CO_2 released in combustion is assumed to end up into the atmosphere, accelerating climate change. In this thesis, the special characteristics discussed are the peatlands which release GHG emissions in their current state and how they affect the GHG impact of peat fuel use. The maximum impact is calculated through the peatland type which generates the highest GHG emissions without peat utilization based on preassumptions. In peat studies, the area afforestation after peat production and differences between carbon stocks before and after peat production are included in the 100-year assessment period. Wood is classified as a renewable fuel, but compared to other cultivated biomasses, the time needed for growth is relatively high. Regrowth of the forest stand takes place during the 100-year assessment period. In the example in paper III, wood stand and forest residues are produced from managed forests and no LUC takes place. The special feature of this example is to assess the short-term carbon stock reduction of stands and account for the slow re-binding of carbon stock during the forest stand regrowth with average carbon stock calculations. In the case of forest residue, the impact on the forest carbon stock is taken into account by estimating the natural decomposition of carbon and the resulting CO_2 emissions. GHG emissions of cultivated biomasses are discussed in paper IV with regard to three different biomass feedstocks. Rapeseed is an annual cultivated crop, jatropha is a perennial crop and palm oil wood a plantation. These feedstocks form different carbon binding biomass amounts and time periods and the long time average carbon stocks are estimated and compared to rank these feedstocks. Potential land use change impacts are compared and the soil emissions and fertilization emissions are accounted for. These cultivations are assessed over a 20-year period for average carbon stocks based on the provisions of the Renewable Energy Directive. The biomass types and their classification are presented in Figure 1.

The GHG emissions and the global warming potential (GWP) of the studied fuel chains are calculated by using the static life cycle assessment (LCA) approach in which the timing of the sinks and emissions is ignored and the impact assessment is carried out by using the GWP values for a time horizon of 100 years. Also, the impact of an alternative method is discussed.

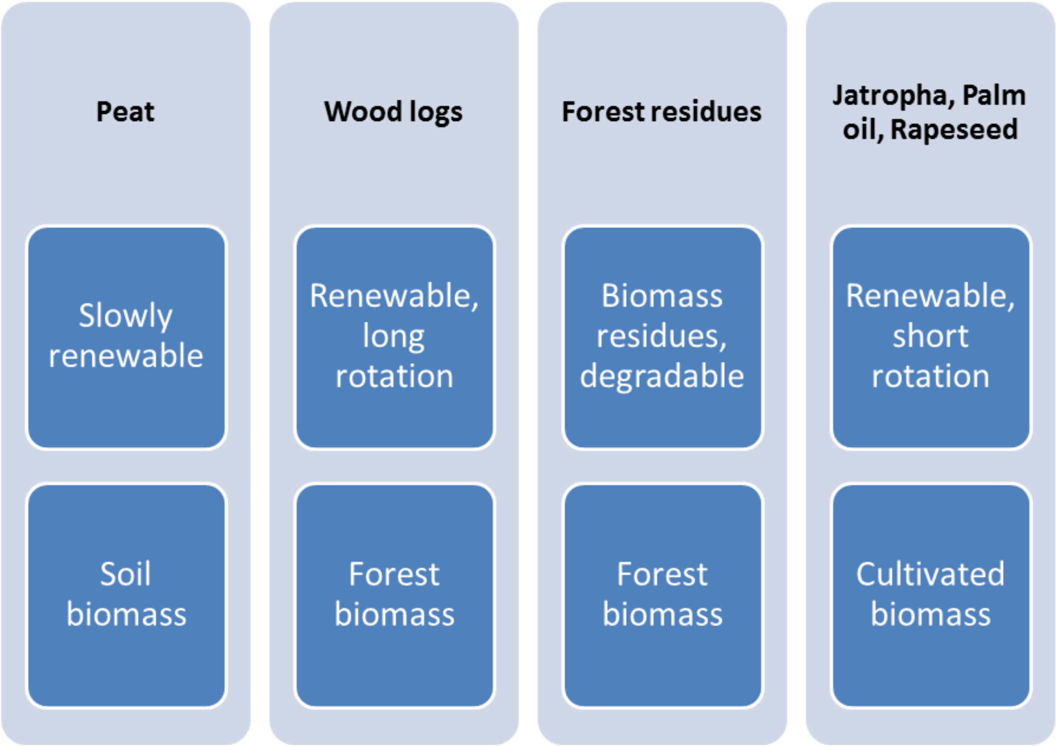

Figure 1. Biomass types included in the thesis.

1.3 Structure of the study

The thesis consists of six chapters:

Following the introduction, chapter 2 describes the current general framework for biomass utilization, biomass sources and technology.

Chapter 3 presents the methods, the LCA methodology used in biofuel GHG emission calculations and key assumptions. Sections 3.7 and 3.8 introduce the case studies of peat, forest and cultivated biomass and present the methodology used in the research papers.

Chapter 4 summarizes the research results. Finally, the discussion and conclusions are presented in chapters 5 and 6. The life cycle unit processes of biofuel production and different emission sources are presented in the schematic Figure 2.

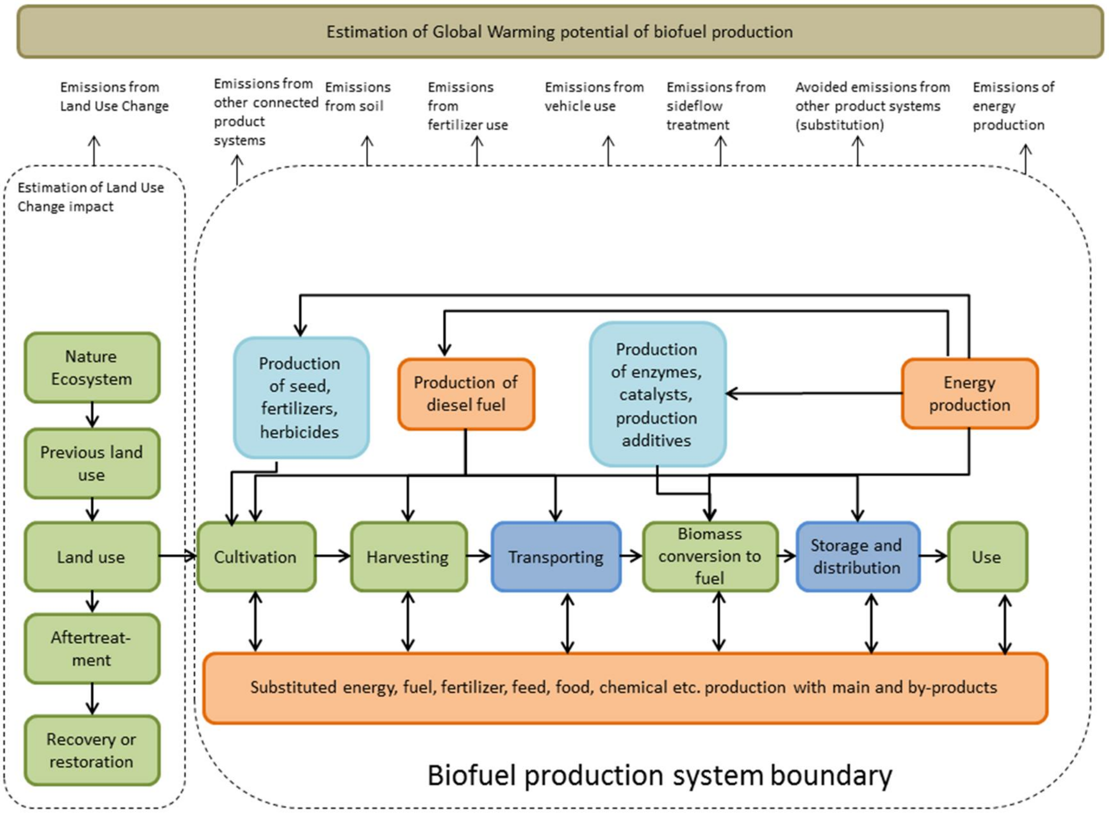

Figure 2. Overview of the estimation of GHG emissions of biomass-based fuels.

2 Biomass utilization for electricity, heat and biofuel production and its role in climate change mitigation

This chapter presents biomass utilization for fuel, electricity and heat production: the availability and technology for biofuel production and the outlook for biomass source specific issues related to the GHG impact. The first section describes the commonly known classification of biomasses. The second section describes the role of biomass in the carbon cycle and the principles for climate change mitigation with biofuels. In the following sections, forests, peatlands and agricultural land areas are briefly presented to give an overview of the current situation of utilization and the factors which affect the GHG emissions of the biofuel feedstocks produced from these land areas. The last section under this chapter gives a short overview of the processing technologies for biomass utilization for electricity, heat and biofuel.

2.1 Classification of biomasses

Biofuels, heat and electricity can be produced from a wide palette of biomass feedstocks: residues from forest, agriculture or livestock; forest biomass from short rotation forest plantations; cultivated energy crops; the organic component of municipal solid waste and other waste streams (IPCC, 2012).

The biomass feedstocks used for producing biofuels can be grouped into three basic categories: so-called first, second and even third generation feedstocks (Mohr and Raman, 2013; Worldwatch Institute, 2008; Subhadra and Edwards, 2010). The first generation feedstocks, like grains, oilseeds, animal fats and waste vegetable oils, are harvested for their sugar, starch or oil content and can be converted into first generation biofuel with conventional technology (Worldwatch Institute, 2008; IPCC, 2012).In the second generation feedstocks, also known as lingo-cellulosic biomass feedstocks, the biomass is utilized to its full extent and the fibers can be converted into second generation biofuels through non-traditional technical processes. (Worldwatch Institute, 2008; IPCC, 2012) Lignocellulosic feedstocks include by-products (cereal straw, bagasse, forest residues), wastes (organic component of municipal solid waste), and dedicated feedstocks (grasses, forests and energy crops) (Sims et al., 2010). Third generation biofuels, will be derived from third generation feedstocks, like algal biomass, with advanced processes which are still under development. The second and third generation biofuels are also named as next-generation biofuels (IPCC, 2012; Subhadra and Edwards, 2010).

Cellulosic biomass, such as wood, grasses, straw and forestry residues, is considered for several reasons as an attractive option to cater to the increasing electricity, heat and biofuel demand. First, the residue biomasses (forest residues, straw) consist of material which would otherwise decompose, and therefore offers a way of creating value when it replaces a fossil fuel. Second, in the case of residues and waste, there is no need for additional land for production. Third, energy crops are able to grow on poorer soil than annual food crops. Perennial crops, such as short rotation woody crops, can be grown on a wide range of soil types and their roots help prevent erosion and increase the carbon storage in soil (Kort et al., 1998; Malik et al., 2000). On the other hand, high yields will only be achieved on good soils and with sufficient watering conditions. (Worldwatch Institute, 2008) Second generation feedstocks might not be able to compete with food production, but they compete for land, water, nutrients and energy (da Schio, 2010; Sims et al., 2010).

Different biomass feedstocks can be grouped also into renewable, partially renewable or non-renewable biomass based on their renewal rate and their impact on the ecosystem. Biomass from sustainable managed forests, croplands or grasslands and biomass residues are defined to be renewable when their use does not involve a decrease in carbon pools (UNFCCC, 2012). Peat is only partially renewable or non-renewable because of its slow rate of renewal (Finnish Academy of Science and Letters, 2010). Peat is a cellulosic feedstock and needs advanced processes if converted to liquid fuels.

The biomass supply energy potentials are accompanied by significant uncertainties (IPCC, 2007b). The future of biomass-based energy is connected to the ability of agriculture to boost the food and feed yields of conventional crops and increase the production of dedicated energy crops so as to avoid the increased pressure to convert forest and natural areas (Worldwatch Institute, 2008; IPCC, 2007b). The size of the human population and its collective need for food and land, the competitive use of biomass and land, the development of energy conversion technologies, the impact of climate change, and ecological limitations will also determine the quantity of biomass energy available. (Worldwatch Institute, 2008)

The long-term potential for biomass resources varies widely and is dependent on factors which are difficult to predict and control. The size of the population, the popularity of vegetarianism as a prevalent diet and trend in agricultural yields determine the size of the biomass energy reservoir (Worldwatch Institute, 2008; Gregg and Smith, 2010; IPCC, 2007b). In the worst case scenario, the human population increases and the consumption of meat and dairy products continues its rapid rise at the same time the climate change and limited investments in rural areas limit the growth in food crop yields. (Worldwatch Institute, 2008)

2.2 Biomass sources and carbon cycle

Carbon is stored in various pools, in the ocean, land, forests, atmosphere and fossil reserves, with dynamic flows between the pools (Figure 3). The forests, oceans and soils with peat and dead biomass stocks have a two-way flow of carbon in the sense that these stocks can absorb and emit carbon from the atmosphere. In contrast, the fossil fuel reserves provide a one-way flow to the atmosphere when these fuels are burnt to generate heat, electricity and mechanical energy. While there are uncertainties in measuring carbon stocks and flows globally, the objective of reducing GHGs suggests increasing carbon stores in non-atmospheric pools (for example growing forests) and substituting the use of fossil fuels and fossil fuel intensive products with renewable materials. The displacement of carbon emissions and the increased absorption of carbon in carbon stores are equally important in reducing the atmospheric carbon. (Lippke et al., 2011)

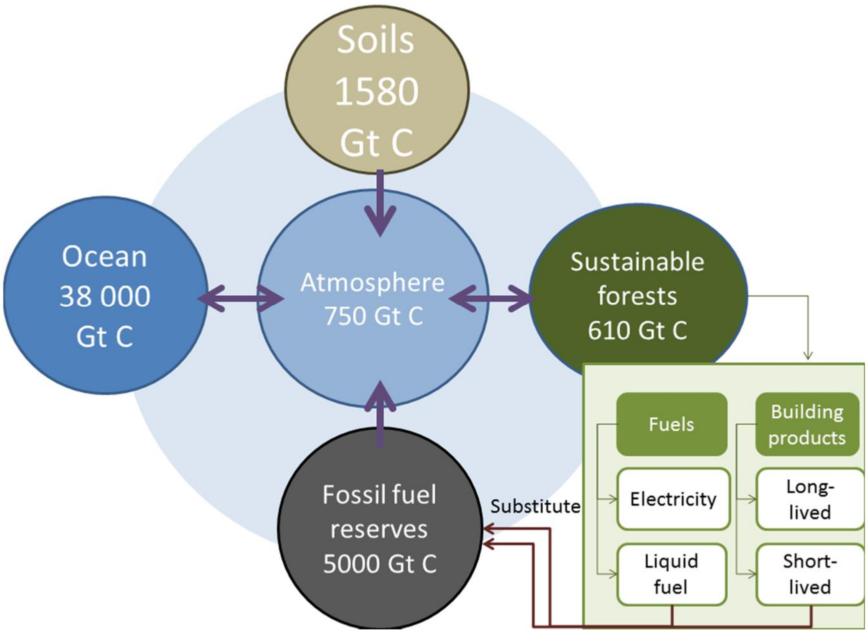

Figure 3. Global carbon stocks in soils, forests, oceans and the atmosphere (Lippke et al., 2011).

Biomass is a renewable option for fuel, electricity and heat production. Biomass is an organic, carbon-based material which forms in living organisms and uses carbon dioxide during photosynthesis, acting thus as a carbon dioxide sequestering agent. In this process, the energy of the sun is stored in chemical form and the sun is the ultimate source of energy. The combustion of biomass releases carbon dioxide back into the atmosphere (Sankaranarayanan et al., 2010). The sun is the ultimate source of biomass-based energy and the biomass is the intermediate. The combustion of biomass is an example of renewable technology. When the unit of growing biomass absorbs one unit of carbon dioxide while growing and releases it during combustion, there is no net increase or decrease in carbon emissions in this cycle (de Swaan Arons et al., 2004).

Climate change mitigation through biomass use is based on the mechanisms presented in Figure 4. The growing capability of biomass to absorb and accumulate carbon is an essential feature, and especially peatlands and forests carbon stocks capture carbon from the atmosphere into both biomass and soil (Joosten and Clarke, 2002; Trettin et al., 2005; FAO, 2010). Climate change mitigation can be promoted with the development of biofuel production and its life cycle stages. Increasing the productivity of agriculture and decreasing emissions from conversion processes leads the development in the right direction. Other important mechanism in climate change mitigation is to replace fossil fuels and other non-renewables with biomass-based products (Lippke et al., 2011). When the carbon storage of the fossil fuel reservoir stays outside the carbon cycle, the increase of the atmospheric CO_2 level will slow down over time. With carbon capture, there is even potential to use biomass as a part of the energy supply, which can lead to negative emissions (Schiermeier et al., 2008). In other sectors, such as building, the carbon binding capability of biomass can be used while substituting other materials. If buildings are constructed from wood instead of concrete, the wood will withhold carbon from the atmosphere until the wood decomposes and the CO_2 emissions of concrete manufacturing will be avoided (Lippke et al., 2011).

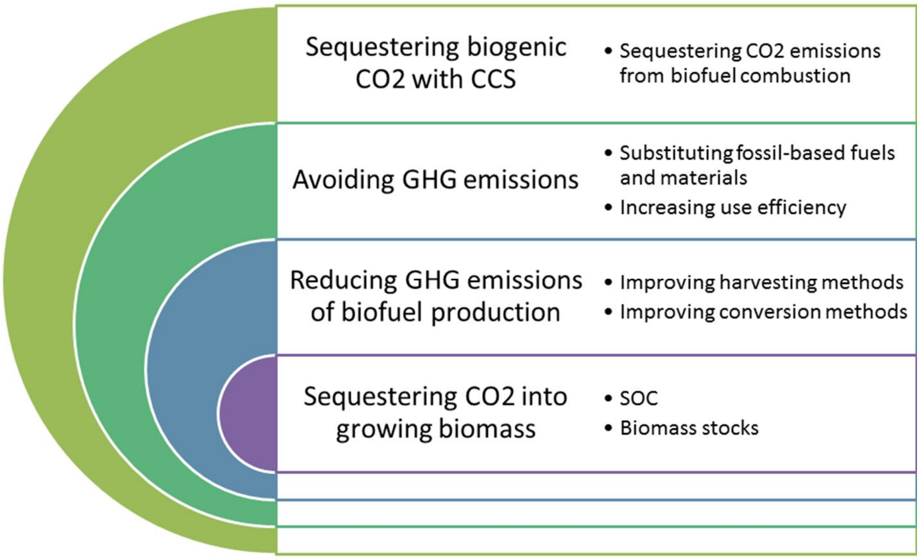

Figure 4. Climate change mitigation through biofuel use.

2.2.1 **Forests**

Forests cover over four billion hectares of the world's total area. The forest areas are scattered in a way that the five most forest-rich countries account for more than half of them. In contrast, ten countries or areas have no forest at all. (FAO, 2010). Deforestation – mainly the conversion of tropical forest to agricultural land – and natural disasters threaten the forests. On the other hand, afforestation and the natural expansion of forests in some countries and regions reduce the net loss at the global level. The net change in forest areas during the period of 1990-2000 was -8.3 million hectares per year, whereas it is estimated that the net change in forest areas during 2000-2010 is at -5.2 million hectares per year. The largest net losses of forest between 2000 and 2010 were reported by South America and Africa. Also Australia suffered a great net loss due to severe drought and forest fires. The area of forest in North and Central America was almost at the same level in 2010 as in 2000, and in Europe, the forest area has continued to expand. Asia has changed from net loss to net gain in the period 2000-2010 primarily due to the large-scale afforestation in China (FAO, 2010).

Forests contain a large part of the carbon stored in land and present a significant carbon stock. The sustainable management, planting and rehabitation of forests can increase the forest carbon stock and deforestation, while degradation and poor forest management reduce them (FAO, 2010). The highest part of the forest carbon is stored in soils and litter, 317 Gt (top 30 cm), and nearly the same amount, 283 Gt, in forest vegetation, and 38 Gt in dead wood. The total carbon content of forest ecosystems exceeds the amount of carbon in the atmosphere and approximately half of the total carbon in forest ecosystems is found in biomass and dead wood. (UNFCCC, 2012; FAO, 2010)

The mineral forest soils typically store between 20 to over 300 tonnes C ha^{-1} of carbon (C) (to 1 m depth) (Jobbágy and Jackson, 2000). Soil organic carbon (SOC) pools are affected by differences between C inputs and outputs over time. The C inputs are determined by the forest productivity, the decomposition of litter and its incorporation into the mineral soil and following loss with mineralization or respiration (Pregitzer, 2003). Other losses of SOC can take place through erosion or the dissolution leaching to ground land or overland flow. In forest soils, the above-ground litter forms a large input and because of this, organic matter is mainly concentrated in the upper soil horizons: roughly half of the soil organic C resides in the upper 30 cm layer. The upper layer is also usually the most chemically decomposable and exposed to disturbances. (IPCC, 2006b)

When the carbon footprint of a product is calculated, products produced from forest biomasses can form a carbon stock when the release of carbon bounded in photosynthesis is delayed (GHG Protocol, 2011). The biomass utilized for electricity, heat and biofuel production releases the carbon content almost immediately after harvesting, whereas the wood used as a building material can remain as a part of a building for decades. But even the wood harvested from the forest and utilized for e.g. construction finally releases the carbon content at the end of the life cycle. As a consequence, it is possible to take the product carbon stocks into account in terms of mitigating the carbon emissions. Moreover, in buildings, wooden materials can replace other materials that release carbon dioxide (Lippke et al., 2011). The impact of this process on GHG emissions is favorable in many ways. When the carbon stock of the product is accounted for as a reduction in GHG emissions of the product, the point of reference is set to the point of time before the growth of the utilized biomass and thus the accumulation caused by growth. The delayed emissions due to the long lifetime can, for example, be weighted with a weighting factor which divides the years of existence of the carbon stock by the years of the reference period. This procedure (GHG Protocol, 2011; PAS 2050:2011, 2011) promotes the use of biomass in products with a long lifespan.

From a national perspective, laid down in the reporting guidelines for GHG inventory reports (IPCC, 2006b), the carbon bound in forest biomass has a carbon neutral impact as far as the amount of biomass remains at the same level. The forest biomass can be utilized in a carbon neutral way if the carbon loss from the forest is smaller or at least equal to the forest carbon gain due to growth. The carbon accumulation can also increase if the growth exceeds the harvest. With this boundary, the possible increase in forest growth due to forest management can be accounted for (Lippke et al., 2011). The point of reference for carbon stock changes is the carbon stock of the forest in a given year where the forest can be a managed forest and the carbon stock can differ from the carbon stock capability of a pristine forest.

The sink/source dynamics of the forest ecosystem is controlled by the carbon uptake in tree growth and the emissions of decomposition which together form the carbon balance of the forest affecting the carbon emission reduction in electricity, heat and biofuel production (Kilpeläinen et al., 2011; Routa et al., 2012). In many developed countries, forest management is characterized as sustainable management when that wood removed for use does not exceed the net forest growth (Lippke et al., 2011). Lippke et al. (2011) state that when more wood is not removed than is grown, the forest carbon is not reduced and becomes of minor importance to the way the wood is used to substitute fossil emissions (Lippke et al. 2011). Globally, the estimated net effect of wood harvesting is a carbon source because the rate of harvest is increasing (Houghton and Goodale, 2004). In individual regions, declining harvest, increased efficiency of harvest and changes in forest growth may result a change on the sign of net annual flux (Houghton and Goodale, 2004).

2.2.2 **Peatlands**

A peatland is a wetland ecosystem with a relatively thick (>40 cm) soil layer of organic matter above a mineral substrate (Trettin et al., 2005). Mire is a term broadly defining both deep and shallow accumulation referring to any wetland where organic matter is accumulated at the surface (Trettin et al., 2005). Currently, peatlands cover about 4 million km^2 of the Earth’s surface (~3% of the land area) (Joosten and Clarke, 2002). The climatic conditions strongly affect peat formation. Peatlands are found especially in Canada and Alaska, Northern Europe and Western Siberia, Southeast Asia and parts of the Amazon basin, where over 10% of the land area is covered with peatlands (Joosten and Clarke, 2002; Lappalainen, 1996). Peatland ecosystems contain one third of the world’s soil carbon (approximately 526 Gt C) (Joosten and Clarke, 2002). The extensive peatlands found in Sweden, Finland and the United Kingdom hold almost half of the total soil carbon in the EU-27 countries. Other high organic soil areas are found in Northern European countries, including Ireland, Poland, Germany, Norway and the Baltic States. (European Commission, 2011)

The largest peat producers are Belarus, Finland, Ireland, Sweden, Russia and the Ukraine. At the national level, the importance of peat fuel is greatest in Finland and Ireland, where approximately 5-7% of the primary energy consumption is produced with peat (Paappanen et al., 2006).

Finland as a country has the highest proportion of peatlands in the world (Vasander et al., 2003). Peatlands cover 27% of the land area of Finland, and 73% of them are drained. The four main tree species in the peatlands of Finland are the Scots pine (Pinus sylvestris), Norway Spruce (Picea abies), Silver birch (Betula pendula) and Downy birch (Betula pubenscens), covering approximately 95% of the volume and annual increment of the growing stock (Statistics Finland 2011).

Peat from the uppermost and deeper peatland layers are used for different purposes. Highly decomposed peats with a high heating value and carbon content are used for heat and electricity production. The uppermost peat layers of peatland are not as well decomposed and are suitable for environmental protection, gardening and agricultural purposes because of their physical, chemical and biological properties. The structure of low decomposed surface peat results in a great water storage capability. In addition, it can absorb nutrients, metals and gases. (Ministry of Agriculture and Forestry of Finland, 2011)

Peat production is seasonal, performed from mid-May until the beginning of September. Production depends on the weather and the yields from one hectare vary according to production years and areas. (Ministry of Agriculture and Forestry of Finland, 2011) In case of a poor peat year, reserve stocks, imported peat and other fuels are used to the extent possible. (Mähönen, 2008).

In Finland, the area used for energy peat production was 62 000 hectares in 2009, and an additional 9400 hectares of peatland were under preparation or ready for production. In 2009, ca. 7.6% of the peat production area was used for peat for agricultural purposes. The need for energy peat production land in Finland is estimated to increase to over 70 000 hectares by 2020, with an annual need of about 4500 hectares. A further 8000 hectares of new production land are needed for horticultural peat production. (Ministry of Agriculture and Forestry of Finland, 2011)

Peat is used either as the main fuel or with coal or renewable biomasses in a co-combustion (Hupa, 2005). Combustion of biomass increases the risk of operational problems. Biomass with an enhanced content of chlorine (Cl) can increase deposit formation and superheated corrosion and these problems can be reduced with co-combustion and the use of additives (Kassman et al., 2010). There are several possible additives suitable for this use – e.g. olivine, quartz, lime, sand, limestone, dicalcium phosphate, chalk, elemental S, and coal fly ash - and also peat can be used for this purpose (Vassilev et al., 2014). The use of co-combustion in heat and electricity production, containing peat or coal and other biomasses, reduces the malfunctions caused by the latter in boilers (Lundholm et al., 2005; Hakkila, 2006). Even as little as 5% peat fuel has been found to have a significant effect on some studied properties (Lundholm et al., 2005). Peat is especially used for co-combustion in combined heat and power (CHP) production, where the boilers are dimensioned for high steam pressure and temperature. The disadvantages of forest chips are lower in heat plants and, as a consequence, peat is not necessarily used. CHP production is also possible without peat, but only if the electricity production efficiency is set lower, only cut stem wood is used or additional chemicals such as sulphur are added into the fuel. (Ministry of Agriculture and Forestry of Finland, 2011)

A large amount of carbon (C) is accumulated and stored in the peatlayer of peatlands. Hydrology and plant community regulate the dynamics of the C cycle in peatlands (Trettin et al., 2005). The principal source of soil C is an organic matter from biomass production. Productivity varies widely in different wetland forest types depending on differences in climate, hydrology and vegetation community (Trettin et al., 2005). In mires, the cycle of matter is incomplete, resulting in a positive carbon balance. When plant production exceeds decay, carbon is accumulated as peat.

The changes in land use in these peatland areas could have a significant influence on the climate. Some unsustainable practices, such as continued drainage, conversion to grassland, cropland or forests and, to a lesser extent, horticulture, fires or peat extraction for use as a fuel, are a threat to these peatlands. Also the impact of climate change is a threat itself. (European Commission, 2011)

In Finland, the peatlands are utilized for agriculture, forestry and the harvesting of peat. The agricultural use began already in the Middle Ages and systematic drainage to increase the growth of tree stands in peat soils and wet mineral soils started in 1908 (Vasander et al., 2003). Forest drainage was first practiced in state and industry owned lands, and the private sector started it in 1928 when the first Forest Improvement Act was introduced. Drainage to increase forest growth developed into a nation-wide campaign in the 1960s. (Vasander et al., 2003) Industrial peat harvesting in Finland began in 1876 and the large scale energy use of peat started during the oil crisis in the 1970s.

The drainage of peatlands (organic soil) is the hot spot of CO_2 emissions. (European Commission, 2011) Draining mires for various uses has lowered the water tables, changing the conditions in soil. Draining increases the aerated soil volume, which affects the decomposition process, the increase in the productivity of tree species and hence the GHG fluxes (Paavilainen and Päivänen, 1995). The storage of carbon and the rate of carbon accumulation in peatlands can increase or decrease after drainage (Minkkinen et al., 2002), depending on the productivity, peat nutrient status and degree of drainage (Nilsson and Nilsson, 2004). After water table drawdown, emissions may increase multifold (Silvola et al., 1985; Moore and Knowles, 1990), depending on the effectiveness of the drainage and nutrient level. If the peat layer of peatlands drained for forestry causes significant GHG emissions, peat harvesting from these peatlands will reduce the GHG emissions to some extent and is thus preferable (Seppälä et al., 2010). The utilization of these areas for peat production is not common and these emissions from soil/land areas are not taken into account in the selection of production sites. The current peat extraction areas are established both on peatlands previously drained for forestry and on pristine fens (Selin, 1999). This causes approximately the same climate impact as coal in a 100-year reference period (Kirkinen et al., 2007).

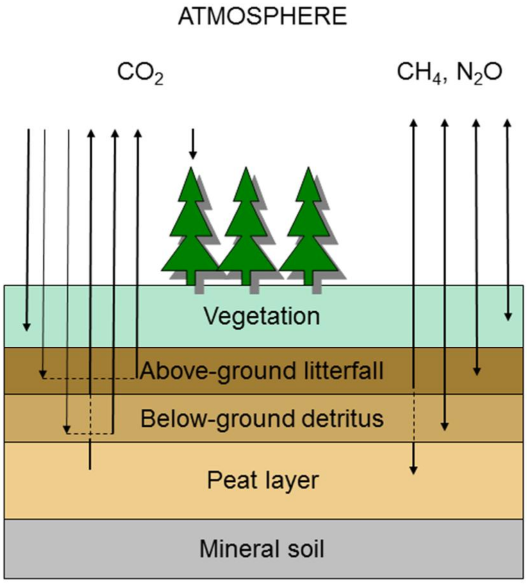

Figure 5. Soil layers in peatlands (Minkkinen et al., 2007).

The GHG emissions from different peatlands drained for forestry vary depending on the type and state of management. Before peat production, the area is covered with vegetation and the peat layer is generous. In this state, the forest stand, vegetation and litter layer binds carbon from the atmosphere. The peat layer releases GHG emissions during degradation. When the peat production starts, the above-ground vegetation and litter layer are removed and the soil stays uncovered until after the treatment of the peatland. In this state, the peat layer releases emissions, but the absence of vegetation does not enable binding it. After peat production, the cut away peatland is afforested as soon as possible to reduce the climate effects of uncovered land (Alm et al., 2007). The remaining peat layer (residual peat) improves the forest growth and thus the carbon accumulation to the growing biomass (Aro and Kaunisto, 2003; Aro and Kaunisto, 1998; Hytönen and Saarsalmi, 2009; Hytönen and Aro, 2010; Aro et al., 1997; Kaunisto, 1981; Kaunisto, 1985; Päivänen, 2007). During afforestation, the degradation of the residual peat layer releases emissions until all degradable carbon is used.

2.2.3 Agricultural land areas and land use change

Agricultural lands can be divided into pastures and croplands. The main difference between these two land types is that croplands are used for cultivation and pastures are not (Houghton and Goodale, 2004). In the IPCC definition (IPCC, 2006b), cropland includes arable and tillable land, rice fields and agroforestry systems where the vegetation falls below the thresholds used for forest land. Agricultural land areas cover nearly 40% of the earth's ice-free land surface and in many cases the agriculture has replaced forest, savannas and grasslands (Foley et al., 2005). In 2000, there were 15 million km^2 of croplands (roughly 12%) and 31.5 million km^2 of pasture (22% of the global land area) (Ramankutty et al., 2008). The agricultural regions are distributed all around the world. The largest proportion of croplands are found in South Asia (39%), Europe (27%) and the USA east of the Mississippi (23%) (Ramankutty et al., 2008). Pastures are found mainly in Argentina, Uruguay and Chile (33%) the Pacific developed countries (33%), China (33%), Mexico and Central America (31%), the USA west of Mississippi (31%) and Tropical Africa (30%) (Ramankutty et al., 2008). There is a need to increase agricultural production globally. The growing population, increasing incomes in developing countries, an urbanizing population, high-protein diets and expanding biofuel production are all increasing the demand for agricultural products. The potential to meet this demand by increasing the amount of land in agriculture is limited, and for this reason, agricultural production needs to be increased through increased productivity. The actual yields are well below the potential yields in many developing countries with yield gaps in excess of 50% (OECD/FAO, 2012).

Changes in land use affect the vegetation and soil of an ecosystem. This changes the amount of carbon held on a hectare of land (see Figure 6). When the land is cleared for cultivation, all of the initial vegetation is replaced by crops (Houghton and Goodale, 2004). The clearing of forests for croplands results in the largest estimated fluxes of carbon into the atmosphere from land use change because a hectare of trees holds more carbon than a hectare of crops (Houghton and Goodale, 2004). The impact of cultivation is not limited to the change of above-ground biomass: cultivation reduces the soil carbon in the upper layer of soils by 25-30% (Houghton and Goodale, 2004). The clearing of tropical forests for cultivation or grazing has created 12-26% of the total emissions of carbon dioxide into the atmosphere based on a study by DeFries and Anchars (2002) in Houghton (2003), (Houghton, 2003; DeFries and Anchard, 2002; Ramankutty et al., 2008). As such, agriculture is partially responsible for many environmental concerns, such as tropical deforestation and biodiversity loss and GHG emissions (Foley et al., 2005). In addition to the conversion of natural ecosystems to cropland, also changes in cropland management result in changes in the net flux of carbon. Tillage practices, changes in the crop varieties and density or changes in fertilization impact the GHG emissions of cropland (Houghton and Goodale, 2004).

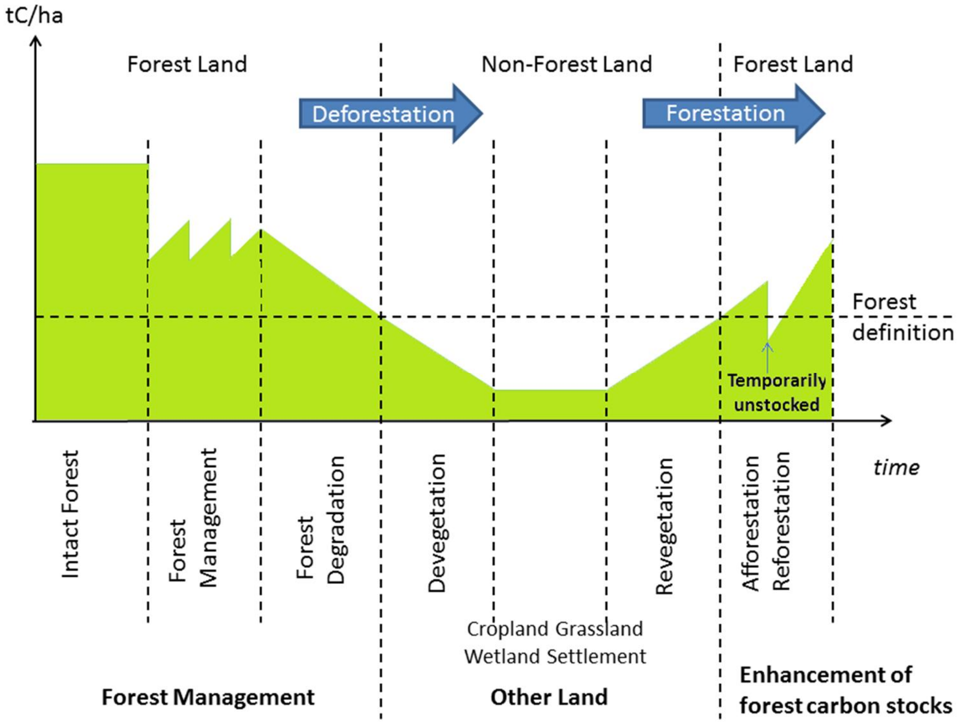

Figure 6. Classification of land use based on biomass carbon stocks (Murdiyarso 2013).

Conversion of land from one purpose to another, or direct land use change (LUC), is a large source of GHGs and contributes to climate change. LUC can also take place in locations which are not directly associated with biofuel production. The economic market forces can cause indirect land use change (ILUC) outside the production boundary when energy crop production on agricultural land displaces agricultural production and causes additional LUC (Searchinger et al., 2008). In a study in 2008 (Fargione et al., 2008), GHG released from LUC was termed a “carbon debt” of land conversion which can be repaid with biofuels if the GHG emissions of biofuel utilization are lower than those of the fossil fuels they displace. In the Fargione paper, this time to repay the biofuel carbon debt was referred to as the payback time and before it biofuels have greater GHG emissions than those fossil fuels they displace. On the other hand this delay in delivering GHG mitigation benefits can also be considered as a CO_2 investment of which is needed to establish a biomass based renewable energy system (Cowie et al., 2013).

Concerns regarding the degree to which and the time period over which (bio)fuels derived from biomass provide substantial reductions in carbon emissions can only be answered by tracking the carbon emissions across a life cycle. Life cycle accounting tracks the inputs and outputs at every stage of the process, from land clearing and fertilizer production, biomass harvesting, fuel processing and fuel use. To determine the impact of a change in fuel use or a change in land management, the carbon emissions between the various fuel or management alternatives are compared (Lippke et al., 2011). This estimation associated with each alternative is referred to as LCI or LCA based on guidelines developed by the International Organization for Standardization (EN ISO 14044:2006)

2.3 Biomass processing to fuels or energy

The biomass energy content can be utilized for heat or electricity production through combustion or processing it into biogas or biofuels (Figure 7). Of all renewable energy used in the European Union, biomass currently accounts for approximately half (44 to 65%) (COM(2005) 628 final). An increase in the biomass use in Europe would be beneficial as it would diversify the energy supply, increase the use of renewable energy and decrease dependency on imported energy. Biomass utilization reduces GHG emissions and potentially lowers the price of oil as a result of weaker demand. The biomass industry also creates direct employment for local people – especially in the countryside. (COM(2005) 628 final)

The use of biomass is promoted in the transportation, heating and electricity sectors, yielding various benefits in each. While the highest employment intensity and the greatest security of supply are achieved in the use of biofuels in transport, the electricity sector yields the greatest GHG benefits, and heating with biomass is the least expensive application for biomass use. So far, competition for raw materials between these sectors has been limited. While biofuels are mainly produced from agricultural crops, electricity and heating have traditionally relied on wood and waste (COM(2005) 628 final).

The technology for biomass use in heat production for residential and industrial buildings is low-cost and simple. The use of biomass in this field has a strong tradition, and this is the sector where it is used the most. Wood and clean residues can be turned into pellets that are easy to handle and environmentally safe to use. Given its established position, the growth rate of biomass use is the lowest in heating. District heating (collective heating) can manage the use of biomass easily and burn various types of fuel with lower emissions than individual heating. Already 56 million EU citizens are served by district heating, and the European Commission encourages district heating schemes to develop in a way that improves efficiency by means of modern plants and infrastructure as well as the efficient management of conversion towards biomass use. (COM(2005) 628 final)

Electricity can be produced from all types of biomass using various technologies. EU member states are encouraged to harness the potential of all cost effective forms of electricity generation from biomass. In particular, combined heat and power plants make the simultaneous production of heat and electricity from biomass possible. Member states are also encouraged to take this double dividend into account in their systems. (COM(2005) 628 final)

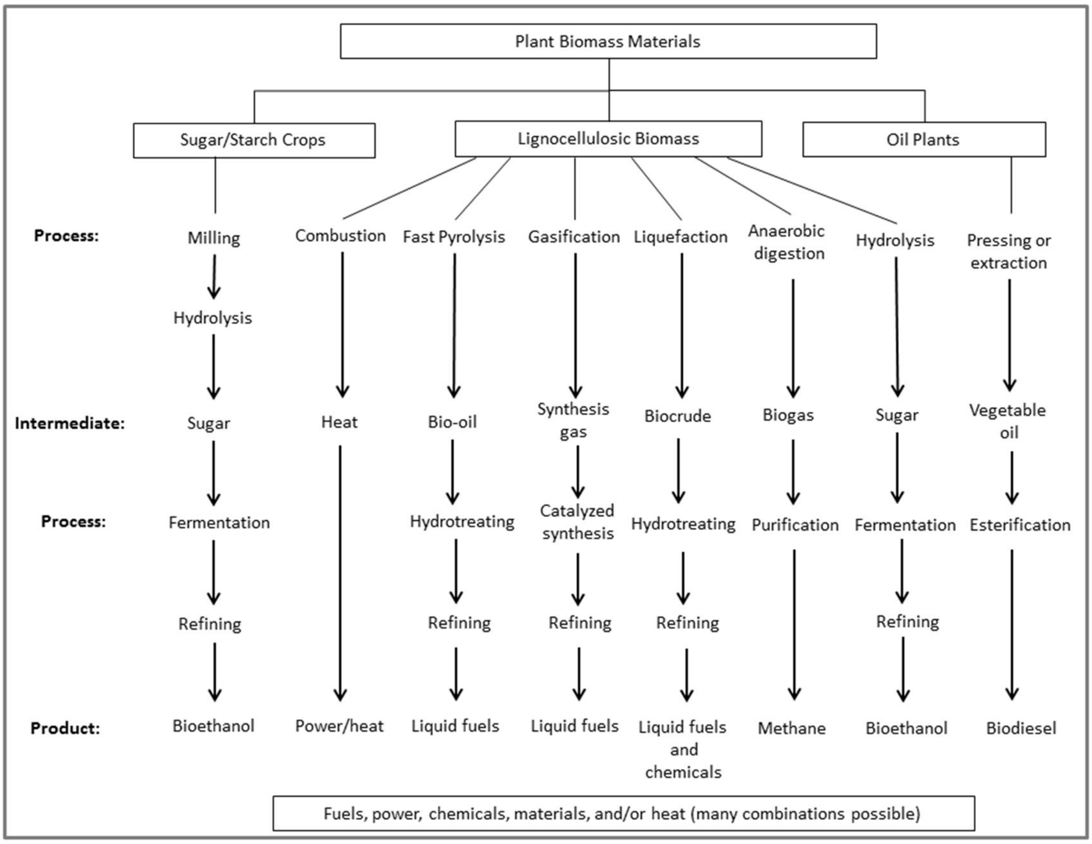

Figure 7. Overview of primary conversion process pathways of biomass to biofuels (Worldwatch Institute, 2008; Demirbas, 2009).

Besides heat and power plants, forest industry and oil refining companies seeking new products for their product family can produce biomass for energy. In addition to electricity and heat, suitable products include solid, liquid and gaseous fuels. A biorefinery is a production mill which produces biofuels (e.g. bioethanol or biodiesel), bioenergy (e.g. wood chips, combustion of black liquor) and traditional and new bio-based products (e.g. biopolymers) or several of the above. A biorefinery can be either a stand-alone unit or integrated into pulp or paper mill, for example.

The production of bio-based products can start from raw materials or upgrade intermediate products produced elsewhere. (Savolahti and Aaltonen, 2006) Bioethanol can be produced from biomass raw materials containing sugar starch or celluloses. In the first step, the feedstock is converted into sugar monomers. The complexity of this step depends on the feedstock. The second step, the fermentation of sugars to alcohol with the help of yeast, is more or less similar for all feedstocks. The third step, distillation and dehydrogenation, increases the ethanol concentration for proper engine operation. (Tomaschek et al., 2012)

The technology used in a biorefinery can be either biotechnology or a combination of biotechnology and industrial or pure chemistry (Savolahti and Aaltonen, 2006). Biotechnology utilizes biological processes that convert materials into biofuels or intermediates with fermentation or photosynthesis. Chemistry is used in chemical processes that convert materials into fuels. Finally, some hybrid processes combining both biological and chemical steps exists (Pietsch, 2012). Primary pathways for bioenergy production are presented in Figure 7. Biorefinery products are mainly used to replace products made from fossil resources (coal, oil, natural gas). (Savolahti and Aaltonen, 2006)

Transport is responsible for an estimated 21% of all GHG emissions in the European Union and the percentage is rising. Almost all the energy used in the transport sector comes from oil, the reserves of which are limited in quantity. Oil reserves situate in a few world regions and newly found reserves typically become more and more difficult to exploit. (COM(2006) 34 final). Biofuels have a central role in the biomass policy of the European Union. The transportation sector is pivotal for the economy and is highly dependent on oil-based energy. Only biofuels can directly replace oil-based products in transportation and thereby reduce the dependency of the economy on oil prices and imported energy. (COM(2005) 628 final) As a form of biofuel, biomass has better storage properties than the unprocessed biomass.

Market price of biofuels and the cost of producing them determine the economic viability of biofuels. In the long run, the market price of a biofuel product should be equal to the price of the energy-equivalent fuel option it replaces if the fuels are perfectly substitutable (Khanna et al., 2009). The costs of conversion of cellulosic biomass to fuel are expected to constitute a large part of the costs of producing cellulosic biofuel. Also the costs of the feedstock can be significant, depending on the value and alternative profit of the land area (Khanna et al., 2009). The market price of biofuels is also influenced by existing policies that require their use as an additive to liquid transportation fuels by tax credits, tariffs and mandates (Khanna et al., 2009).

Industry and commerce see the biomass question as a business opportunity and a way to increase profits. Prices affect the competitiveness of biomass substantially. Oil prices are predicted to continue rising while reserves are diminishing and more resources are required for acquisition. Rising oil prices strengthen the profitability of biofuels, which can replace oil when the decreasing price difference increases the interest to use biofuels. (Valtonen, 2010) On the other hand, rising oil prices contribute to higher raw material prices with increased production costs, and the increased demand may raise the breakeven price of biomass for biofuel (Khanna et al., 2009).

The forest industry utilizes wood biomass primarily as a raw material of pulp and paper products and sawn wood. During the manufacturing processes of primary products, a significant amount of the raw material ends up in side flows that are utilized in electricity, heat and biofuel production (Alakangas & Heinimö 2011). Because forest industry mills are used to handling large amounts of wood biomass and transforming the bio-based side flows efficiently into energy and as the infrastructure partly exists, it is natural that the forest industry is expanding its business to biofuel production with an interconnection to their existing mills. In Finland, the forest industry cluster benefits from several opportunities for second generation biofuels production. There is potential to utilize process integration and existing raw material through sourcing organizations and facilities (Joelsson et al., 2009; Sipilä et al., 2009).

The profitability of biomass utilization is affected by location, technology, investments and the prevailing price level. Profitability can also be improved through national support measures. The geographical location affects the cost-effectiveness and economical availability of raw materials as transporting biomass from long distances raises the costs. Production sites by the coast or waterways which are connected to sea have an advantage in terms of lower transport costs of products and raw materials. The integrated production of biofuels alongside traditional production in the forest industry, energy sector or oil refining offers an opportunity to produce excess energy in integrated production. A unit which produces a diverse range of products can utilize the energy content of biomass to a high degree. Biomass processing generates various side flows, which can be combusted in a boiler producing heat. This heat can be utilized within the unit or sold outside it, for example in the form of district heating. Part of this heat can also be converted to easily sellable and transportable electricity. In plain electricity production, efficiency is lower and part of the energy potential is lost. (Valtonen, 2010)

Market instruments in national support policies could be planned to account for the external costs caused for society. National support policies can lower the threshold of establishing biofuel business. Tax exemptions and production support in the form of feed-in-tariffs can accelerate investments and promote the use of biofuels in production. The support to research and development and investment reduces the risks involved in new facilities. Sanctions set to increase the share of biofuels used in transportation have increased the demand and helped establish markets for biofuels. In Finland, the government uses energy taxation to promote renewable fuels as set in the Renewables Directive. The taxes are set on the basis of the energy content, CO_2 emissions and raw materials utilized. All biofuels that meet the sustainability criteria of the Renewables

Directive benefit from a flat rate tax reduction of 50%. Second generation biofuels, originating from residue or waste, as well as wood and biomass used for heat or electricity production are entirely exempted from the CO_2 tax. Peat use is punished with a gradually increasing tax level (Heinimö and Alakangas, 2011) owing to its relatively high CO_2 emission value.

3 Methodology and Case Descriptions

In this chapter, the methodology applied to the biomass GHG emission impact assessment is presented, first by presenting the LCA methodology and guidelines for LCA. This is followed by a literature review on LCA studies for biofuels in order to obtain an understanding of the main factors affecting the GHG emissions of biofuel production. In the third part, case studies included in this thesis are introduced and case-specific methodological issues are presented.

3.1 Life cycle assessment

LCA is a management tool that enables the assessment of environmental impacts through the product life cycle. It is a structured, comprehensive and internationally standardized method. There is broad agreement in the scientific community that LCA is one of the best methodologies for the evaluation of environmental loading associated with biofuel production (Cherubini et al., 2009).With LCA, environmental aspects and potential environmental impacts are addressed through the entire life cycle of a product. Using the systematic overview and perspective of LCA, the shifting of a potential environmental burden between life cycle stages or processes can be identified and avoided. Typically, LCA does not address economic or social aspects, although the life cycle approach and methodologies may also be applied to them. (EN ISO 14044:2006)

In LCA, the life cycle of a product is modeled as a product system which performs one defined function or more. The essential feature of a product system is defined by its function instead of in terms of the final products. Product systems contain a set of unit processes which are linked to each other by flows (intermediate products, wastes, products or elementary flows).

An example of a product system is presented in Figure 8. Dividing a product system into its components facilitates the identification of the inputs and outputs of the product system. The boundaries and the level of modeling detail are determined to satisfy the goal of the study. (EN ISO 14040:2006)

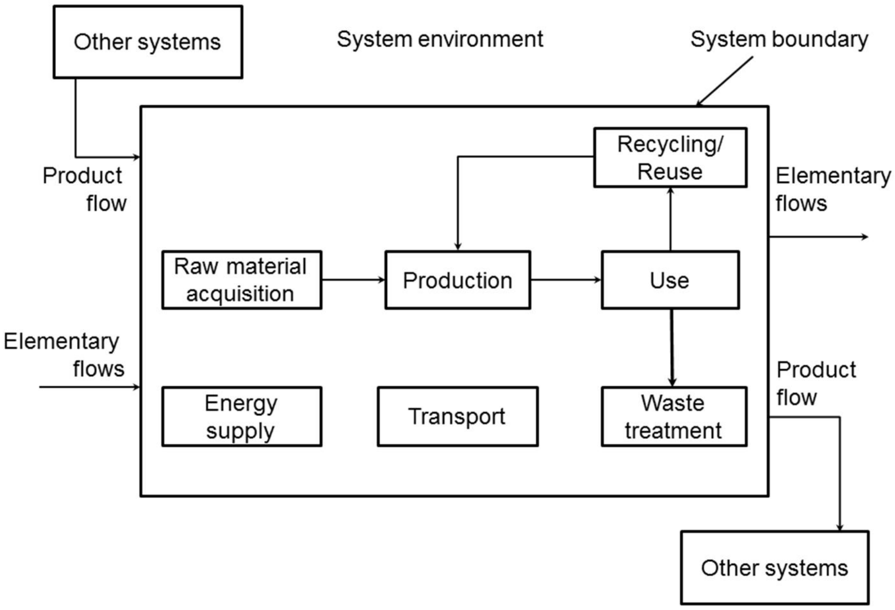

Figure 8. Example of a product system for LCA (EN ISO 14040:2006).

LCA is a relative approach (EN ISO 14040:2006), consisting of the comparison of one system to another (Fava, 2005). LCA is designed on the basis of a functional unit of a product or a service. The functional unit defines the object of the study, and the life cycle inventory is relative to the functional unit (EN ISO 14040:2006; Fava, 2005). In the application of LCA for biofuel production, the approach often applied is to use measures as input-output ratios (especially for energy input/output) or per unit output (km, kWh, MJ) based on the purpose of use. If the focus of the study is on the question of relative land use efficiency, the results can be presented on a per hectare basis. On the other hand, for biomass feedstock use efficiency, the results can be expressed as a per unit output (Cherubini et al., 2009).

The goal and scope of an LCA shall be defined and consistent with the intended application. The scope may have to be refined during the study due to the iterative nature of LCA (EN ISO 14040:2006; EN ISO 14044:2006). The ISO 14040:2006 standard presents two different approaches to LCA: one which assigns flows and potential environmental impacts to a specific product system, and one which studies the environmental consequences of possible (future) changes between alternative product systems. In the ILCD Handbook (2010), these two fundamentally different logics (European Commission, 2010) are referred to as the attributional (ALCA) and consequential approaches (CLCA) (Figure 9). The attributional approach relates what the environmental impact of a system is and the consequential approach unveils the environmental impact of increasing the production.

ALCA, also named as a retrospective or accounting perspective, describes the environmental properties of the life-cycle and deals with the emissions that are directly connected to the production of interest (Schmidt, 2008; Ekvall, 2002; Tillman, 2000). In ALCA, average or supplier-specific data is used and co-production is handled by applying allocation factors (Tillman, 2000). ALCA is said to provide more precise and certain results but less accurate due to the possible blind spots which are revealed with the consequential LCA approach (Schmidt, 2008). CLCA, also known as a prospective perspective, describes the effects of changes and attempts to estimate what is going to happen as a result of potential decisions (Ekvall, 2002; Tillman, 2000). The CLCA assessment reaches to the secondary effects of the studied production of interest and focuses on the processes that are actually affected by a change in the studied production including the market mechanisms into the analysis (Zamagni et al., 2012). The marginal data is defined and used and the allocation is avoided by using system expansion (Tillman, 2000). Consequential LCA provides a more complete and accurate but less precise and certain result (Schmidt, 2008). The CLCA is most useful for examining alternative scenarios when it produces understanding of the range of potential environmental outcomes instead of a single most-likely outcome (Plevin et al., 2013).

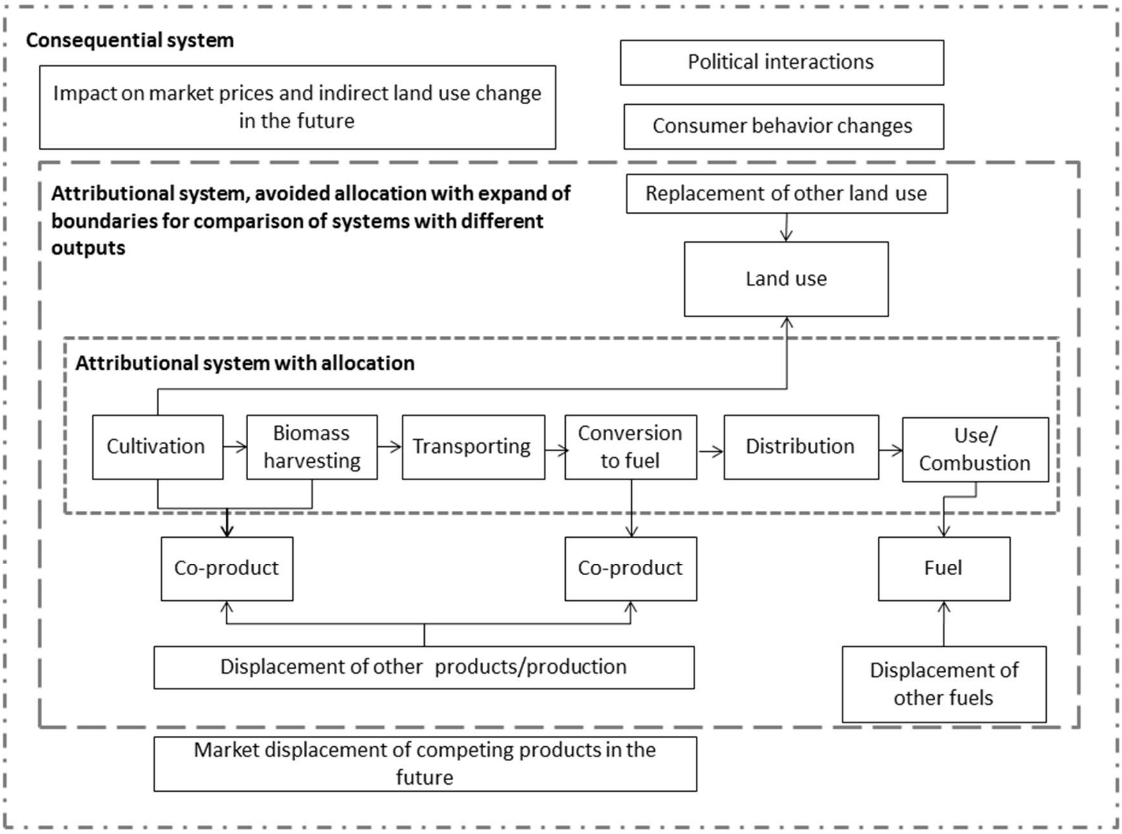

Figure 9. The system boundaries of the attributional system expansion and consequential system approach (Reinhard and Zah, 2009; European Commission, 2010)

ALCA and CLCA are different types of LCA applications for different decision making situations. Because ALCA focuses on the environmental performance of the production of interest, it is suitable for example for making a market claim or for the identification of improvement possibilities within the life cycle (Tillman, 2000). The CLCA approach follows the consequences of decisions from one product system to all other product systems that can be identified to be affected by this chain of consequences and is thus useful for future oriented studies where the effects for example on the product design or regulatory measures are estimated (Tillman, 2000). In Publications I–II, the aim is to assess the climate impact of the peat utilization from different peatlands by comparing two alternative systems: peatlands with energy utilization of peat and peatlands without energy utilization when the same amount of energy is produced with coal. Also in Publication III, changes are studied between the following systems: a pulp mill with ethanol production and a pulp mill without ethanol production. When the definition of ISO 14040:2006 is used, these perspectives are more consequential than attributional. On the other hand, the assessments include only emissions that are directly connected to the studied product systems, and the indirect impacts on other product systems are excluded. Thus, in Publications I–III, defining the approach between these two categories is not obvious because of the varying definitions in the standard and literature. In Publication IV, the GHG emissions of renewable diesel is studied, and the GHG impacts of one specific product system is assessed, which reminds more the attributional perspective On the other hand the study involves several feedstock alternatives to examine alternative scenarios to understand the range of potential environmental outcomes instead of a single outcome, which can be seen as a consequential approach (Plevin et al., 2013). With the definitions presented above, Publication IV is not purely using the attributional perspective but involves several similar aspects than ALCA.

Thus, LCA provides probably the most objective description of the potential environmental impact of a product system, but a certain level of subjectivity is unavoidably included in methodology itself. The initial step of a fuel life cycle analysis is to identify system boundaries to make the study manageable. The location of the boundaries has an influence to the final outcome. For example, the substitution of one energy source with another can have a broad effect throughout the economy (Schlamadinger et al., 1997). The greenhouse gas and energy balances of biofuel systems differ depending on the feedstock, conversion technologies, end-use technologies, system boundaries and the reference system with which the bioenergy chain is compared. Also regional differences may be significant due to land use and the reference energy system. Biofuel production usually produces also co-products, which can replace conventional products, providing further environmental benefits. (Cherubini et al., 2009)

The data sources of LCA differ from the data sources used in more traditional modeling methods. The data used in LCA can be based on measurements, calculations or alternatively on estimations or information from literature. Therefore, sensitivity analyses on the uncertainties of the results are needed in LCA.

3.1.1 **Framework for LCA**

The ISO 14040 and 14044 standards provide the framework for LCA (see Table 1). Before ISO made the initiative to normalize LCA, the most active institution in the methodological consensus was the Society of Environmental Toxicology and Chemistry (SETAC). The framework provided in ISO standards leaves the practitioner with a range of choices which may significantly affect the results of an LCA study. While flexibility is essential, more guidance is needed to support consistency and quality. To this end, the International Reference Life Cycle Data System (ILCD) was developed to provide guidance for LCA data and studies.

Table 1. ISO series of standards for LCA, carbon footprint, quantification of GHG emissions and other guidance.

Life Cycle Assessment - LCA		**Publisher**
ISO 14040:2006	Environmental management - Life cycle assessment - Principles and framework	International Organization for Standardization
ISO 14044:2006	Environmental management - Life cycle assessment - Requirements and guidelines	International Organization for Standardization
ISO/TR 14047:2003	Environmental management - Life cycle assessment - Examples of application of ISO 14042	International Organization for Standardization
ISO/TS 14048:2002	Environmental management - Life cycle assessment - Data documentation format	International Organization for Standardization
ILCD handbook (2010)	General guide for Life Cycle Assessment - Detailed Guidance	European Union
Carbon footprint of product (CFP)		**Publisher**
PAS 2050:2011	Specification for the assessment of the life cycle greenhouse gas emissions of goods and services	British Standards Institution
ISO/TS 14067:2013	Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification and communication	International Organization for Standardization
GHG Protocol	Product Life Cycle Accounting and Reporting Standards	World Business Council for Sustainable Development (WBCSD), World Resources Institute (WRI)
Life Cycle GHG emissions (some carbon footprint aspects)		**Publisher**
Directive 2009/28/EC	Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources	European Commission
ISO 14064-1:2006	Greenhouse gases — Part 1: Guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals	International Organization for Standardization
ISO 14064-2:2006	Greenhouse gases — Part 2: Guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements	International Organization for Standardization
ISO 14064-3:2006	Greenhouse gases — Part 3: Guidance for the validation and verification of greenhouse gas assertions	International Organization for Standardization
ISO 14065-3:2007	Greenhouse gases — Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition	International Organization for Standardization

3.2 Allocation in LCA

In LCA, the product system consists of several unit processes which are connected to each other. When the product system is divided into sub-processes, at some point the process description ends in a situation where one process is producing several different products instead of only one. If these processes have input or output flows which are not included inside the system boundaries, it is necessary to either expand the boundaries of the system or to decide, how the used resources and caused emissions are allocated (directed) to the different input and output flows. For example when different waste fractions are combusted in the same combustion unit, it has to be decided, which share of the emissions is directed to each waste fraction. (Lindfors et al., 1999)

Allocation should be avoided when possible either by dividing the multifunctional process to several mono-functional sub-processes or by expanding the product system to include the functions related to other products in a way that the modified options produce the same amounts of the same final products (ISO/TR 14049:2000(E), 2000; EN ISO 14044:2006).

The example of the product system expanding presented in the technical report ISO/TR 14049 (2000(E)) handles a case where the same waste material can be utilized either to material or energy recovery (see Figure 10). Because in this example alternative recovery options yield different products (plastic film from material recovery or heat from energy recovery), the consumption of resources and produced emissions due to these options cannot be compared directly. With this approach the expansion can be implemented in such a way that the two modified options produce the same amount of the same final products. The material recovery option is complemented with a process producing 26 of MJ heat from primary energy sources. Likewise, a process which produces plastic film from the primary resources is added to the energy recovery option. With this method it is guaranteed that both systems produce the same amount of heat and plastic and their raw material use and environmental impacts are comparable.

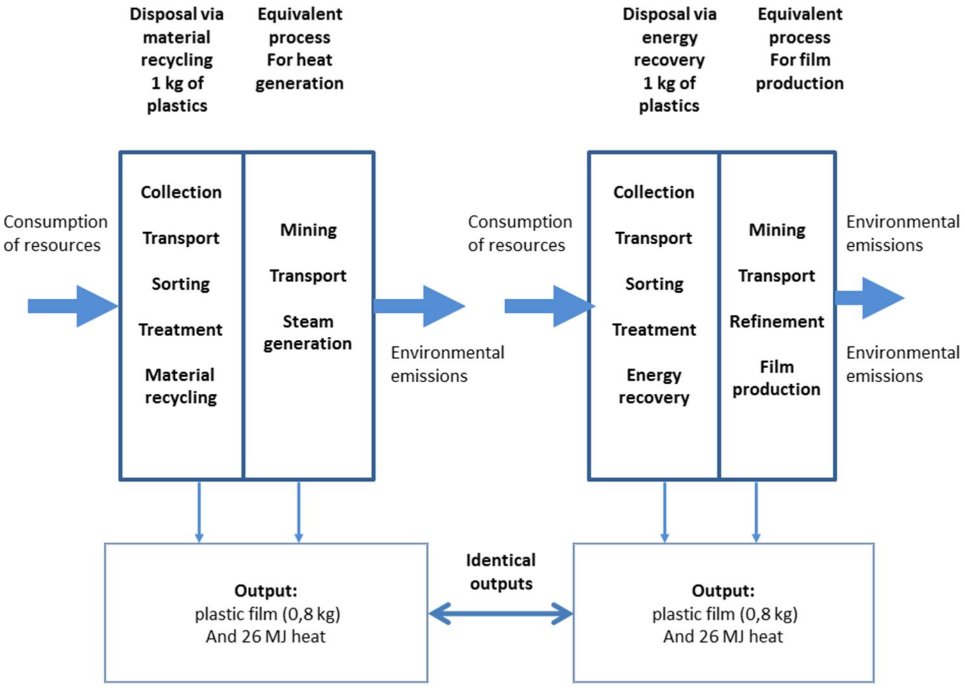

Figure 10. Example of avoiding allocation with system expansion, presented in ISO/TR 14049 (2000(E)).

When the allocation is not avoidable, the input and output flows of the system should be partitioned between the products and functions reflecting the relationship between the changes in products and functions to inputs and outputs (EN ISO 14044:2006). If the physical relationships cannot be used as a basis of the allocation, ISO 14044 advises to use other relationships like the economic value of the flows.

The aim of the allocation is to direct the inventory results of the multifunctional process and the previous life cycle stages to different products in such a way that part of the environmental load can be allocated to the flows which are outlined from the studied system. In this case, allocation will reduce the environmental load of the studied system. Allocation decisions are affecting the results significantly, and the results may change if the allocation method is changed (Svanes et al., 2011; Wardenaar et al., 2012). Also some allocation factors themselves may change due to external reasons (for example the economic allocation factor changes when the price of product changes), and this affects the results.

3.3 The Global Warming Potential (GWP)

The Global Warming Potential (GWP) concept (IPCC, 1990) is a relative measure of the potential effects on the climate from various greenhouse gas emissions. It has been developed at the request of policy makers, and it can be used to calculate the emission reductions for greenhouse gases (Wuebbles et al., 1995). The GWP index of a greenhouse gas as defined in IPCC (1990) is the time-integrated global mean radiative forcing (RF) of a pulse emission of 1 kg of some gas (i) relative to that of 1 kg of the reference gas CO_2. The GWP is defined by the following Equation (IPCC, 2007c; Fuglestvedt et al., 2003):

$$GWP_i = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_{CO_2}(t)dt} = \frac{\int_0^{TH} a_i c_i(t)dt}{\int_0^{TH} a_{CO_2} c_{CO_2}(t)dt} = \frac{AGWP_i}{AGWP_{CO_2}} \tag{1}$$

where TH is the time horizon and RF_i is the global mean radiative forcing of gas i. Terms a_i and a_{CO2} are the radiative forcings due to a one unit increase in the atmospheric concentration of gas i and CO_2, respectively. Terms c_i and c_{CO2} are the time decaying abundances of the injected gases, and terms RF_i and RF_{CO2} are the radiative forcings due to the gases i and CO_2. The numerator and denominator are named as the absolute global warming potential (AGWP) for gas i and the reference gas CO_2 (IPCC, 2007c).

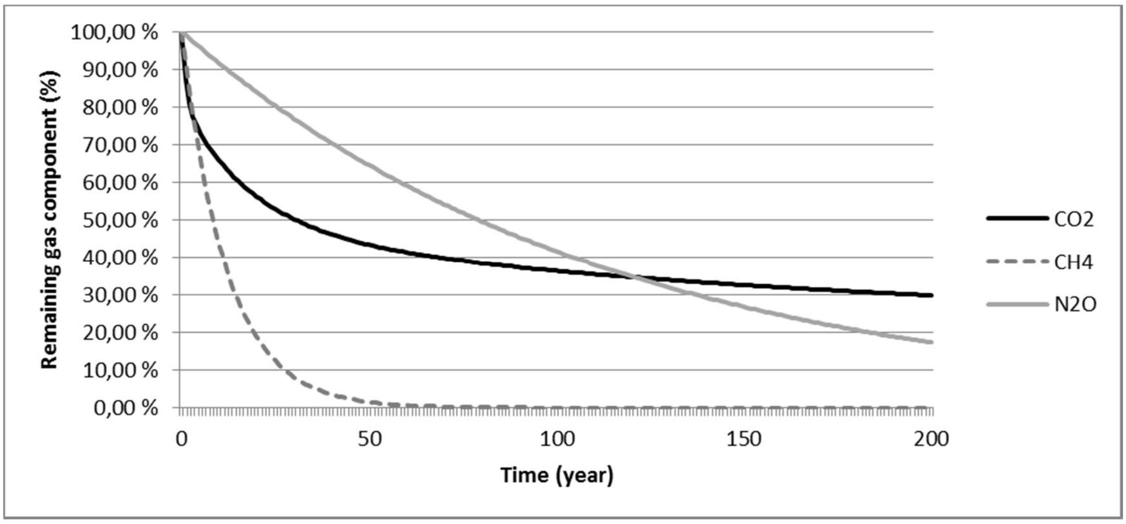

Figure 11. Decay of CO_2, CH_4 and N_2O in the atmosphere. Decay of CO_2 is based on the Bern Carbon Cycle Model (IPCC, 2007b). The area under the curve is the time-integrated mass load of gas component *i*.

The adequacy of the GWP concept has been widely criticized since its inception (Fuglestvedt et al., 2003; O'Neill, 2000). The GWP values are dependent on the selection of the time horizon, and there is no obvious recommendation to this choice (Harvey, 1993; Fuglestvedt et al., 2003). The GWP for shorter living gases (e.g. CH_4) than for the average CO_2, decreases when the time horizon increases (Levasseur et al., 2010)(see Table 2). The impact of methane (CH_4) emissions on the short-term temperature change is greater than that of the CO_2 emissions that have a greater long-term effect (Fuglestvedt et al., 2003). The robustness of the GWP as a metric depends on the uncertainty in the RF concept and in the lifetimes of the gases (Fuglestvedt et al., 2003). The concept is based on the assumption that the integrated RF is a good indicator of global warming but in reality, the effect may be non-linear, and the GWP does not attempt to take this into account (Fuglestvedt et al., 2003). Also, various assumptions cause sensitivity to the GWP index values, especially to the background atmosphere (Fuglestvedt et al., 2003). As an answer to this criticism, alternative metrics have been created (Tanaka et al., 2013). Despite all the uncertainties related to the GWP metric, the IPCC (2007c) recommends it for the comparison of the future climate impacts of the emissions of long-lived climate gases.

Due to the politics the GWP has become the default metric for transferring the GHG emissions to ‘CO_2 equivalent emissions’ (Shine, 2009). The Global Warming Potential with a 100-year timeframe is commonly used for policy frameworks like the Kyoto protocol (Article 5 in the Kyoto Protocol). The 100-year time horizon is useful since it is long enough to approximate the lifetime of CO_2 which is the dominating GHG in the climate change (Lelieveld et al., 1998). GWP –values are given for some selected gases in IPCC reports (1990 etc.). The common definition of ´CO_2-equivalents’ is presented in Equation 2. The CO_2 equivalent amount of gas i measured by mass is (Fuglestvedt et al., 2003):

$$CO_2 - eq.(TH) = GWP_i(TH)E_i \tag{2}$$

where $GWP_i(TH)$ is the Global Warming Potential of gas i, E_i is the emission of gas measured by mass and $CO_2\text{-}eq(H)$ is the CO_2-equivalent amount of gas i using GWP for a time horizon TH.

The GWP values from 2007 IPCC AR4 for methane and nitrous oxide have been used in this study. The values and also the IPCC AR5 values in parenthesis are presented in Table 2. The GWP values change when new knowledge has emerged and will continue to change in the future partially due to new knowledge of the radiative forcing and lifetime of the gases and also due to the changing atmosphere (Smith and Wigley, 2000; Fuglestvedt et al., 2003). The time horizon of 100 years for the GWP values is selected for the assessment in accordance with the Kyoto Protocol and IPCC recommendation. The emissions occurring during the time period of 100 years are assessed, and the impact assessment (LCIA) is carried out with the GWP 100-years values. In this approach, the timing of the emissions is not taken into account, and this expands the time of the impact assessment until the year 199 when the global warming potential of the emissions occurring during the first 99 years is assessed with the GWP of the following 100 years. Compared to the situation, where the GWP values from 1 to 99 years are used and the emission impact on the year 100 is calculated based on these GWP values, the warming impact of methane emissions are underestimated. This inaccuracy affects mainly the GWP of CH_4 emissions due to the short lifetime. The impact on the GWP of N_2O emissions would be smaller due to the small difference between GWP 20 and GWP 100 values. Due to the relative nature of the GWP index, changing the time horizon is not affecting the GWP value of CO_2.

Table 2. The GWP values and atmospheric lifetimes of carbon dioxide, methane and nitrous oxide from 2007 IPCC AR4. IPCC AR5 values in parenthesis. Lifetime of CO_2 is derived from the Bern carbon cycle model and single lifetime can be not defined for CO_2. The GWP for CH_4 includes indirect effects on other gases in the atmosphere.

		GWP time horizon		
Gas	**Lifetime, years**	**20 years**	**100 years**	**500 years**
Carbon dioxide	Variable	1 (1)	1 (1)	1 (1)
Methane	12 (12,4)	72 (86)	25 (34)	7,6
Nitrous oxide	114 (121,0)	289 (268)	298 (298)	153

The impact of the dynamic LCIA on the results is further discussed in Chapter 4.2.

3.4 Spatial dimension in forest biomass energy studies

On analyses of global warming impacts from forest bioenergy systems, two alternative approaches, either at a stand level or at landscape level, are used (Cherubini et al., 2013; Cowie et al., 2013). In a stand level approach, the biogenic carbon fluxes are accounted by including the dynamics occurring in one single stand during a reference time after harvest (Cherubini et al., 2013). In this approach the carbon from forest stand is released entirely in the beginning of the reference time and the regrowth with carbon accumulation takes place at the same stand during the following growth cycle (usually 90-100 years). In the landscape level approach, the area included is wider than just the one stand harvested in the beginning. In a landscape approach, the carbon fluxes are accounted for all the stands, which are needed to maintain continuous supply over the reference period (Cherubini et al., 2013). For example, if the reference time is 100 years and also the rotation time of forest stand is assumed to be 100 years, the area needed for sustain the forest biomass feed is 100 times wider than for stand approach. These stands have a uniform age class distribution, where each stand is at a different stage of the rotation period and one of these stands is harvested during a one year. During these conditions, the time averaged carbon in a forest stand level during a 100 year reference time is the same than for landscape level.

The carbon of forest stand cycles with periods of growth and harvest removals. In a landscape and stand level this cycle is seen differently: when harvest are maintained at a sustainable rate, on a landscape level there is no change in forest inputs or outputs even these impacts are periodic during the growth cycle for an individual stand (Lippke et al., 2011). Thus, carbon neutrality with instant accumulation to the forest can be justified by using the landscape level approach, even this accumulation is a result of earlier harvest and thus this approach involves risk for double counting of the sequestration potential of the forest (Cherubini et al., 2013). This might be the case, if accumulation is counted to balance the sequestration of both earlier harvest on the same stand and current harvest on the nearby stands at the same time.

In both approaches (stand or landscape) the definition of reference scenario, where biomass is not used for the studied purposes, is a critical selection (Cowie et al., 2013; Cherubini et al., 2013). Usually the reference scenario includes either forest management with production to other products and services or forest conservation (Cowie et al., 2013). Also clear land may be used as a starting point where the impact of previous harvest is not included (Sathre and Gustavsson, 2012), for example when peatlands without tree vegetation are drained for forestry and a new stand is established. This selection has an impact to the average carbon stock of a studied area when the carbon stock of conserved forest or other old, mature forest is significantly higher than for managed and thus constantly harvested forest (Roxburgh et al., 2006; Holtsmark, 2013a; Keith et al., 2009; Luyssaert et al., 2008). When managed forest is considered, summing CO_2 fluxes across the rotation period form a CO_2 neutral system, but for forests that contain more carbon in the reference scenario the stands are not achieving the carbon neutral situation (Cherubini et al., 2013). It is also possible that improved forest management increases the carbon accumulation to the forest stand when compared to the present sivilcultural technologies in managed forest (Poudel et al., 2012). Improved forest productivity leads also to increased biomass substitution (fossil fuel and GHG intensive materials) and thus avoided carbon emissions when compared to the reference forest management with harvest (Poudel et al., 2011; Sathre and Gustavsson, 2012).

Even the findings from the forest bioenergy studies are sometimes interpreted contrasting, the spatial scale itself does not impact to the results of direct impacts of biogenic CO_2 emissions (Cherubini et al., 2013). Instead the manner of representation and reference scenario are affecting more to the interpretation of results. In a stand level approach using of non-harvesting scenarios is more common choice and in landscape level approaches the reference scenario is more often the managed forest. When these assumptions are used, the stand level approach attributes more biogenic CO_2 emissions for the forest use than landscape level approach.

3.5 Time dimension in biomass and bioenergy LCA studies

Currently, it is a common practice to assume in the LCA studies of bioenergy systems that the CO_2 emissions from biomass combustion are offset by the biomass growth (Cherubini et al., 2011). The history of this convention starts from 1991 when the first guidelines for estimating national greenhouse gas (GHG) emissions and sinks by the Organization for Economic Cooperation and Development (OECD) stated that the CO_2 emissions from bioenergy consumption should not be included in the emission inventory (OECD, 1991). Instead, changes in forest carbon stocks and other land use impacts are accounted in the land use, land use change and forestry (LULUCF) sector, according to country-specific regulations (Cherubini et al., 2011; UNFCCC, 2003; IPCC, 2006b).

Based on the findings of Cherubini et al. (2011), there are two prevailing alternative accounting procedures to implement this rule of carbon neutrality: ignoring the CO_2 flux of bioenergy system assigning the GWP equal to zero for the CO_2 originating from biomass combustion and refining or offsetting the biomass combustion CO_2 emissions with a sequestration credit equal or nearly equal to the combustion emissions. Both of these approaches generate the same result: the CO_2 emissions from biomass are neglected and only the CO_2 from fossil sources is accounted. This assumption is one of the main reasons which explain why most of the bioenergy system LCA studies generally result in a reduction in the GHG emissions and thus in the contribution to the climate change when compared to the fossil reference system (Cherubini et al., 2011).

Because the land uses already provide storage and carbon sequestration benefits, the cultivation and use of biomass in these areas needs to excess these benefits before the use of biomass can reduce the GHG emissions (Searchinger et al., 2008). Bioenergy use is not climate-neutral because land clearing, cultivation and harvesting biomass for bioenergy results in changes in soil and biomass carbons stocks, and even without the LUC impacts, the increased harvesting of biomass leads to a permanent raise in atmospheric carbon dioxide concentrations (Anderson-Teixeira et al., 2009; Holtsmark, 2012; Holtsmark, 2013a). Due to the time-difference between the CO_2 released during biomass combustion and the CO_2 sequestration back to the growing biomass, the carbon concentration increases temporally (Cherubini et al., 2011; Helin et al., 2013; Pingoud et al., 2012). With intensive forest management the averaged carbon stocks of forest may be increased, and thus it can replace the climate impact which results from the forest biomass stock and soil organic matter during harvesting (Holtsmark, 2013a; Sathre and Gustavsson, 2012). The increased productivity of forest leads also to greater substitution benefits due to replacement of fossil fuels and energy intensive materials (Poudel et al., 2012).

The main question is how the climate impact of biogenic CO_2 emissions should be included in the bioenergy LCA studies. In literature, three alternative options can be found to include temporal aspects of biomass regrowth in the LCA studies: 1) accounting the carbon stocks as a function of time when the net change is presented with a graph and can be used as absolute values or time averaged values in the CO_2 emission estimates (Anderson-Teixeira et al., 2009; Germer and Sauerborn, 2008; Holtsmark, 2012), 2) including the temporal emission aspect in the static bioenergy LCA studies via different factors, e.g. GWP_{bio}, that can be used for biomass derived emissions (Cherubini et al., 2011; Pingoud et al., 2012; Holtsmark, 2013a; Guest et al., 2013) or 3) shifting to a dynamic approach where the impact of timing is assessed with the temporal profile of emissions and time-dependent characterization factors, for example RF or GWP(t) values (Levasseur et al., 2010; Kirkinen et al., 2007; Kirkinen, 2010; Ericsson et al., 2013). The first approach uses the static LCA approach, which does not include the timing of emissions. The second approach is a hybrid of dynamic and static approach, where biomass derived emissions are treated differently than other emissions with characterization factors that include the impact of the temporal variation in the biomass system. In the third approach, the entire LCA uses the dynamic approach, and difference between the biogenic and fossil emissions is not made (Ericsson et al., 2013).

The impact of the method selection between static and dynamic approach on the results has not been comprehensively handled in literature but some remarks can be found, according to which the impact is not significant (Kirkinen et al., 2009; Holtsmark, 2013a). Kirkinen et al. (2009) compared the greenhouse impact of jatropha and forest residue diesel with static assessment with the GWP 100 values and dynamic with Relative Radiative Forcing Commitment (RRFC), respectively. As a result, the GHG impact of forest residue was 12% higher with the RRFC method than when the GWP was used with a 100-year time horizon. As a contrast, the GHG impact of jatropha was 3% smaller with the RRFC than when the GWP was used. The surprisingly small and divergent difference between these results indicates that there are no significant difference between the dynamic and static method with these two biomass sources when RF-based characterization factors are used (Kirkinen et al., 2009). Holtsmark (2013b) analysed the effects on atmospheric CO_2 levels of increased forest bioenergy use adjusting the results of an earlier study (Holtsmark, 2012) by incorporating the impulse response function in the analyses. As a result, the fundamental change to the results was not found (Holtsmark, 2013b).

3.6 Literature review from LCA Studies for Biofuels

The objective of this section is to present GHG emission balances of various biofuel production chains. Published LCA studies are used to interpret observed relations between chain-specific features and GHG emissions of biofuels where possible. The research discussed in this chapter includes research on various biomass sources, biofuel products and processes. This chapter is placed in the context of life cycle GHG emission estimation and reduction in biofuel production.

The research papers for this review were selected based on the following conditions: 1) Subject: the papers study the GHG emissions of biofuel production chains, 2) Time relevance: the papers are published in the 21st century, 3) Quality: the publication is in a peer reviewed journal and 4) Usability: the results are presented in a way that the comparison of emissions from different life cycle phases between different studies is possible.

This review covers 29 research papers from which 71 different biofuel production chains were selected. Of these 71 production chains 35 represent ethanol production, and 18 of the 35 can be classified as first generation processes (Ometto et al., 2009; Nguyen and Gheewala, 2008a; Ngyen and Gheewala, 2008b; Seungdo and Dale, 2009; Seungdo and Dale, 2005; Hsu et al., 2010; Whitaker et al., 2010; Hennecke et al., 2012; Chouinard-Dussault et al., 2011) and 17 as second generation (Cherubini and Jungmeier, 2010; Seabra and Macedo, 2011; Luo et al., 2009; Sheehan et al., 2004; Hsu et al., 2010; Kumar and Murthy, 2012; Slade et al., 2009; Chouinard-Dussault et al., 2011) based on feedstocks utilized. A total of 26 production chains produce first generation biodiesel (FAME) (Chouinard-Dussault et al., 2011; Reinhard and Zah, 2009; Seungdo and Dale, 2005; Soratana et al., 2012; Silaletruksa and Gheewala, 2012; Whitaker et al., 2010; de Pontes Souza et al., 2012; Yamfen et al., 2012; Harsono et al., 2012; Ndong et al., 2009), (Wicke et al., 2008; Hennecke et al., 2012), two chains produce second generation synthetic biogasoline and biodiesel (González-Garcia et al., 2013; Hsu, 2012), and seven chains represents direct biomass use for electricity and/or heat production (Seabra and Macedo, 2011; Wicke et al., 2008; Gabrielle et al., 2013; Guest et al., 2011; Grönroos et al., 2013). The published papers cover 22 different raw materials and 202 scenarios. Consequently, information about the most important production factors that have an impact on GHG emissions was sought.

Based on the articles, the three most important life cycle stages were identified. The results are presented in Figure 12. For comparison, the biofuel production chains are divided into five stages: (I) biomass production and cultivation, (II) transport of biomass to the plant, (III) conversion of biomass to biofuels, (IV) transport and distribution to gas stations (only traffic fuels) and (V) use in vehicles or combustion plants. Also (VI) carbon uptake to biomass and (VII) land use change (LUC) are taken into consideration when these stages are included in the chains.

Figure 12 shows the three most important GHG emission sources. The first column is a summary and the next four columns include the same results divided based on the method or product used in production: ethanol from first and second generation feedstocks (EtOH 1st gen. and EtOH 2nd gen.), biodiesel and solid fuels. When all fuel chains are considered together, the carbon uptake to biomass (VI) during cultivation is reported the most commonly to cause the highest impact on the GHG balance. The conversion of biomass to biofuels (III) and the cultivation stage (I) follow immediately. Only 17 chains included the change in land use in the results, and it should be noted that all of these papers included the LUC impact among the three most important categories. In 14 of the 17 articles, LUC was reported as the most important stage in the GHG balance formation. When the different fuel chains are considered separately, the LUC remains important and also cultivation (I), conversion (III) and use (V) are mentioned in the most important category. Based on this review, it is by no means self-evident that one life cycle stage would cause the highest GHG impact in these biofuel chains and there is need to examine the reasons which explain the variation between these studies.

Carbon uptake to biomass (VI) has a significant impact on GHG emissions when reported. In practice, biomass studies which do not account for the carbon uptake and release directly assume that carbon uptake and release in biomass utilization cancel each other out and their flows do not need to be calculated. Only one paper accounted for the uptake without use (Kumar and Murthy, 2012), and in the rest, the carbon is released during conversion and use. Usually only carbon uptake or LUC are included in the same study, with one exception (Hennecke et al., 2012).

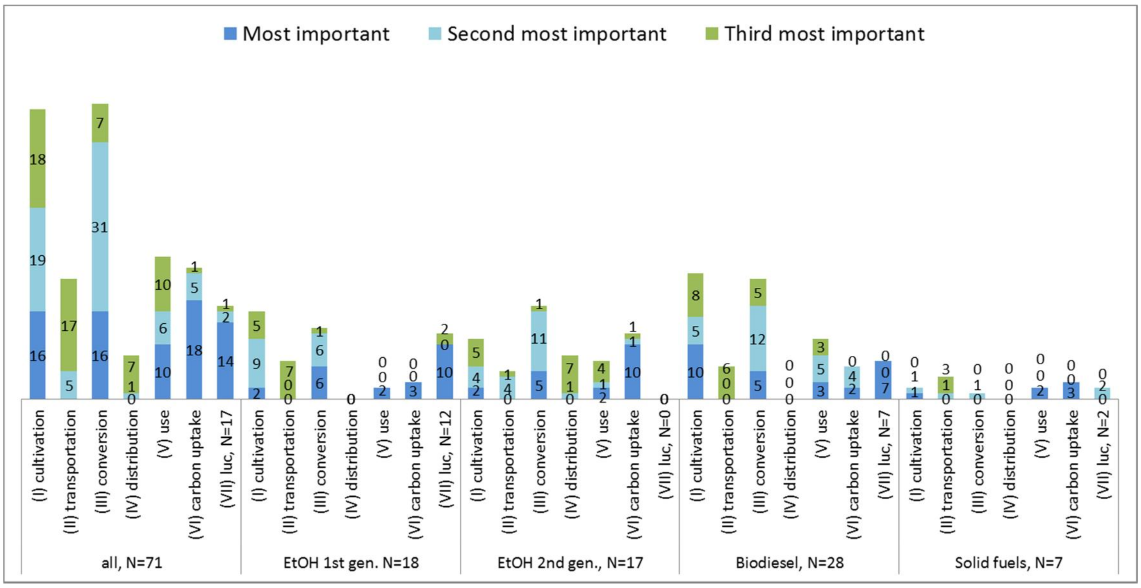

Figure 12. Contribution of different life cycle stages to the GHG results of the studied biofuel chains.

LUC (VII) was reported to be among the three most important stages in all of the studies included. This impact was especially highlighted in the papers which handle biomass from organic land areas (Grönroos et al., 2013; Harsono et al., 2012). The most decisive factor for GHG emissions from LUC is the carbon content of land where biomass cultivation is established (Harsono et al., 2012; Wicke et al., 2008). More favorable results are obtained when the cultivation area is degraded land where the carbon content can be increased with new plantations (Wicke et al., 2008).

In biomass cultivation, GHG emissions are mainly caused by fertilizer use and production, machinery fuel consumption and the release of biomass and soil carbon (Ometto et al., 2009). The carbon content of biomass is released in the beginning of land preparation, in particular if burning is used to help land clearing between crop rotation (Ometto et al., 2009). The N_2O emissions from nitrogen fertilizers are significant in all biomass cultivation: the cultivation of sugar and starch biomass (Whitaker et al., 2010; Hennecke et al., 2012; Chouinard-Dussault et al., 2011), cellulosic biomasses (Cherubini and Jungmeier, 2010; Sheehan et al., 2004; Gabrielle et al., 2013), oil crops (Whitaker et al., 2010; Ndong et al., 2009), microalgae cultivation and palm oil plantations (Yamfen et al., 2012; Silaletruksa and Gheewala, 2012). The use of organic fertilizers instead of synthetic ones might reduce these emissions (Harsono et al., 2012). Fertilizer use and crop yield have the most significant impact to GHG emissions (Whitaker et al., 2010). The utilization of all biomass including its residues increases the biomass yield from a given land area (Seungdo and Dale, 2005). When the residues are used for biofuel feedstock, cultivation emissions can be divided between the main and residual biomass (Seabra and Macedo, 2011). In contrast, when residues are assumed as waste, the emissions are all attributed to the main crop (Luo et al., 2009; Hsu et al., 2010), which is greatly advantageous to the utilization of residues.

The conversion of biomass to biofuels (III) has a significant impact on the GHG balance of biofuel chains. GHG emissions are caused by energy consumption, the need for process chemicals (enzymes, catalysts) and waste water treatment (Nguyen and Gheewala, 2008a; Ngyen and Gheewala, 2008b). When biomass-based fuels are treated as a carbon neutral energy source, the size of the fossil source of heat and power for the fuel conversion step significantly impacts the GHG emissions (Whitaker et al., 2010; Nguyen and Gheewala, 2008a; Ngyen and Gheewala, 2008b). The GHG emissions vary depending on the production method used and the utilization of side flows (Hsu et al., 2010). In ethanol production, dry milling consumes more fossil energy than biochemical and thermochemical pathways if the lignin and residual syngas provide heat and power to biochemical and thermochemical processes (Hsu et al., 2010). The use of cellulosic feedstocks in ethanol production requires advanced pretreatment processes which, on the one hand, consume more energy, but on the other, produce residues such as lignin suitable for use in carbon neutral process heat and electricity production, which may even result in excess electricity (Hsu et al., 2010; Seungdo and Dale, 2005). However, electricity production from lignin does not always cover the electricity need of an ethanol plant (Kumar and Murthy, 2012). Energy consumption in pretreatment is a crucial parameter and may overturn the benefits of replacing fossil fuels with biofuels in the transport sector if it cannot be satisfied with a zero-emission energy form (Soratana et al., 2012). When biogenic carbon emissions are included in a study, ethanol production, ethanol yields of conversion and the amount of excess co-produced electricity are the main factors influencing the GHG emissions (Chouinard-Dussault et al., 2011). In biorefinery concepts, the efficient utilization of sideflows of production for heat or electricity production is beneficial as far as it does not affect to the yield of the main product when the emission impact of the avoided electricity is smaller than the emission impact of the replaceable liquid fuel (Hsu, 2012). Ethanol yield improvements in the fermentation process result in lower emissions of the fuel product (Slade et al., 2009). In biodiesel production, the process alcohol additives, methanol (Harsono et al., 2012; Ndong et al., 2009) or ethanol (de Pontes Souza et al., 2012) and NaOH catalyst production (de Pontes Souza et al., 2012; Harsono et al., 2012) are significant emission sources due to high cultivation emissions of alcohol feedstocks. During biofuel production, it is common that multiple products are formed. These co-products depend on the feedstock used, the product formed and the process applied to biomass conversion to biofuel. When the GHG balance of a certain biofuel product is calculated, these co-products need to be taken into account. One option is to allocate emissions to both the fuel product and its co-production, which reduces emissions attributable to the primary fuel (Slade et al., 2009; Hsu et al., 2010; Chouinard-Dussault et al., 2011). The allocation methodologies applied in the studied articles vary and are presented in Table 3 with raw materials and co-product options. The production of co-products in the same process may even halve the GHG emissions attributable to the main product (Wicke et al., 2008). In addition to the allocation methodology, also the system expansion approach and substitution is used to reduce emissions from co-products.

The system expansion approach assumes that the co-product can replace the same or a similar product from another feedstock. With this displacement, credit is assigned when the original production emissions are avoided (Wicke et al., 2008). Especially if the co-product is energy intensive, such as synthetic glycerin in biodiesel production, and the production of the co-product does not significantly increase the fossil energy use in the process, a high emission credit is generated (Wicke et al., 2008). Sideflows and co-products may have many utilization alternatives with different emission reduction impacts (Nguyen and Gheewala, 2008a) and there is a possibility to plan the process design to support maximal GHG benefits.

High GHG emission impacts of the use phase in biomass studies are generated due to 1) the inclusion of biogenic carbon emissions in the study (Bai et al., 2010; Chouinard-Dussault et al., 2011; Grönroos et al., 2013; Hsu et al., 2010; Luo et al., 2009), 2) the inclusion of the avoided emissions of the substituted fossil fuel (Seungdo and Dale, 2005; Sheehan et al., 2004) or 3) non-CO_2 emissions in the combustion of the fuel product in the use phase (Guest et al., 2011). In the first case, overall impact remains zero because the carbon uptake overturns the emissions released when all life cycle GHGs are assessed. One exception is peat fuel, which is not handled as renewable fuel (Grönroos et al., 2013). In the second case, the emissions of the use phase are usually negative, which indicates that the use of produced biofuel reduces greenhouse gas emissions when it replaces a selected fossil fuel. In this case, the selection of a replaceable fossil fuel and the fuel blend used determine the result (Sheehan et al., 2004).

Table 3. Types of biomass feedstock and allocation methodology in the LCA studies of the reviewed papers.

Fuel	Feedstock	Co-product options	Allocation methodology	Reference
Ethanol	Sugarcane	Electricity	Mass allocation (Steam)	(Ometto et al. 2009)
	Sugar beet	DDGS + straw	System expansion or energetic or economic allocation	(Whitaker et al. 2010)
	Cane molasses	Sugar	Economic allocation	(Nguyen et al. 2008b)
		Electricity	Closed loop, Electricity credit	(Nguyen et al. 2008b)
	Cassava	Electricity	Closed loop	(Nguyen et al. 2008a)
	Corn	DDGS	Corn, soybean meal and N-urea credit	(Kim & Dale 2009)
	Corn	DDGS	System expansion	(Kim & Dale 2005)
	Corn	DDGS	System expansion (soy, corn, urea, reduced CH4 emissions)	(Hsu et al. 2010)
	Corn	DDGS	System expansion, Economic allocation	(Chouinard-Dussault et al. 2011)
	Wheat grain	DDGS + straw	System expansion or energetic or economic allocation	(Whitaker et al. 2010)
	Wheat	DDGS	System expansion (avoided emissions soy meal, rapeseed oil, palm oil)	(Hoefnagels et al. 2010)
	Wheat	Straw, DDGS	System expansion (animal feed, fossil energy) or allocation energy, economic, carbon, dry mass	(Gnansounou et al. 2009)
Cellulosic ethanol	Grass straw	Grass seed	Economic allocation	(Kumar & Murthy 2012)
	Grass straw	Surplus electricity	System expansion	(Kumar & Murthy 2012)
	Wheat straw	Electricity	System expansion (grid displacement)	(Hsu et al. 2010)
	Straw	Electricity/solid fuel	Energy allocation, system expansion	(Slade et al. 2009)
	Sugarcane residual biomass	Bagasse, Electricity	Energy allocation	(Seabra & Macedo 2011)
	Corn stover	Electricity	System expansion (grid displacement)	(Hsu et al. 2010)
	Corn stover	Electricity	System expansion (displacement)	(Chouinard-Dussault et al. 2011)
	Corn stover	Electricity	Closed loop	(Luo et al. 2009)
	Corn stover	Electricity	System expansion (CO2-credits)	(Sheehan et al. 2004)
	Switchgrass	Bioenergy, chemicals	System expansion	(Cherubini & Jungmeier 2010)
	Switchgrass	Electricity	System expansion (grid displacement)	(Hsu et al. 2010)
	Switchgrass	Electricity	Energy allocation	(Bai et al. 2010)
	Switchgrass	Electricity, heat, phenols	No allocation	(Cherubini et al. 2010)
	Spruce	Electricity/solid fuel	Energy allocation, system expansion	(Slade et al. 2009)
	Forest residues	Mixed alcohols	Energy allocation	(Hsu et al. 2010)
Biodiesel	Jatropha	Glycerin, FFA	Energy allocation	(Ndong et al. 2009)
	Palm oil	POME, glycerol, kernel oil	Mass allocation (POME)	(Harsono et al. 2012)
	Palm oil	Palm kernel meal, glycerine	Economic allocation, no allocation, system expansion	(Reinhard & Zah 2009)
	Palm oil	Palm kernels (PKO, PKE)	System expansion (credits)	(Wicke et al. 2008)
	Palm oil	Palm kernell, shell	Economic allocation	(Silalertruksa & Gheewala 2012)
	Palm oil	Fiber (steam and power)	Closed loop	(Silalertruksa & Gheewala 2012)
	Microalgal biomass	No co-product credits because of uncertainties related to yield and quality	No allocation	(Soratana et al. 2012)
	Oil seed rape	Glycerine, rapemeal, straw	System expansion or energetic or economic allocation	(Whitaker et al. 2010)
	Soybean	DDGS/electricity	System expansion (displacement)	(Chouinard-Dussault et al. 2011)
	Soybean	Soybean meal, Glycerine	Economic allocation, no allocation, system expansion	(Reinhard & Zah 2009)
	Soybean	Soybean meal, Glycerine, Electricity	System expansion	(Kim & Dale 2005)
	Used cooking oil	No coproduct credits	No allocation	(Souza et al. 2012)
	Rapeseed	Glycerine, gums	Economic allocation	(González-Garcia et al. 2013)
Pyrolysis gasoline	Forest residues	Diesel	Energy allocation	(Hsu 2012)
Pyrolysis diesel	Forest residues	Gasoline	Energy allocation	(Hsu 2012)
Heat/Power	Forest and sawmill residues	Electricity/heat	Exergy allocation	(Guest et al. 2011)
	Sugarcane residual biomass	Bagasse	Energy allocation	(Seabra & Macedo 2011)
	Eucalyptus	No coproducts	No allocation	(Gabrielle et al. 2013)

In the LCA studies of the reviewed literature, the GHG balance results of biofuels are mainly reported with a broad classification into cultivation, transportation and production emissions. This practice makes it difficult to identify possibilities to reduce GHG emissions. Whitaker et al. (2010) state that variation in these values suggests that when some processes and chains produce less GHG emissions than others, there is a possibility to employ more efficient production chains for biofuels. This short literature review supports this idea. The variations in the GHG emissions of biofuels are due to differences in local conditions (available energy form, soil quality and land availability), the design of the production systems, different calculation methods and system boundaries. Based on this review, some critical issues can be recognized. Most of the studies consider cultivated biomasses. Common critical factors for cultivated biomass-based biofuel production are 1) the efficiency of nitrogen fertilization and production of fertilizers, 2) the use of fossil fuels or biomass residues for heat or electricity production, 3) the type of land used for cultivation and alternative land use, 4) the types of co-products produced and their use, and related to the previous point, 5) allocation practices. For forest biomass, the critical factors were production and transport fuel use and the need for energy and chemicals in the conversion of biomass to fuel. For forest residues, the harvesting and conversion to fuel were equally important as a source of GHG emissions. With soil biomass utilization (peat), the combustion of peat caused the largest share of GHG emissions, and land use decisions and harvesting emissions came after that.

3.7 Case examples

3.7.1 Data collection

Data selected for LCA studies are collected considering the goal and scope of the study. Data are collected from the production sites (peatlands, power plants), literature, experiments and simulations and include a mixture of measured, calculated and estimated data. The data for this research have been gathered from different sources (Tables 4, 5 and 6).

In peatland studies, scenarios were created to compare different chains which consist of different peatland emission baselines, harvesting methods (excavation/milling), after-treatment (afforestation/restoration) and peat utilization for fuel use (combustion). For this study, GHG emissions data were obtained from various sources, such as field measurements (Niko Silvan), the peat industry (Alkkiomäki, 2009; Turveruukki, 2005), other ongoing and previous studies (Kirkinen et al., 2007; Alm et al., 2007; Alm et al., 2007; Minkkinen et al., 2007; Nykänen et al., 1996; Silvan, 2007), and available related literature (Pingoud et al., 1997; Mäkinen et al., 2006; Vesterinen, 2003). The data were utilized to estimate potential GHG emissions reductions and peat production per unit of land area in CO_2 equivalents (CO_{2e}/ha) of utilized drained peatland area. A 1 ha area of drained peatland was used as the functional unit in order to make a straightforward comparison between scenarios. The system boundary covers peat production from field preparation to after-treatment and peat combustion. For fossil fuel, the system boundary extended from extraction to utilization. The GHG emissions from ash disposal are assumed to be negligible in both fuel chains.

Table 4. Type of data used in peatland studies.

Data	Source (Literature, Calculated, Measured, Estimated)
Emissions from peatlands	
Heterotrophic respiration	Measured in high emission peatlands, literature in average peatlands
Litter fall	Measured in high emission peatlands, literature in average peatlands
Forest growth and carbon accumulation	Literature and simulation
Soil emissions from field during harvesting	Measured
Soil emissions from ditches during harvesting	Estimated/calculated based on literature
Soil emissions from stockpiles during harvesting	Measured
Natural processes	
Decomposition processes	Literature and simulation
Machinery fuel consumption during peat harvesting	Measured (Vapo Oy)
Emissions from diesel combustion in machinery	Literature (Statistics Finland)
Emissions from direct combustion	Literature (Statistics Finland)
Gasification process	Calculated (Vaskiluodon voima)
Transportation	Literature (Life cycle software database)

In the study of a biorefinery, two ethanol production routes related to the biorefinery concept were analyzed. Because the study considered the idea of a new type of biorefinery concept, the data were generated with simulation, which was the best way to obtain information about the impacts of biomass processing. The data for the simulation of the biorefinery are obtained from prehydrolysis experiments carried out in the Laboratory of Applied Chemistry at the University of Jyväskylä and from cooking experiments on prehydrolyzed chips carried out in the Department of Forest Products Technology at Helsinki University of Technology. Based on these laboratory data, and with the data obtained from the literature, a mill-wide simulation model was created (Jesse Kautto) using the WinGEMS simulation software. This mill-wide WinGEMS approach supplied the material and energy balances of the biorefinery-pulp mill concept, and the other stages of the life cycle (harvesting, transporting) were added around this process information in the GaBi software platform.

Table 5. Type of data used in biorefinery-pulp mill study.

Data		Source (Literature, Calculated, Measured, Estimated)
Biorefinery-pulp mill processes		WinGems simulation by the following information:
	Raw material available for production	Estimated
	Ethanol yield	Measured (prehydrolysis experiments)
	Pulp yield	Measured (cooking experiments)
	Residue yield	Measured (experiments)
	Sugar yields from hydrolysis	Measured (prehydrolysis experiments)
	Energy production	Calculated (simulation)
	Energy consumption	Calculated (simulation)
	Chemical consumption	Literature
	Amount of yeast	Literature
	Caustizising	Calculated/Literature
Processes outside the pulp mill		
	Chemical production	Literature (Life cycle software database)
	Transportation	Literature (Life cycle software database)
	Transportation emissions	Literature (Life cycle software database)
	Wood harvesting	Literature
Natural processes		
	Decomposition of forest residues	Simulation (Yasso07)
	Carbon stock of forest stand	Simulation (Minkkinen et al. 2001)
	Forest growth	Literature

The renewable diesel study examines the GHG emissions of renewable diesel production from three optional biomass feedstocks. The conversion technology selected for the study is an existing technology and process information was collected from two refineries – one in Finland and another in Singapore. Two refineries were used to define the impacts of mill location on the GHG emission sources and emissions. Other emissions sources of the renewable diesel (RD) life cycle were calculated based on values published in literature.

Table 6. Type of data used in renewable diesel studies.

Data	Source (Literature, Calculated, Measured, Estimated)
Emissions from cultivation	
Fertilizer use and emissions	Literature
Pesticide use and emissions	Literature
Insecticide use and emissions	Literature
Emissions from diesel combustion in machinery	Literature
Soil emissions	Literature
Oil extraction process	
Methane production	Literature
Electricity use	Literature
Steam use	Literature
Hexane use	Literature
NExBTL process	
Electricity consumption	Calculated (Neste Oil Oy)
Steam consumption	Calculated (Neste Oil Oy)
Hydrogen production	
Natural gas consumption	Calculated/Literature
Steam consumption	Calculated/Literature
Storage electricity use	Calculated/Literature
Emissions of electricity from grid	Literature
Processes outside the mill	
Chemical production	Literature
Transportation distances	Calculated/Literature
Transportation emissions	Literature
Emissions of distribution of fuel	Literature
Replaced production (system expansion approach)	Literature
Natural processes	
Average carbon stocks in biomass	Calculated/Literature
Biomass carbon stock changes due to LUC processes	Calculated/Literature
SOC decrease due to LUC processes	Literature

It can be seen that peatland studies have used e.g. field measurements as the primary data sources, whereas the biorefinery study relies more on laboratory experiments and simulations. When the soil emissions differ significantly in different ecosystems, the measurements are the most reliable way to collect information about GHGs in different areas. In the case of the biorefinery concept, the simulated mill was the only way to estimate GHG emissions from processing. The renewable diesel study and comparison is based on process information from the oil refinery owner and the information on cultivation and the initial values for carbon stock impact calculations are collected from various published sources.

3.7.2 LCA calculations

LCA is a relative approach (EN ISO 14040:2006) comparing one system to another (Fava, 2005). It is designed on the basis of a functional unit of a product or a service. The functional unit defines the object of the study, and the life cycle inventory is relative to the functional unit (EN ISO 14040:2006; Fava, 2005).

In Publication I, the functional unit is 1 ha of peatland and the corresponding production of heat in combustion plant. Publications II-IV use 1 MJ fuel energy content as a functional unit with the corresponding surface area of land (peatland, forest, grassland or cultivated land) producing this fuel. The net GHG emissions of the fuel utilization chain are compared to the reference scenario based on the functional units. The reference (non-utilization) scenario includes both the current energy system and land use in which the utilization scenario is affecting. As a result, the impact of the studied system on the existing one is assessed. If the emissions of utilization scenario are lower than those of the reference scenario, the emission reductions with this biomass use will be achieved. In the opposite situation, the emission reduction will not be achieved.

This thesis is based on four different papers. LCA is applied as a methodological framework to study how the utilization of biomass resources and the use of generated fuels affect the greenhouse gas balances. Two of these papers are related to peatland utilization (I, II), one concerns the significance of biogenic carbon emissions in integrated forest biomass-based ethanol production (III) and one the utilization of cultivated biomasses (IV). These papers include the following stages of utilization: raw material acquisition (harvesting, transport, pre-treatment, storage), processing the biomass into fuel, including energy and chemical consumption and production for this purpose, fuel use and biomass utilization impacts on the GHG emissions in the production areas.

In the analysis of the greenhouse gas emissions of the studied fuel chains, the emissions have been compared to the non-utilization scenario emissions (reference system) to reveal the changes in the existing system caused by starting the biomass utilization. The reference system depicts the present development without the biomass utilization, including the current heat, electricity and fuel production which the new biomass-based heat, electricity and fuel production will be replacing (electricity with coal, gasoline, fuel) or other systems where the production would be affected. Also current land use is included in the reference system (peatland without peat harvesting, forest residue decomposition in the forest, forest stands without logging and ecosystem carbon stocks). In the peatland studies, the assumed greenhouse gas emissions from soil during the reference period are included in the reference. In the case of the biorefinery-pulp mill integrate, the present state is defined as a pulp mill integrate operation without a biorefinery. In cultivated biomass utilization, the present state includes the correspondence production of diesel and co-products and the ecosystem before cultivation.

The model for life cycle greenhouse gas emission calculations for these systems was constructed with GaBi software (PE Europe GmbH 2009). GaBi software is a tool developed for life cycle engineering including databases for processes, flows and environmental quantities for life cycle impact assessment. The software enables the administration of a large amount of information and the calculation of various balances helping to put together the information calculated in model. The flowchart modified for the study and presented in Paper II can be seen in Figure 13. The software used is a modular system where processes, flows and plans form modular units.

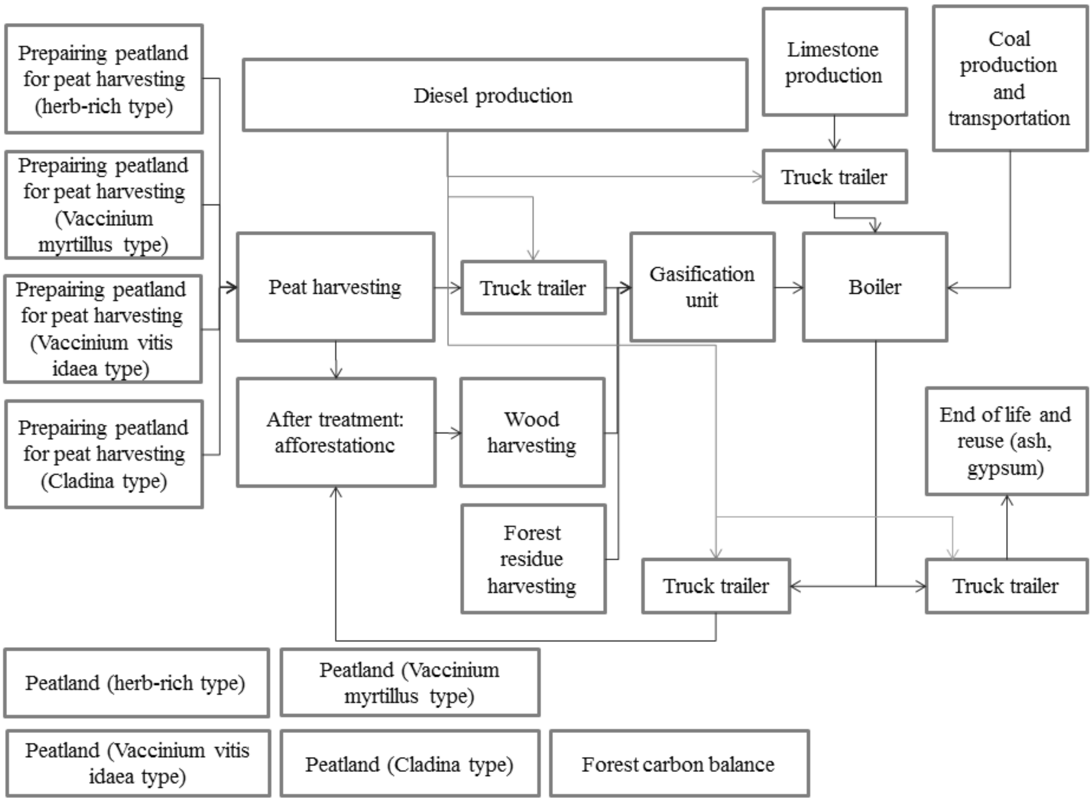

Figure 13. System flowchart modeled for and used in the third peatland study (Paper II).

In the models applied in the studies presented in this thesis, consist of processes in which inputs and outputs are important from the GHG point of view. The most important variables are located such that they can be easily changed, enabling different scenario observations and sensitive analysis.

3.7.3 Treatment of biogenic emissions and soil carbon

Papers I and II study the utilization of peatlands, where the human activities have a significant impact on both above-ground and below-ground vegetation and soil carbon stocks. In Paper III, the raw material used is wood or forest residues which are assumed to have minor effects on the soil containing carbon and thus the paper considers only change in the above-ground carbon stock, limiting to the carbon content of the raw material and regrowth of the forest stand in the case of logs and the remaining carbon in the forest residues. The LUC impact of various biomasses, oilseed rape as an annual cultivated crop, jatropha as a perennial and palm oil as a wood plantation are included and the differences in above-ground biomass carbon, below-ground biomass carbon and SOC are estimated based on literature.

When the biomass is produced in peatlands (peat fuel, oil palm plantation on organic soils), the soil emissions are considered. In the estimation of the soil carbon stock change, the soil layers are divided into the following components: above-ground litter layer, below-ground litter layer, peat layer and mineral soil (Figure 14). The assumption has been made that the mineral layer does not contribute to greenhouse gas fluxes. Instead, the impact of the litter layers and peat layer is presented in Finnish peatland studies based on measurement data (Silvan) and literature on GHG fluxes, biomass accumulation and degradation. In the palm oil case, published values for biomass carbon stocks were used.

The net greenhouse gas balance (kg CO_2 equivalent) from the peatlands were calculated by reducing the CO_2-eq. emissions of the heterotrophic respiration $E_{resp.}$ and the litter decomposition $E_{litter,decomp.}$ from the carbon accumulation in the forest $C_{forest\ stand}$ and the litterfall $C_{litterfall}$, which together form the net flux (Equation 3).

$$E_{net} = C_{forest\,stand} + C_{litterfall} - E_{resp.} - E_{litter,decomp.} \tag{3}$$

The effects on the biogenic carbon storage change in forest stands (Papers I-IV), forest residues (Paper III) and forest soil (Papers I,II and IV) are included in the study.

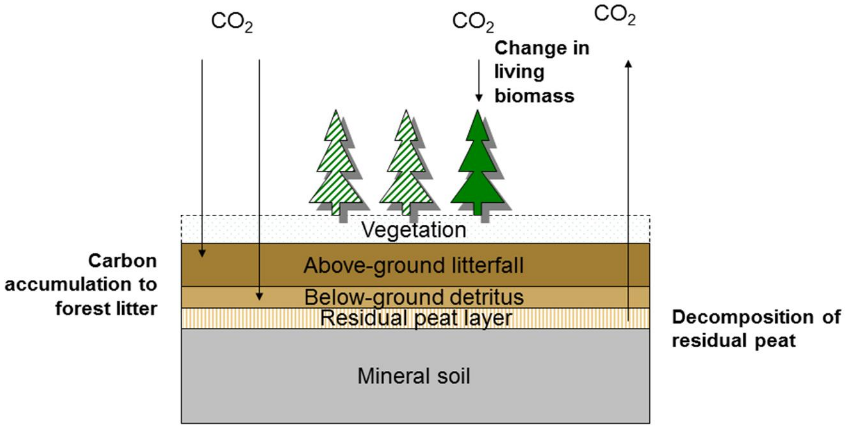

Figure 14. Carbon accumulation and release between soil layers and atmosphere in peatlands (Minkkinen et al. 2007).

The assessments of biomass and carbon stocks and changes focus on the total amount of biomass, growth and removals. The literature information about forest stand growth is used as a basis for this study. Forest stand growth values are documented in merchantable volumes (=stem wood) excluding non-merchantable above-ground parts such as tree tops, branches, twigs, foliage, roots, and in certain cases, stumps (IPCC, 2006b). In Papers I and II, the data on the merchantable volume of growing stock is transformed by applying the biomass regression function (Minkkinen et al., 2001). In Paper III, stand volume growth is converted to the total amount of tree biomass in terms of carbon with conversion factors. (Karjalainen and Kellomäki, 1995).

Different biomasses grow at a different pace. The assumption is that in the case of wood log regrowth, the time needed to grow the same amount of biomass in the harvested forest after the final felling is 100 years. Thus, when the wood log is used as a raw material, the time needed for the biomass to re-absorb CO_2 in the same area is long. In Papers I-IV, this delay, which weakens the capability of the biomass to reduce greenhouse gas emissions in the atmosphere, is taken into account by using the weighting factor for the biomass carbon uptake. The weighting factor that represents the weighted average time of carbon storage in the unutilized biomass or carbon uptake in forest stand regrowth is the following (Equation 4):

$$WF = \frac{\sum_{i=1}^{t} x_i}{t} \tag{4}$$

where *i* refers to the years during which the storage exists, *x* is the proportion of total storage remaining in any year *i*, and *t* is the assessment period (years). In the case of forest residues, the latest simulation data available (Repo et al., 2011) were used to estimate the carbon storage change in forest soil caused by residue utilization. In the case of prehydrolyzed chips, the carbon debt of the utilized wood biomass was estimated by assessing the stem volume and then using the regression model to estimate the carbon content of the total amount of wood biomass (Minkkinen et al., 2001). The carbon storage change in forest/peatland soil was estimated due to the litter layer accumulation and degradation.

In Paper II, the total amount of biomass growth at the end of the time period was not calculated with this weighted average approach. Instead, the total amount of carbon accumulated in forest biomass (wood biomass and litter) was estimated and compared to the reference scenario.

3.8 Publication-specific methods and the contribution of the publications to the dissertation

3.8.1 Forestry drained peatlands and peat fuel utilization with new excavator production method (Paper I)

The GHG emissions of forestry drained peatlands are commonly studied using the average emission value of these peatlands. As it is known that emissions might vary a great deal depending on the local water conditions, peatland type and climate of the region, we decided to study the GHG emissions of fuel peat use by using measurement data available for so-called ‘hot spot’ peatland areas which are recognized to produce emissions which deviate from the average (Silvan et al., 2012). The objectives were to study the GHG emissions from both the excavation-drier method and the milling method, and to compare the long-term (100 years) climatic impacts of these methods modeled for three different peatland types.

Different scenarios are compared by setting the system boundary according to a system expansion approach (explained in section 3.2) using a case study which deals with peatland utilization and peat fuel production from drained peatlands. It is assumed that the increase in the utilization of peat decreases the use of coal in the studied system, and consequently replaces the emissions from coal combustion. Coal is selected for a substituted energy source for peat because both of them are used in co-combustion with biomass (Hakkila, 2006; Lundholm et al., 2005) and it is a current practice to replace peat with coal in old heat and electricity production units when coal is economical or when the availability of peat is insufficient (Vainio, 2013; Palokallio, 2013). This LCA approach helps to define the change in the climatic impact over a 100-year time span if peat is extracted from drained peatlands and utilized for the production of energy, compared to a non-utilization scenario where energy is produced from coal.

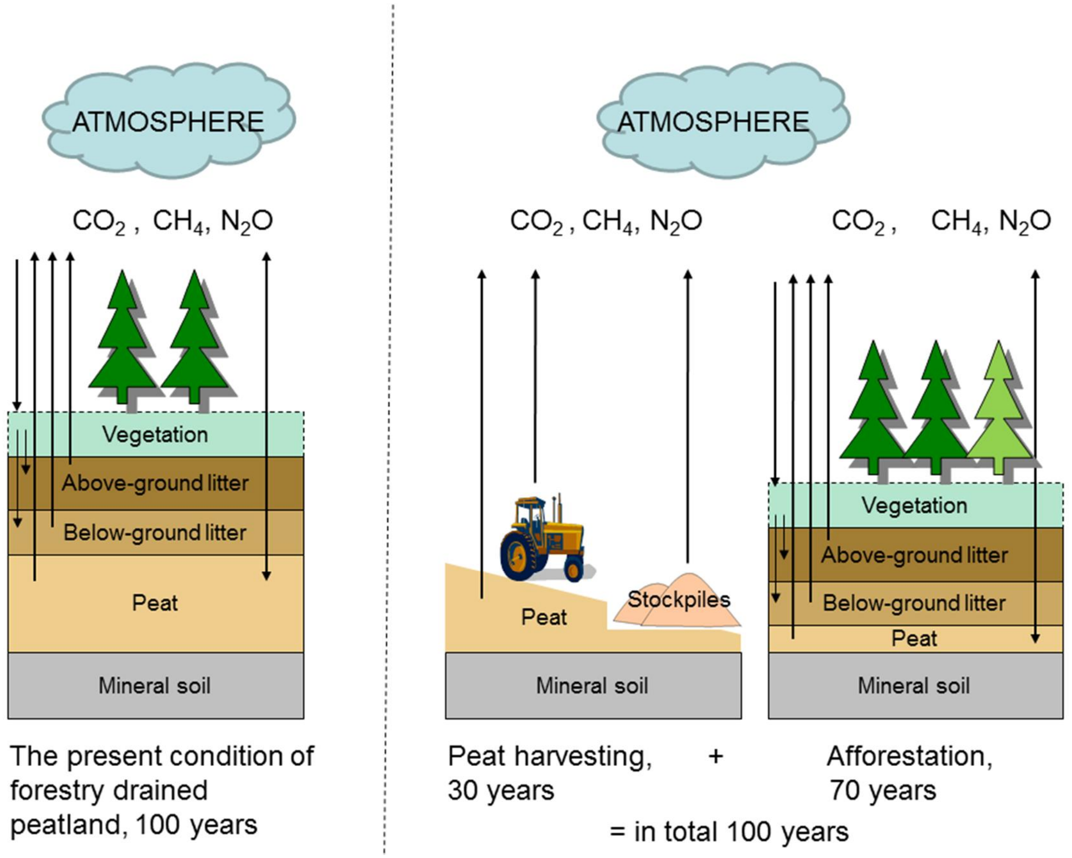

Figure 15. Greenhouse gas impact of peat production on peatland emissions are estimated for a 100-year reference period, taking into account the peat harvesting emissions of the first 30 years and emissions/sequestration in afforestation for the remaining time. The emissions and sequestration generated in the utilization scenario are then compared to the emissions of peatland over 100 years when the area remains in its present condition.

In the comparison of the systems, all of the options reduce emissions from the alternative fossil fuel chain in proportion to the energy content of the fuel. The differences in the greenhouse gas impacts of various peatland utilization scenarios are due to the original emissions of production reserves (non-utilization scenario), peat extraction fields and the peat extraction method. To compare the greenhouse gas net impact of different utilization options, 16 scenarios were created for the calculation procedure. Emissions from these 16 scenarios and the greenhouse gas impact were calculated in a similar procedure as in the first study: peatland utilization is compared to the non-utilization scenario (Figure 16). The non-utilization state of drained peatland is considered as the reference state and results from other scenarios are compared to it.

For this study, greenhouse gas emissions data were obtained from various sources, such as field measurements (Silvan N.), the peat industry, results of other ongoing and previous studies and available related literature. The data were utilized to estimate potential GHG emissions reductions per unit of drained peatland in CO_2 equivalents (CO_2-eq./ha.).

An area of 1 ha of drained peatland and the corresponding production of heat in a combustion plant was used as the functional unit in order to compare scenarios in a straightforward manner. The system boundary covers the peat production from field preparation to after-treatment and peat combustion. For fossil fuel, the system boundary extended from extraction to utilization. The greenhouse gas emissions from ash disposal were assumed to be negligible in both fuel chains. The flowchart for the studied system and the reference system is presented in Figure 16.

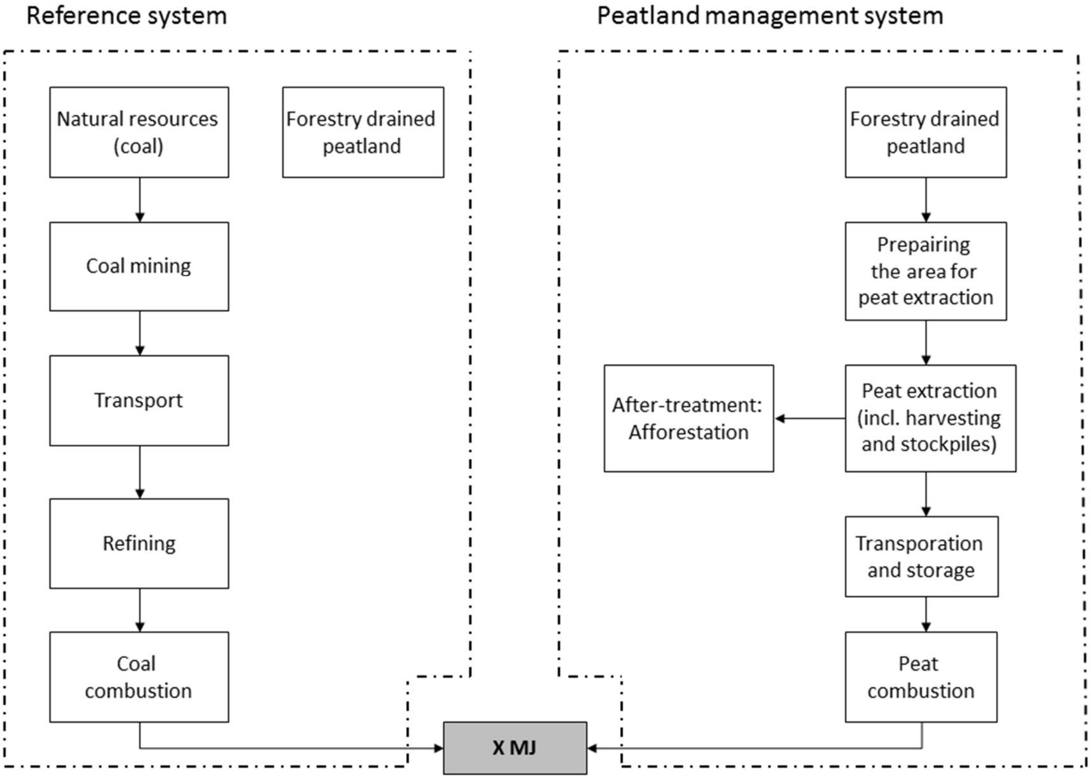

Figure 16. The utilization of a 1 ha peatland area for heat energy production is considered by comparing the utilization (peatland management) scenario to the non-utilization (reference) scenario. Combustion efficiencies are assumed to be the same for peat and coal fuel.

3.8.2 Directing peat production to high-emission peatlands (Paper II)

The second peatland study (presented in Paper II) follows the conclusions made based on Paper I. In Paper II, the tree different forestry drained peatlands, which can be identified to have a high emission impact due to pre-assumptions made, were studied in more detail with the same method. In this study, the focus was to define the impact of directing the peat production to higher emission level peatland areas on the life cycle emissions of peat utilization. The question was whether the replacement of coal in the energy generation unit with peat produced from a high-emission peatland area reduces the

GHG emissions. In addition, we wanted to assess the GHG emission impact when this kind of peat is replaced with forest residues and the reduction of the forest carbon stock is included.

Two examples were selected to study the overall GHG impact of peat production from the high-emission peatland when peat is used to replace coal or forest residues is used to replace peat in the local combined heat and electricity production plant. In the first example, peat replaces coal in the Vaskiluoto gasification plant in Vaasa. In the second one, the use of forest residues is increased to replace peat fuel in the Toppila power plant in Oulu.

In this study, all forestry drained peatlands with Downy birch (Betula pubescens) dominated sample plots with a peat layer over 1 m thick and with a distance of less than 150 km from the field to the planned site were assumed to be high-emission areas. The resources of high-emission peatlands near Vaasa and Oulu were estimated by using the national forest inventory results (NFI10). The resulting surface areas of peatland types (Laine and Vasander, 1998) are based on measurements carried out at sample plots. The field data of the NFI10 were collected in 2004-2008 (Finnish Forest Research Institute, 2008).

In both cases, a third of the peat was assumed to be produced from herb-rich type (Rhtkg), another third from the myrtillus type (Mtkg) and the remaining third from the Vaccinium vitis idaea type (Ptkg). The forest residues were assumed to contain 50% branches and 50% stumps. The emissions from the peat layer (heterotrofic respiration), carbon accumulated in the forest stand and in the above-ground and below-ground litter layer were included in the study. The peat production emissions were calculated taking into account the harvesting of peat, transportation and combustion emissions. For the coal fuel cycle emissions, both the combustion and production of coal were accounted for. Forest residues were considered as carbon neutral in combustion, but emissions from harvesting, transportation and reduction in the forest carbon stock due to residue removal was accounted for.

In LCA, the GHG emission measurements from three drained peatland site types with a high greenhouse gas emission level were used. The sites were nitrogen rich but mineral nutrient poor, were dominated by pubescent birch (Betula pubescens), and were originally open fens between the herb-rich type and Vaccinium vitis idaea type. The carbon accumulation in the forest was calculated based on the following forest stand growth values: herb-rich type 8 m^3/ha/a, Vaccinium myrtillus type 6 m^3/ha/a, Vaccinium vitis idaea type, 4.5 m^3/ha/a and Cladina type 0.5 m^3/ha/a (Päivänen, 2007). Above-ground litter decomposition was estimated based on the assumption that 95% of the litter will be decomposed after 60 years (Vávřová et al., 2009).

As in the first and second peatland studies presented in this thesis, the greenhouse gas impact of peat use was estimated by comparing the situation before peat harvesting (reference system) to the change due to peat harvesting during the selected reference time. To compare the peat harvesting scenario to the reference scenario, the system expansion approach was used to include all land use, heat and elecrticity production and fuel substitution impacts in the system (Figure 17). The net impact on the greenhouse gas emissions (E_{net}) is calculated based on the difference between the studied energy system (E_{System}) and reference system ($E_{Reference}$).

$$E_{net} = E_{System} - E_{Reference} \tag{5}$$

In the peat harvesting scenario, the emissions are released from peat production ($E_{peat,prod.}$) and combustion ($E_{peat,comb.}$) and the emissions from peatlands ($E_{peatland}$), coal production ($E_{coal,prod.}$) and use ($E_{coal,comb.}$) are avoided (Equation 6).

$$E_{net} = E_{peat,comb.} + E_{peat,prod.} - (E_{coal,comb.} + E_{coal,prod.} + E_{peatland}) \tag{6}$$

where E_{net} represents the net greenhouse gas impact of peat use, $E_{peat,comb.}$ the emissions from peat combustion, $E_{peat,prod.}$ the emissions from peat production including the emissions from peat harvesting, stockpiling and transportation and soil, $E_{coal,comb.}$

the emission from coal combustion, $E_{coal,prod.}$ the emission from coal production including the emissions from coal mining and transportation, and $E_{peatland}$ is the net emissions from peatland. Peat production and combustion form the peat energy system under study and coal combustion, production and peatland emissions without peat harvesting form the reference system.

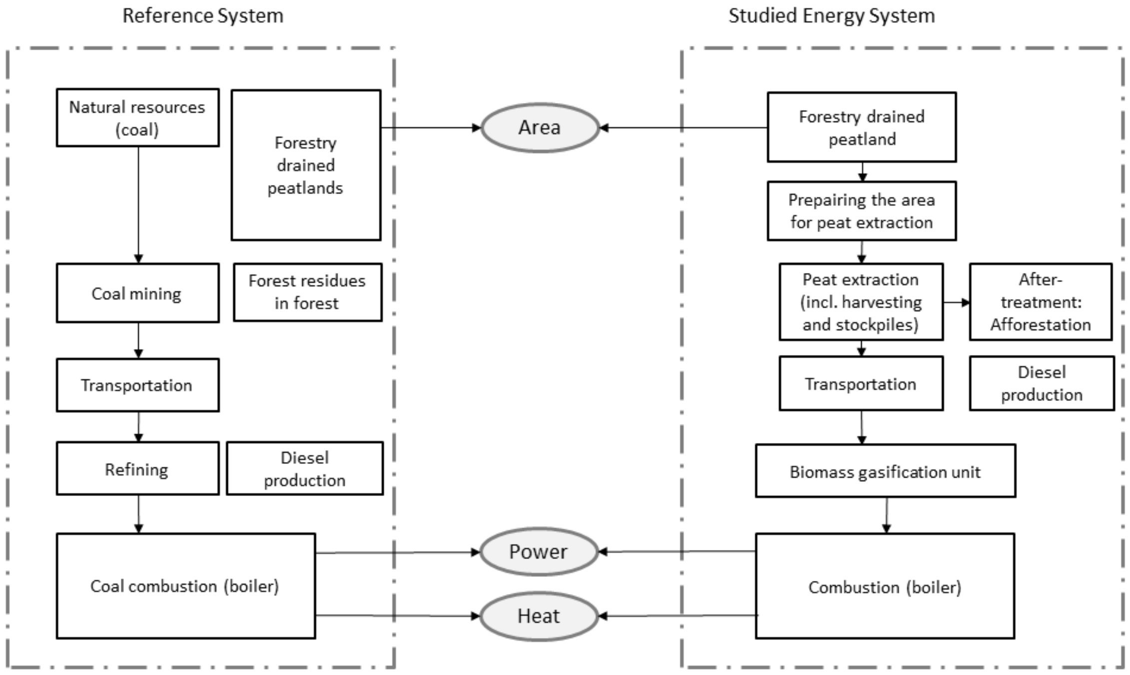

Figure 17. LCA comparison between peat from high-emission peatlands and the reference system with coal combustion.

The greenhouse gas impact in the case where peat is replaced with forest residues was estimated by comparing the situation with peat harvesting to the situation where forest residues are used ($E_{forest\ residues,prod}$), (Figure 18 and Equation 7). When forest residue use is increased, emissions are released from forest residue harvesting, from unutilized drained peatlands ($E_{peatland}$) and the loss of forest residue carbon stock

($E_{forest\ res.\ carb.}$). At the same time emissions from peat production and peat combustion are avoided (Equation 7).

$$E_{net} = E_{forest\ res.\ prod} + E_{peatland} - (E_{peat,prod.} + E_{peat,comb.} + E_{forest\ res.\ carb.}) \quad (7)$$

where $E_{forest\ res.\ prod}$ represents the emission from forest residue production including harvesting and transportation and $E_{forest\ res.\ carb.}$ the carbon storage formed by the forest residues left in the forest. Forest residue production and emissions from peatland without peat harvesting form the forest residue energy system and peat production emissions, peat combustion emissions and carbon stock formed by forest residues left in the forest to decompose naturally form the reference system for the forest residue energy system.

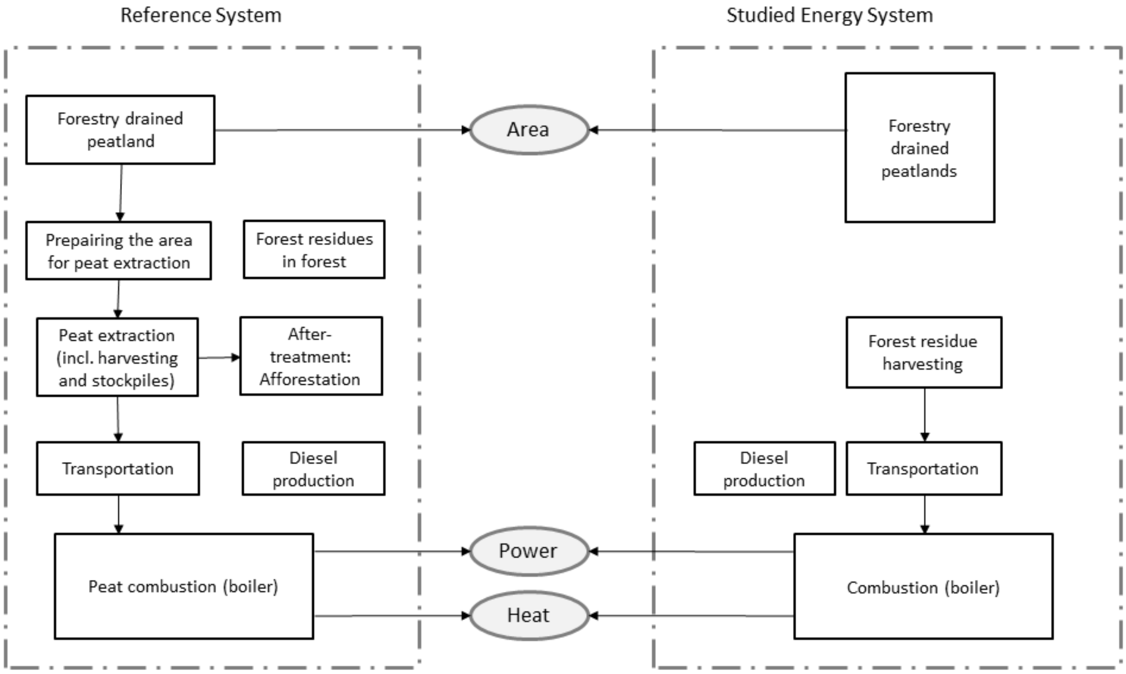

Figure 18. LCA comparison between forest residues and the reference system with peat combustion.

In the estimation of peatland net emissions ($E_{peatland}$), emissions from the peat layer, the carbon accumulation in growing forest stands and the forest litter layer are taken into account on both sides and the amounts of these flows vary based on the utilization and peatland type. Emissions from the peat layer, stockpiling and diesel consumption of vehicles were considered as emissions during peat harvesting. The influence of the site selection on GHG emissions was studied when the peat was assumed to replace coal in an combined heat and electricity production unit. The results are presented as GWP(100) values which are a measure for positive (warming) or negative (cooling) global warming potential (kgCO_2-eq.) and the reference time of 100 years is used as a base assumption. In addition, the impact of the reference time selection on the result was studied with time spans of 15 and 50 years with the GWP 100-year time horizon. These different time spans will reveal how the amount of CO_2-equivalent emissions are affected if different time spans are used for calculations. After 15 years, peatland is in the middle of the harvesting period whereas after 50 years, the peat harvesting is over and afforestation has continued for two decades. Different time spans also reveal how long it takes to compensate the released emissions with the emission benefits from avoided emissions.

3.8.3 Bioethanol production from forest biomass in biorefinery (Paper III)

The principle of carbon neutrality assumes that the greenhouse gas emission released by the combustion of biofuels will be sequestered to new growing plants instantaneously. This assumption is acceptable if the same amount of biomass will re-grow in a very short time. When wood is used as raw material, the time needed to re-absorb CO_2 is long. This delay will decrease the capability of the biomass to reduce greenhouse gas emissions into the atmosphere. As a result, the climate impact of the so-called woody biomass can in the short to medium term be worse than that of the fossil fuels it is designed to replace. (Zanchi et al., 2010).

The carbon neutrality of biofuels and their potential for climate mitigation have been questioned because the utilization of biomass may have a negative impact on the soil carbon stocks (Searchinger, 2008, 2009; Gibbs et al., 2008). Losses in the above-ground biomass carbon stock in the forest occur when forest biomass is utilized for biofuel production (Zanchi et al., 2010, Kilpeläinen et al., 2011). The carbon stock impact of forest residue utilization depends on the rate of decomposition in the forest. It makes a difference to the climate in which fractions biomass is used for energy and removed from the forest. The carbon stock of branches is only a half of that of stumps when the remaining carbon stock is evaluated for 20 years after the final felling. (Repo et al., 2011) Bioenergy reduces greenhouse gas emissions only if the emissions from energy use are offset by carbon capture which is more than would be sequestered anyway (Searchinger, 2009).

This third study evaluates the life cycle of two ethanol production systems: ethanol production from prehydrolysed chips and forest residues. Both of these production systems are integrated into the pulp mill environment. The research focuses on the raw material consumption, useful energy output and greenhouse gas burden of both systems, discussing the greenhouse gas impact of forest residue and wood utilization.

In this study, the processing of forest residue feedstock takes place in the biorefinery which is integrated into the pulp mill (see Figure 20). Emissions and excess electricity production are compared to the conventional pulp mill values in order to estimate the impact of ethanol production on processes which are shared between the pulp and ethanol systems (for instance wood yard, chemical recovery and energy systems). Allocations between ethanol and pulp production flows are made by dividing the functions of the integrated mill between ethanol and pulp production such that increase in the consumption of raw materials is considered as an ethanol production raw material need. In the same way, emissions from increased electricity production are calculated for the ethanol production system when production affects the energy balance of the integrated system (see Figure 19). When the utilization of the ethanol production process side flows affects the energy balance in such a way that excess electricity is produced, greenhouse gas emissions are divided between the fuel and electricity in proportion to their energy content.

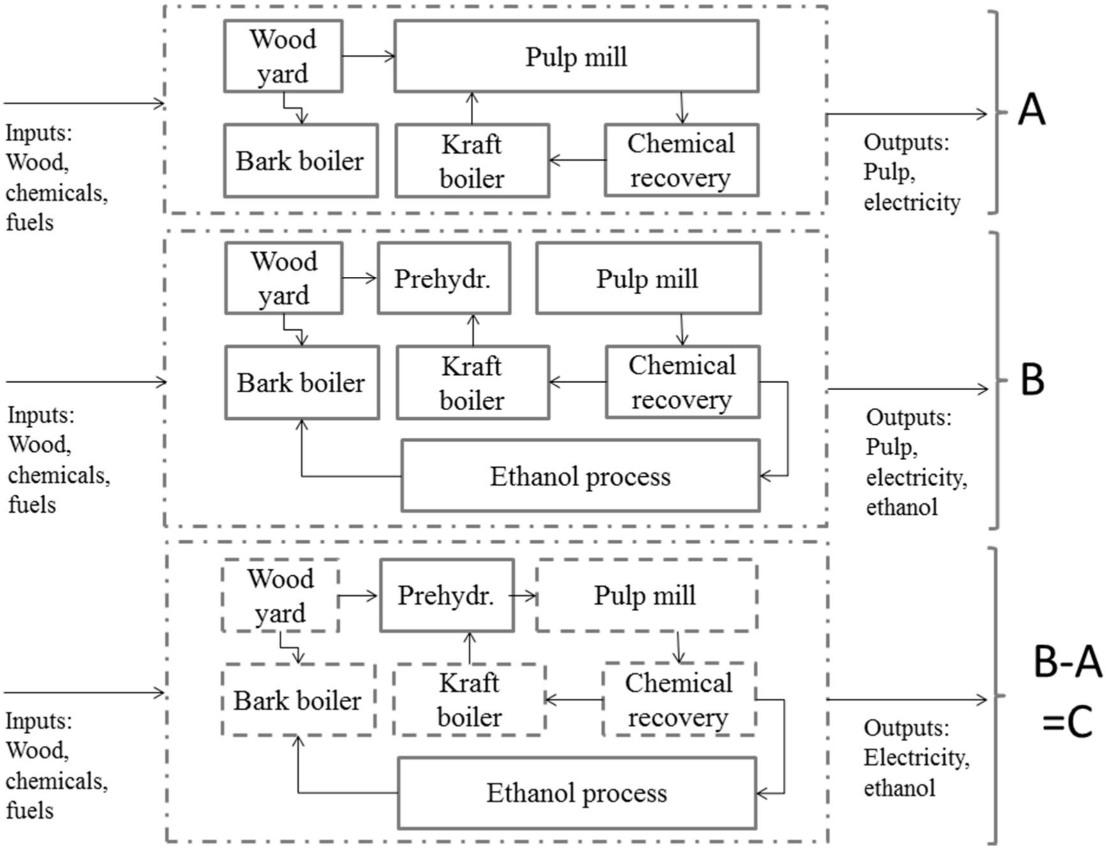

Figure 19. Allocation of different flows between the Pulp mill and Ethanol production processes has been made by comparing the ethanol production in pulp mill (B) with the pulp mill reference case (A). As a result, the flows that are formed or affected by ethanol production are allocated for ethanol. For example the excess electricity production from pulp production (A) is discounted from integrated ethanol and pulp production (B) and only the difference (B-A) is allocated as a benefit for ethanol production processes.

Because the ethanol is not produced from a side flow which could not be classified as waste, the environmental impact of production needs to be allocated to this product. The intergration of ethanol production increases the consumption of wood material in the mill and the benefit is achieved with integration. Integration benefits are the utilization of the process side flows for energy via combustion in the Kraft Mill boiler. This increases the heat and electricity production along with the increase of raw material use. Because the raw material use and heat and electricity production increase is caused by bioethanol production processes, the benefit of electricity production is allocated to the new process using the heat and electricity primarily to meet the bioethanol process energy consumption and secondarily to sell the surplus to the (electricity) grid when the emission reductions in electricity production are achieved.

When forest residues are used for electricity, heat or biofuel production, several life cycle stages needs to be considered. In the beginning of the life cycle, collecting, chipping and transportation as well as additional fertilization to compensate nutrient loss and ash recycling are included. In order to estimate the full life cycle emissions from using the logging residues for energy, a product emission value of 12 kgCO_2eq/MWh (Repo et al., 2011) was used in this study.

When forest biomass is utilized for biofuel production, above-ground biomass carbon stock in the forest is lost. When the wood is used as a raw material, the time needed to re-absorb CO_2 is long. This delay will reduce the capability of biomass to reduce greenhouse gas emissions into the atmosphere. Also removing forest residues for electricity, heat or biofuel production generates carbon emissions: combustion of forest residues soon after harvesting releases the carbon instead of letting it decompose slowly at the harvesting site. These effects on biogenic carbon storage and carbon debt are also included in this study. In the case of forest residues, Yasso07 simulation data on decomposition (Repo et al., 2011; Tuomi et al., 2009; Tuomi et al., 2008) were used to estimate greenhouse gas emissions caused by residue utilization. For prehydrolyzed chips, the carbon debt of utilized wood biomass was estimated by using the regression model (Minkkinen et al., 2001). For both cases, the long-term 100-year carbon impact is calculated by means of the weighted average impact of carbon storage (see section 3.7.3).

Table 7. Raw material consumption and production of biorefinery-pulp mill.

	Reference case	**Ethanol production from prehydrolyzed chips**	**Ethanol production from forest residues**
Raw materials			
Pine raw wood, Odt/day	4660	5400	4660
Forest residue, Odt/day	0	**0**	320
Products			
Pulp, Adt/day	2000	2000	2000
Ethanol, t/day	0	80	83
Excess power, MWh/day	1940	2760	2030
Excess power, kWh/Adt	970	1380	1010
Tall oil, t/day	50	0	50
Methanol, t/day	20	0	20

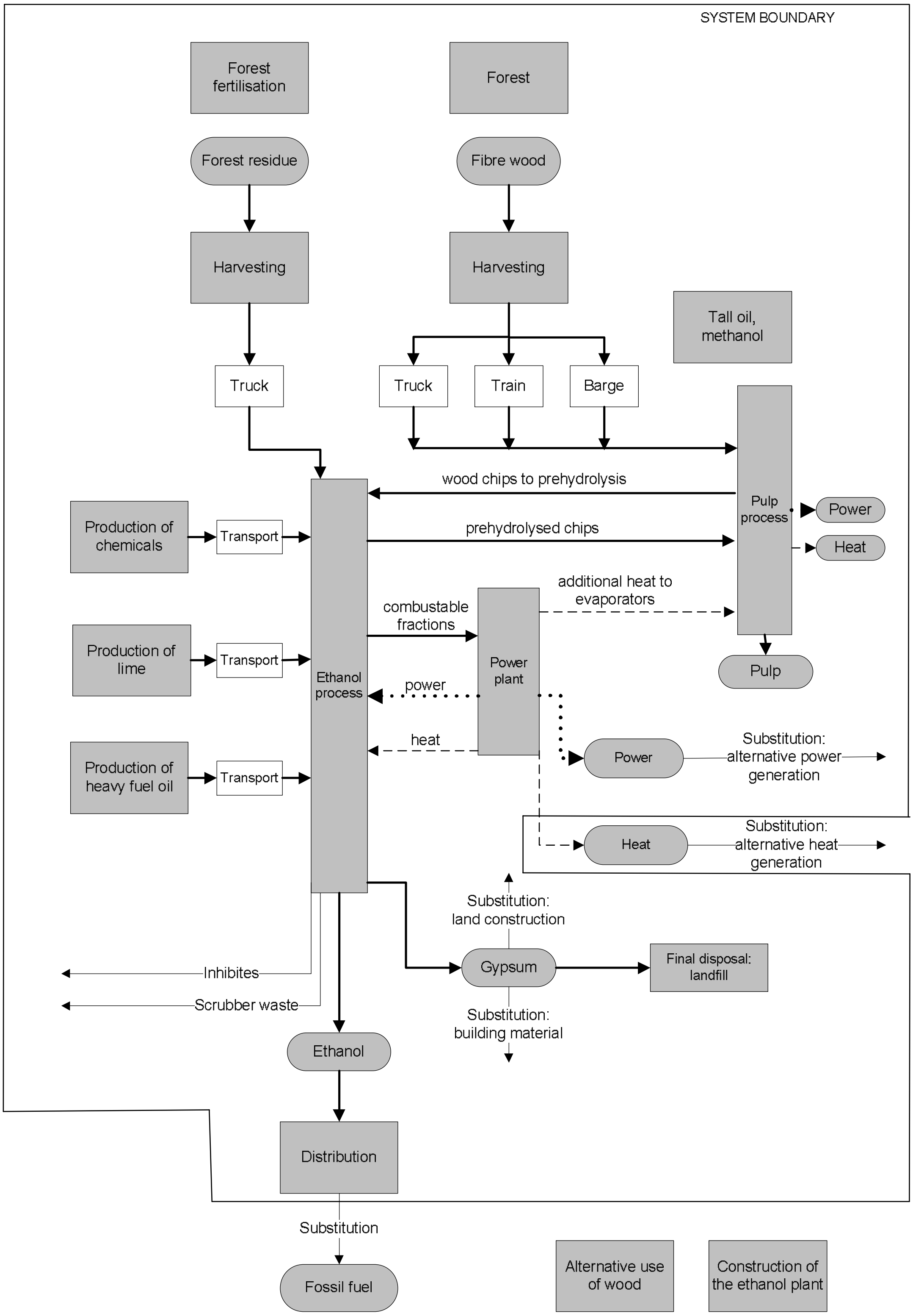

Figure 20. Biorefinery-pulp mill. System boundaries and processes (Modified from original figure of Valtonen T.).

As in the peatland studies presented in this thesis, the greenhouse gas impact of biomass-based fuel production is estimated by comparing the situation before the new production unit and current fuel use (reference system) to the change due to the ethanol biorefinery concept during the selected reference time. To compare the bioethanol production scenario to the reference scenario, a system expansion approach was taken to include biomass use, fuel production and fuel substitution impacts in the system (Figure 21). Emissions from the decomposition of forest residues or carbon accumulation in a growing forest stand were taken into account depending on what biomass source was used. Emissions from storage and from the diesel consumption of vehicles were considered as emissions during biomass harvesting. The emission reduction achieved with ethanol fuels in transport was studied when the studied ethanol was assumed to replace gasoline in the transportation sector.

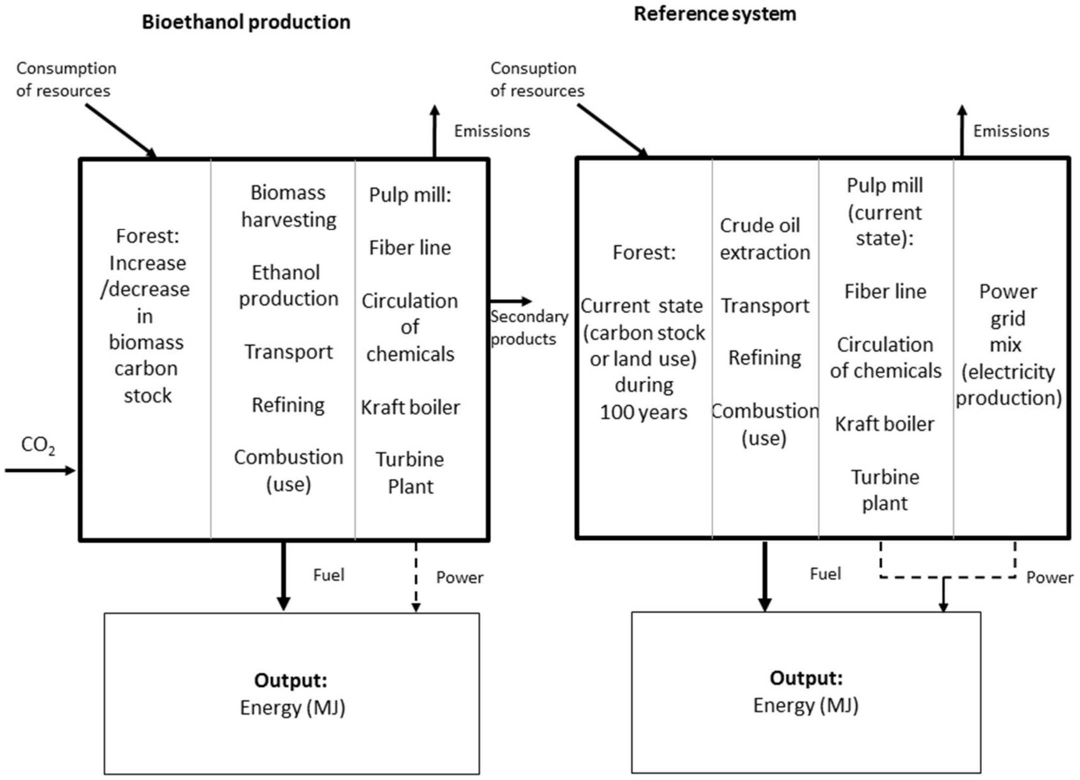

Figure 21. System definition and boundaries. In the reference system, the biorefinery-pulp mill is compared to a pulp mill without a biorefinery and fossil fuel pathway, the utilization of forest

biomass is compared to the non-utilization of forest biomass and the excess electricity production benefit to power grid electricity.

3.8.4 Renewable diesel from cultivated biomass (Paper IV)

The GHG emission impact of biofuel production is caused by several phases and choices made in the life cycle of a biofuel product. In the fourth paper, the potential to reduce emissions of second generation renewable diesel fuel production is studied. The focus is to find out what choices can be made during the production chain to reduce the GHG emissions of this fuel product.

For the fourth paper, three possible feedstocks for production were selected: palm oil, jatropha oil and rapeseed oil. The life cycle of this diesel product is accounted for starting from land use change (LUC) and including the impacts of cultivation, oil extraction, biofuel production, transportation, distribution and use. The functional unit used throughout the RD life cycle is 1 MJ of produced RD and the corresponding land area that produces the feedstock for RD the production. The carbon content of the biofuel and biomass is considered to be carbon neutral and the biogenic carbon emissions are assumed to be bound to the new growing biomass. The key assumptions considering electricity and fuel use and utilization of co-products are summarized in Table 8.

Table 8. Key assumptions made in the renewable diesel study.

	Assumption
Electricity production	Local grid represents the average electricity production of the country where the plant is located (Finland, Singapore). The use of marginal electricity is not included in the study because its impact is not significant in this case. The results do not change significantly, when the emission level of electricity is changed to three-fold from the assumption level.
Fuel use	In Europe, natural gas is currently used for RD production, and it was therefore selected for the used fuel in the European refinery. In Brazil, light oil was selected because cultivation takes place most likely in the sparsely inhabited areas where the infra for natural gas or other forms of energy is not present. This oil is used in the oil extraction from jatropha in Brazil because it is probably the only way to produce heat in the area. Biomass could also be used, but its availability is not certain in the Cerrado area. Heat for the palm oil processing is produced from the side flows of oil palm.
Co-product utilization	The scenario is based on the current practices: palm oil fibres and shells are used for energy. Jatropha cultivation produces mostly leafs etc. which are composted or left on the ground on the cultivation site. The same happens to the jatropha kernels and shells. The toxicity of jatropha disables the use as animal feed. Also the energy use of straws is difficult and not so common as of the palm side-flows. For example in Finland, straw is mainly tilled to the ground or used as a litter. In the result section of Publication IV, it is discussed what would be the impact of using renewable heat instead of fossil heat. This renewable heat could be produced based on these straw or kernels.

Rapeseed, soy and palm oil are currently the most widely used for biodiesel production (Luković et al., 2011), and jatropha is another potential feedstock suggested for wider use. Rapeseed, jatropha and oil palm were chosen for this study due to their different growing regions and cultivation practices. Rapeseed is cultivated in temperate climates and is an annual crop. Jatropha is a perennial crop which can be cultivated on marginal lands and non-agricultural lands (Jongschaap et al., 2007) and can improve the soil carbon content when grown on poorer soils. Oil palm plantations are located in tropical zones and bind more carbon to biomass than rapeseed or jatropha.

Cultivation and oil extraction produce plant parts which cannot be used directly in oil-based RD production. The hydrotreatment process also produces biogasoline and propane which can be sold on the market. In palm oil processing, palm kernel oil (PKO) and palm oil mill effluent (POME) are also produced and POME treatment can further produce biogas and eventually electricity (Shirai et al., 2003). For these products, the allocation of GHG to main and co-products is based on both energy allocation and system expansion methods. In this system expansion approach, it is assumed that PKO replaces other food oils, fossil-based propane production and bio-gasoline displaces fossil petrol. In oil extraction, animal feed is produced to displace soy-based feed, palm kernel oil displaces soybean oil and biogas from POME treatment is used in electricity production, displacing coal based electricity. The GHG credit values used in this system expansion method are presented for palm oil in Figure 22. The system definition and boundaries are presented in Figure 23.

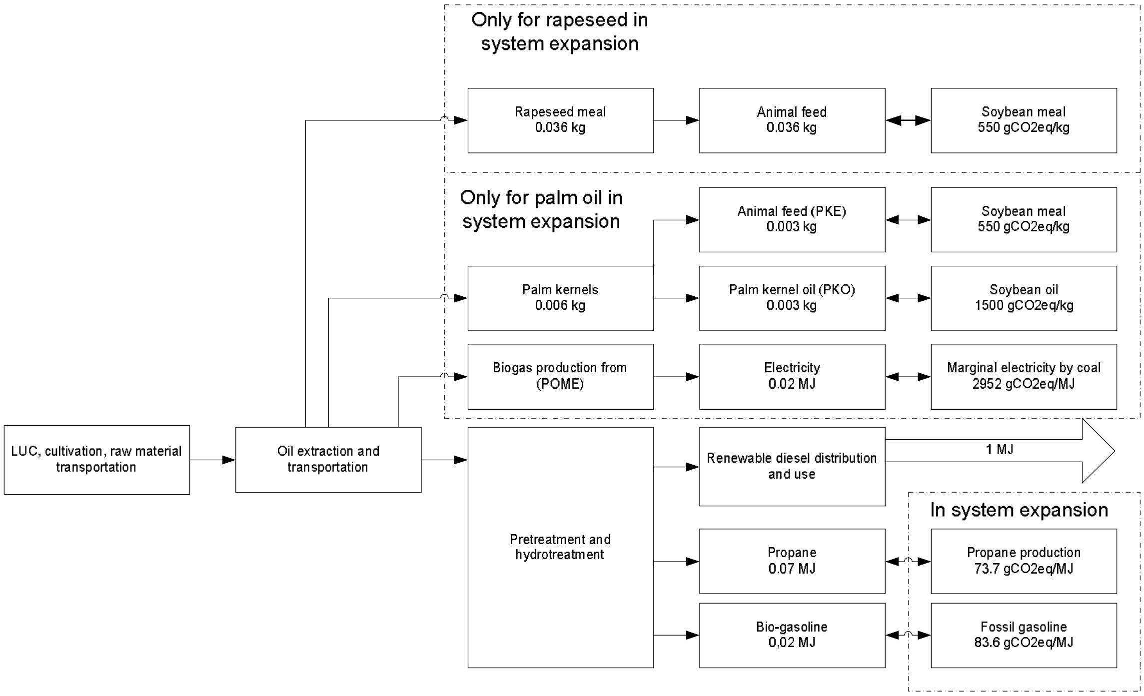

Figure 22. Credit values used for palm oil and rapeseed example when system expansion methodology is used for co-products. (Uusitalo et al. *in press*)

The land use impact of the biofuel production under study is assessed based on published values of biomass and carbon contents of plant parts, SOC levels and reference ecosystem carbon stocks. Information concerning the above-ground and below-ground carbon bound in the plant parts, emissions from cultivation and impacts on SOC was collected and compared. To estimate the average above-ground biomass and carbon levels of different plants during cultivation, the above-ground biomass (AGB) was divided by the cultivation period. In the case of jatropha, the plant was assumed to achieve a mature 3.9 kg AGB and 1.6 kg below-ground biomass (BGB) after 3.5 years, corresponding respectively to 6.5 and 2.7 t ha^{-1} (Reinhardt et al., 2008). In addition, the cultivation was assumed to continue at the end of year 20, producing a harvest annually. Rapeseed as an annual crop was assumed to achieve a mature AGB amount of ca. 7 t ha^{-1} during a 105-day growing season. The land area was assumed to be void of any vegetation cover outside of the growing season. A twenty-five-year period was used as the economic lifetime of oil palm, with 23 production years. The time-averaged AGB and BGB values of 60 and 20 t ha^{-1} were used for oil palm plantations (Germer and Sauerborn, 2008).

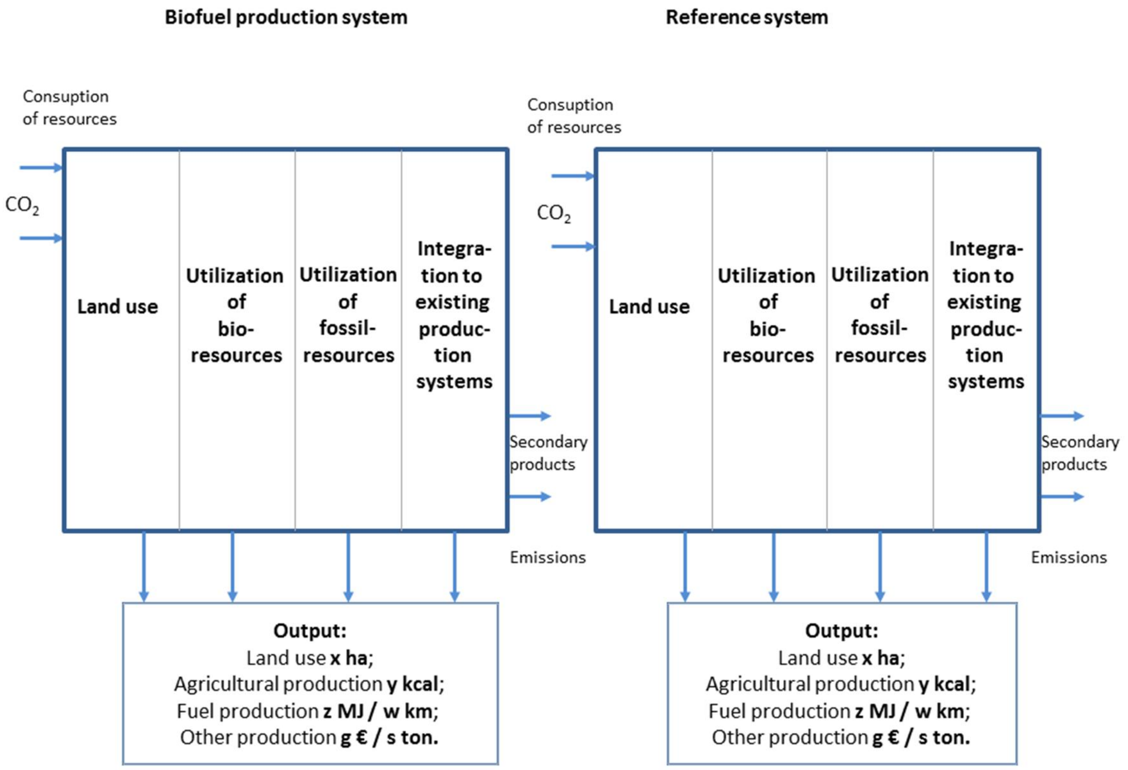

Figure 23. System definition and boundaries of the reference situation when the system expansion approach is used in the renewable diesel study.

4 Results

4.1 Introduction of the main results of the case studies

The main object of the following case examples was to investigate the significance of the different GHG emission sources related to heat, electricity and biofuel production from biomass, opportunities to develop more climate-friendly biomass energy options and to discuss the importance of biogenic emissions of biomass systems, and further to evaluate the impacts of these findings on GHG emission reduction when biomass based fuels are used for substituting fossil fuels. The first section (4.1.1) presents the results of two peat studies (Paper I and II), pointing out the most important factors affecting the GHG emissions of peat produced from Finnish forestry drained peatland areas. In the first paper, the impact of the harvesting method and peatland soil emissions are studied, whereas the second paper focuses more on the impact of the peatland type on the emissions. The second section (4.1.2) presents the results of including biogenic carbon emissions into ethanol production from wood biomass and evaluates the GHG emission saving potential of wood or forest residue based ethanol production when ethanol is used to replace fossil gasoline in the transportation sector. In the third section (4.1.3), the main emission sources and ways to decrease biofuel GHG emissions are studied in terms of renewable diesel production from cultivated biomasses: jatropha, oilseed rape and oil palm feedstocks. Section 4.2 synthesizes these studies.

4.1.1 Peat studies

Paper I studied forestry drained peatlands by using an average emission value and measurement data available from peatland areas which are recognized to produce more emissions than on average (Paper I). The objectives were to study the GHG emissions from two different peat production methods (the excavation-drier method and the milling method) and to compare the long-term (100-year) climatic impacts of peat utilization for three different peatland areas. The results are presented as GWP values which are a measure for positive (warming) or negative (cooling) global warming potential (kgCO_2-eq.).

The results of this first study indicate that the type of peatland has a larger effect on the GWP than the peat production method or the after-extraction treatment (Figure 24). The use of peatland with high original emissions (non-utilization scenario) will create a lower GWP result than the use of “average” values, as in the other Finnish study (Kirkinen et al., 2007)

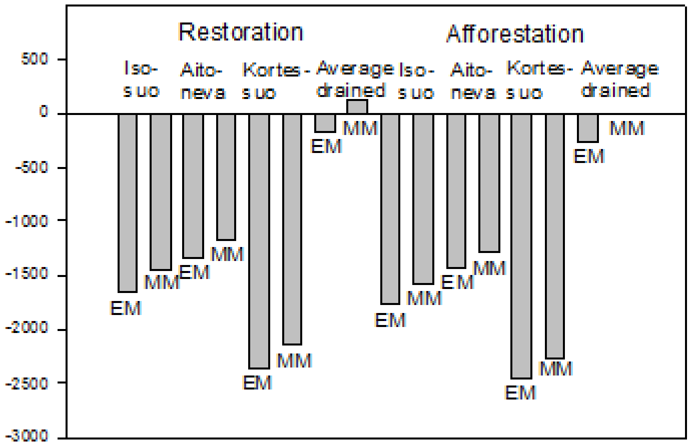

Figure 24. Global warming potentials (GWP, CO_2 equivalents ha^{-1} a^{-1} in a 100-year time span) in different study sites for the excavation-drier method (EM) and the milling method (MM) with two different after-treatment methods. When the GWP result is negative, the CO_2-equivalent

emissions are reduced in comparison to the reference situation where heat and electricity is produced from coal. (Figure by Silvan N.) (Silvan et al., 2012)

The second peatland study (presented in Paper II) followed the conclusions based on Paper I. In the third study, the three different forestry drained peatlands which can be identified to have a high emission impact due to pre-assumptions made were studied in more detail with the same method. In this study, we wanted to assess the GHG emission impact when this type of peat is used to replace coal or is replaced with forest residues.

To estimate the reference situation emissions, the first step was to estimate the GHG emission flux values for the selected peatland types. The GHG flux value components and results used as reference values for peatlands are presented in Figure 25. The most fertile peatland type (herb-rich, Rhtkg) releases the largest amount of emissions from the peat layer, but at the same time, the rapidly growing forests are assumed to sequester more carbon than in the other peatland types. The second most fertile type, Vaccinium myrtillus, releases more GHG emissions because of the lower stand growth rate. After peat harvesting, the cut-away peatland is afforested, which reduces emissions in every other case than in the oligotrophic Cladina type area. These net emissions presented (Figure 25) can be compared to the average soil emission (respiration) value 224 (0-448) $gCO_2/m^2/a$ (Kirkinen et al., 2007) for the forestry drained peatland.

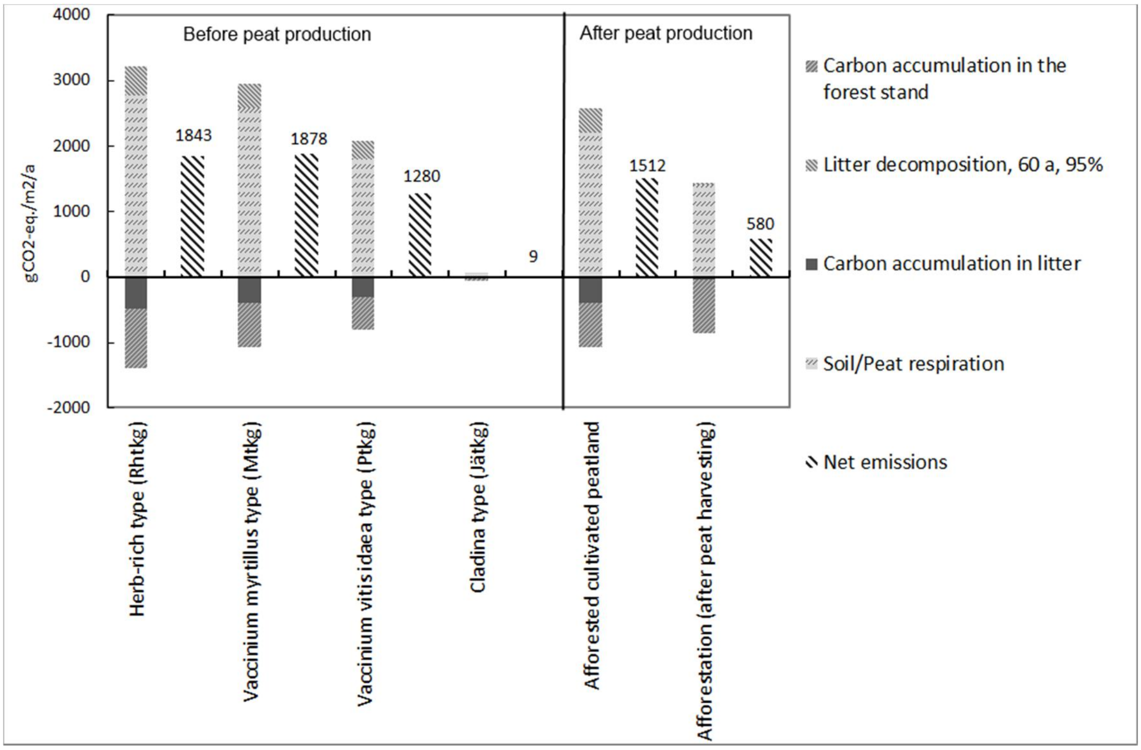

Figure 25. GHG emission values for different peatland types. Positive values mean emissions into the atmosphere and negative values carbon accumulation into the biomass. (Väisänen et al., 2013)

Two examples were selected to study the overall GHG impact of peat production from high-emission level peatland when peat is used to replace coal or forest residues is used to replace peat in the local combined heat and electricity production plant. In the first example, the peat replaces coal in the Vaskiluoto gasification plant in Vaasa, and in the second one, the use of forest residues is increased in the Toppila power plant in Oulu, replacing peat fuel use. The greenhouse impact of replacing 20% of the coal with peat gasification is presented, showing that the overall greenhouse gas reduction is nearly the same as emission reduction achieved in high-emission peatlands (Figure 26). Based on these results, the emission level of unutilized peatland before peat harvesting seems to determine the climate impact of peat utilization when it replaces coal.

When the peat fuel harvested from a high-emission peatlands is replaced with forest residues, the emission reductions due to reduced peat production and combustion overcome the emission increase in unutilized peatlands and released forest carbon stock. In this case, replacing 15% of the peat with forest residues reduces emissions when the peat is produced from high-emission peatlands, but the peatland emissions from non-harvested peatlands reduce the emission benefit of forest residues (Figure 27).

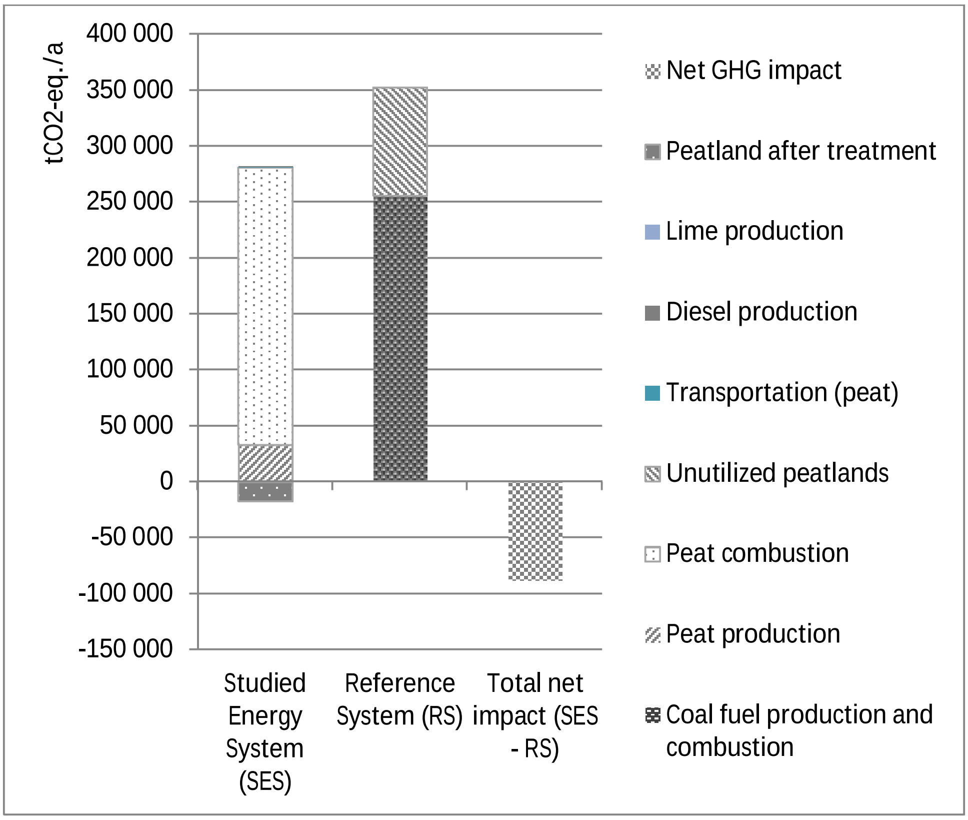

Figure 26. GHG emission results for peat energy system and reference system when coal is replaced with peat in heat and electricity production (peat is produced from high emission level drained peatland areas).

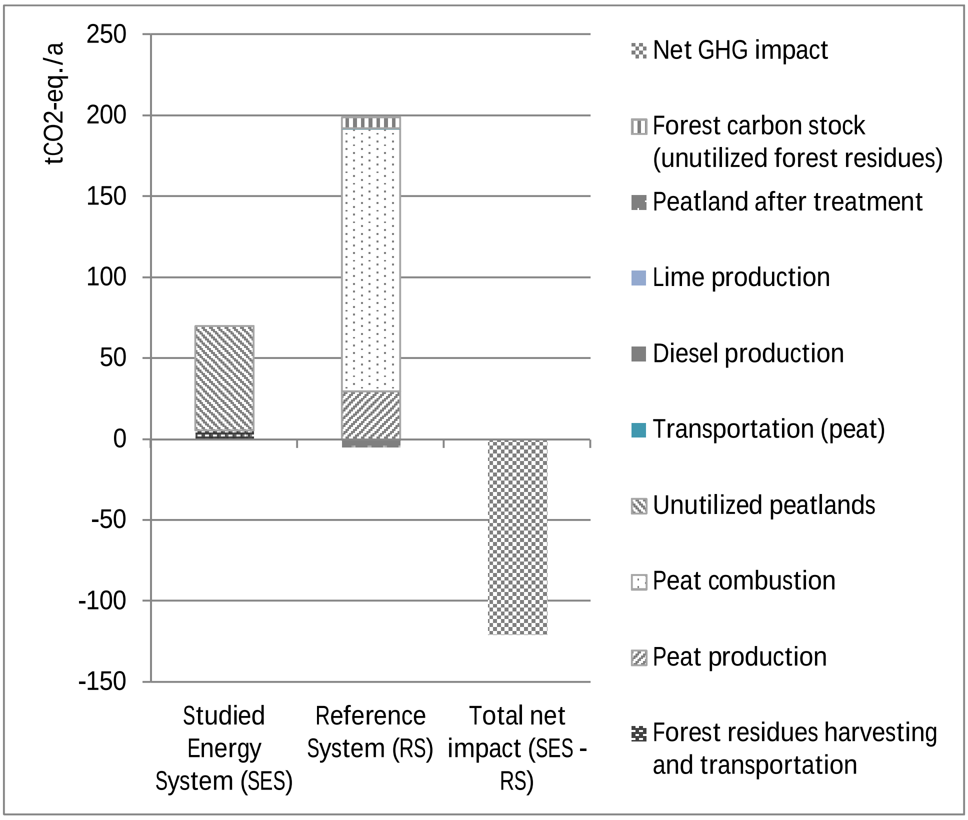

Figure 27. GHG emission results for forest residue energy system and reference system when peat is replaced with forest residues in heat and electricity production (peat is produced from high emission level drained peatland areas).

In addition to the GHG emissions of these two case studies, another objective of the study was to determine how different values of independent variables will impact the peat life cycle emissions. A sensitivity analysis revealed to what extent the results will change if the amount of the residue peat layer is reduced, the production time is shortened, or peat production is directed to the peatland areas in which the greatest reduction could be achieved. The sensitivity analysis was conducted to highlight the factors in peat production which can be impacted by a peat harvesting company. Because of the aims of the sensitivity analysis, we discuss the results including only the peat-based emissions (Figure 28).

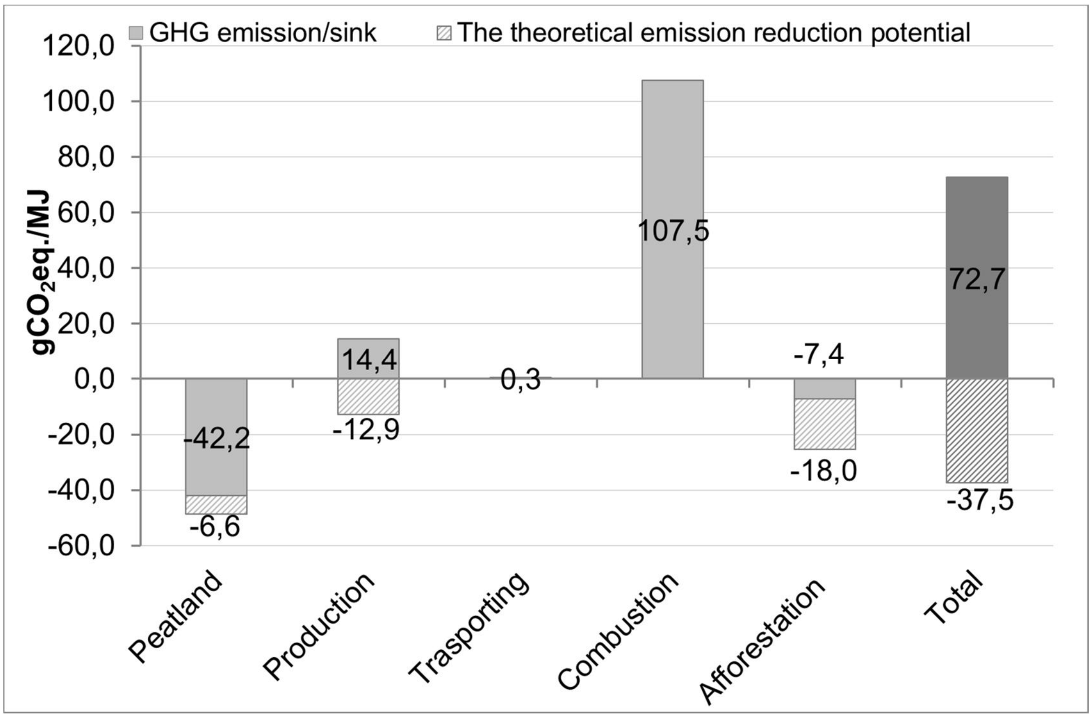

Figure 28. Peat-based emissions (gCO_2-eq./MJ) in a 100-year reference period. The lighter grey bars quantify the theoretical emission reduction potential in different phases of peat utilization (Väisänen et al., 2013).

The life cycle of peat includes several unit processes which have the potential to reduce GHG emissions (Figure 28). Directing the peat production to Vaccinium myrtillus type peatlands instead of the distribution of high-emission peatlands presented in this paper, the emissions would be reduced by 6.6 g/MJ. Shortening the peat production time to one tenth with developed harvesting methods could reduce the emissions of the peat production stage by nearly 90%. In the after-treatment phase, the emissions originate from the residual peat layer and are directly proportional to the amount of residual peat. In this study, the impact of the residual peat layer was 18 g/MJ, which could be avoided if the residual peat layer were fully removed. In practice, the layer improves the forest growth and removing it completely would not be reasonable. Overall, the factors described above have a remarkable impact on GHG emissions, and their relevance in emission reduction in the peat industry needs to be recognized.

The majority of the GHG emissions in the peat fuel chain are generated in combustion. The harvesting stage is the second greatest source of emissions. These emissions do not change depending on the time period. Instead, the peatland emissions in the reference situation and carbon accumulation in the forest biomass change when the reference period changes. The shorter the time, the less the forest stand accumulates carbon dioxide in the biomass and the smaller the amount of emissions released from the peat layer in the reference situation peatland. Figure 28 shows that when the peat is harvested from high-emission peatlands (a third of the peat was assumed to be produced from the herb-rich type, another third from the Myrtillus type and the remaining third from the Vaccinium vitis idaea type), the peat fuel cycle achieves the emission value of approximately 73 g CO_2-eq./MJ. If this result is compared to earlier ones which are calculated based on average peatland emissions, the impact of directing the peat production to the studied peatlands is roughly 30% of the CO_2-eq./MJ emission value in the 100-year reference period.

4.1.2 Integrated forest biomass based ethanol production

The third study evaluated the life cycle of two ethanol production systems: ethanol production from prehydrolyzed chips and forest residues. In both of these production systems, the processing of forest residue feedstock takes place in the biorefinery which is integrated into a pulp mill. The focus of the research was on the raw material consumption, useful energy output and greenhouse gas burden of both systems and on the greenhouse gas impact of forest residue and wood utilization.

The transformation of forest biomass into an ethanol product in the biorefinery environment affects the energy and chemical consumption of the biorefinery-pulp mill integrate in the both cases. WinGems simulations indicated that the integration of ethanol production processes into the pulp mill energy system increased the overall heat, electricity and fuel production.

The production of ethanol from prehydrolyzed chips generated 5130 t CO_2eq of greenhouse gas emissions during a year when the daily ethanol production value of 56 t was applied. In addition to ethanol production, the process increased the amount of excess electricity produced in the integrate. When the emissions from raw material acquisition and biorefinery processes were divided between ethanol and electricity in proportion to their energy content, the greenhouse gas emissions of the ethanol life cycle were 8.6 g CO_2eq /MJ_{fuel} on a per unit energy basis. Consequently, the emission reduction, compared to petroleum fuel (86.6 g CO_2eq /MJ_{fuel}), was 89.7%, and the fuel meets all of the emission saving requirements in the Renewable Energy Directive (35%/50%/60%). The production can respond to the demand for renewable traffic fuels on such a scale that six production units could meet 40% of the Finnish target (10% by the year 2020). When the forest residues were used for the production of ethanol, greenhouse gas emissions of 12450 t CO_2eq were generated during a year with 83 t daily ethanol production. This means that the greenhouse gas emissions of the life cycle are 15.3 g CO_2eq /MJ_{fuel} on a per unit energy basis.

The greenhouse gas impact of forest biomass was calculated for pine logs and forest residues with the following assumptions. The amount of carbon removed from the forest was calculated based on the carbon content of the raw material. The assumption was that in the case of pine logs, forest regrowth will recapture the released carbon after a 100-year rotation time after the final felling. The growth of the forest stand was assumed to be linear and the carbon content of the wood stand was calculated by using the regression model (Minkkinen et al., 2001). The impact of forest residue removal was calculated by comparing the greenhouse gas emissions to the emissions created when the residues are decomposing in the forest. The decomposing rate was calculated based on the simulation results of the Yasso07 model (Tuomi et al., 2009; Tuomi et al., 2008).

As a result, the weighting factor that represents the weighted average time of the carbon uptake in forest stand regrowth during the reference period was 52% of the utilized wood biomass carbon content. This means that on average 48% of raw material carbon content is released into the atmosphere during 100 years when the difference between the original forest stand carbon content and the growing new carbon stock of stand regrowth is observed. This effect increases the emissions of ethanol production by 128.7 g/MJ_{EtOH} when the need of biomass feed for ethanol fuel production is considered.

The greenhouse gas emission impacts of residue removal from forest soil (effect on biogenic carbon storage) and carbon sequestration on the regrowth of stands (carbon debt) after the final felling are presented in Figure 29. Emissions from other life cycle stages are presented as a percentage in Table 9. The biogenic carbon effect is presented for emissions per unit of fuel energy. The columns in Figure 29 show that the carbon of biomass removed from the forest increases the greenhouse gas emissions significantly. To achieve emission reductions through the replacement of gasoline, the total greenhouse gas emissions from the fuel life cycle should be lower than 83.8 g/MJ. The overall emissions from ethanol based on prehydrolyzed chips are higher. Thus based on these results, the total effect of the ethanol route actually increases greenhouse gas emissions when the carbon storage effect of forest biomass is included in the consideration.

Table 9. Breakdown of the emissions from other life cycle stages for both cases allocated for ethanol.

	Ethanol from prehydrolyzed chips	**Ethanol from forest residues**
Harvesting	62,0 %	59,8 %
Transporting	2,7 %	5,6 %
Production of nutrients	6,4 %	6,2 %
Production of make-up lime and chemicals	1,1 %	5,2 %
Production of lime kiln fuel	1,1 %	1,4 %
Pulp Mill incl. Lime reburning	26,4 %	17,8 %
Diesel to transport	0,3 %	0,01 %
Total	100 %	100 %

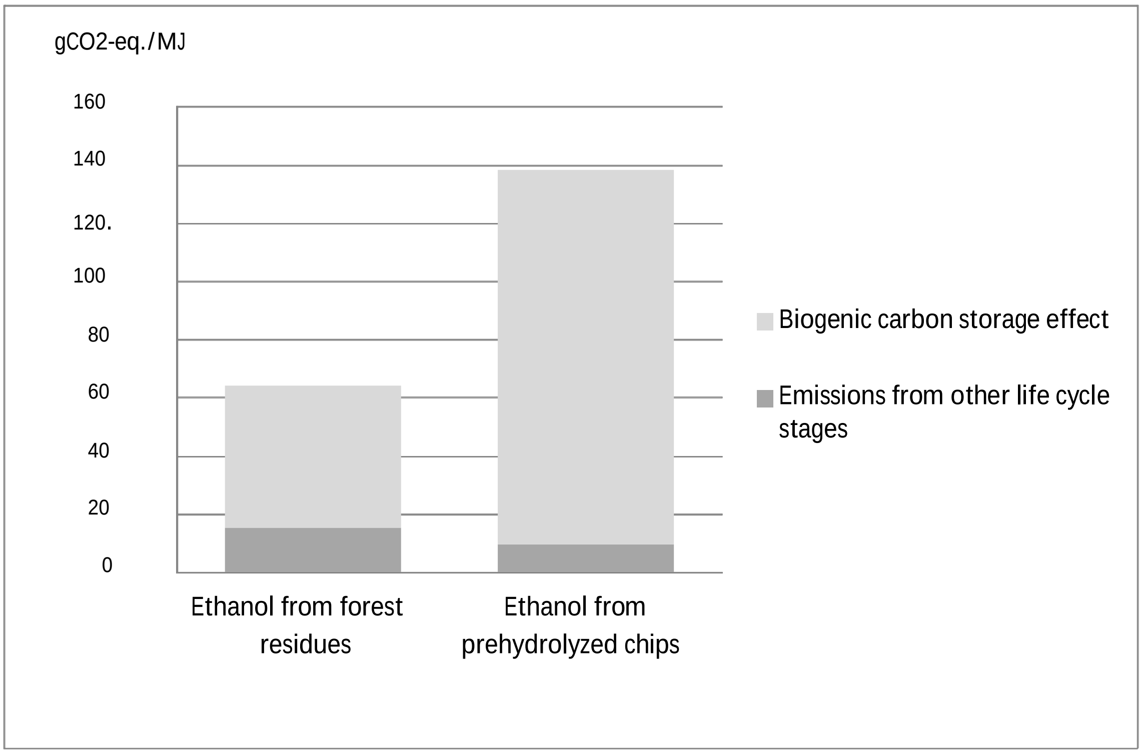

Figure 29. The biogenic carbon debt of forest stand growth and the effect of carbon stock of forest residues on forest soil can significantly increase the greenhouse gas emissions of the studied biomass based fuels (Väisänen et al., 2012).

4.1.3 Renewable diesel

Paper IV examined the GHG emissions of renewable diesel production. The importance of raw material selection was studied by selecting four different raw material options for the process and including both cultivation and land use change emissions into the life cycle alongside the process and transportation. As a result, the main parameters which affect the GHG emissions of renewable diesel production are studied.

The findings indicate that the key contributors to the life cycle GHG emissions of RD are the production area, choices made in biomass cultivation and technology used in the oil extraction process, whereas RD production with hydrotreatment and distribution are relatively less important life cycle stages (Figures 30 and 31). Palm oil plantations generate lower cultivation GHG emissions per MJ_{RD} due to higher oil productivity per hectare than rapeseed and jatropha cultivation. The use of a nitrogen fertilizer and the N_2O emissions it releases cause most of the GHG emissions of the cultivation processes. In this study, palm oil extraction generates lower GHG emissions than oil extraction from rapeseed or jatropha. The main difference between these cases is the utilization of fibers and shells for heat and electricity production, which lowers the fuel production emissions. If the heat and electricity needed for oil extraction from rapeseed and jatropha seeds could be produced by renewable energy sources, the GHG emissions of rapeseed RD would be reduced by 3.5 gCO_2/MJ and of jatropha by RD 7.5 gCO_2eq/MJ. POME generated in this extraction process of palm oil can be a significant emission source. The open pond treatment of POME would contribute to GHG emissions approximately in the amount of 25 gCO_2eg/MJ.

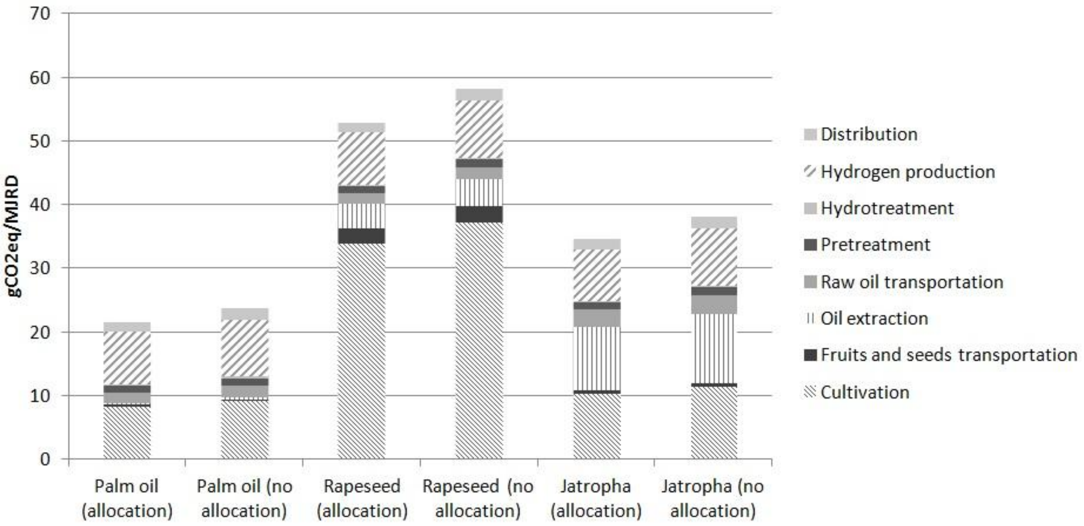

Figure 30. GHG emissions from RD production without LUC (Figure by Uusitalo V.) (Uusitalo et al., in press).

Heat production is the main emission source also in the hydrotreatment process. Currently, the steam for the hydrotreatment process is produced by natural gas. The use of another energy source can either reduce or increase emissions related to hydrogen production depending on the new energy source specific emissions. One option is to use co-produced propane to replace natural gas. This would reduce emissions if the life cycle GHG emissions of propane were below the emissions of natural gas. Furthermore, these emissions are dependent on the land use emissions of RD production (Figure 31). In this paper, both system expansion and energy allocation are used.

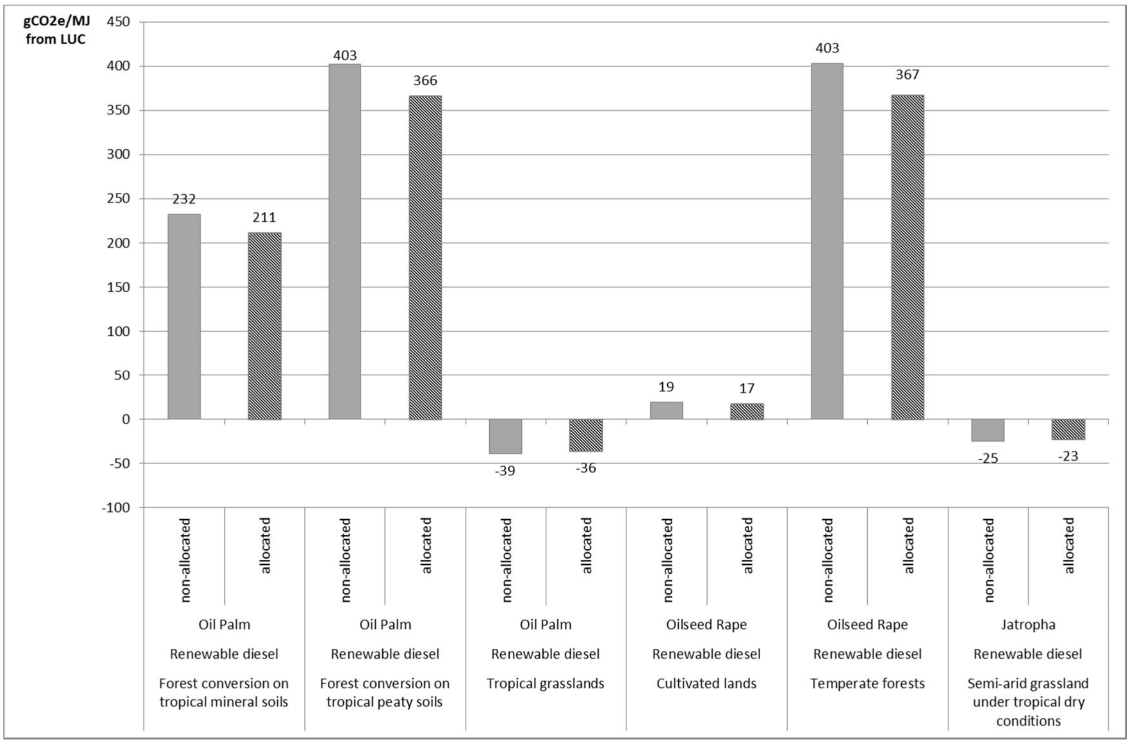

Figure 31. Land use change GHG emissions from the different cultivation options studied in Paper IV (Uusitalo et al., in press).

Results which combine production emissions and LUC emissions are presented by using system expansion approach in Figure 32 (a) and through allocation in Figure 32 (b). The system expansion approach assumes that the co-product generated can replace the same or a similar product that is produced from another feedstock. Due to this displacement, an emission credit for the avoided production can be assigned. In Figure 32 (a), the emission credit is presented by adding the emissions of avoidable production on the bar of the replaced emission sources. The production of the main product replaces fossil diesel.

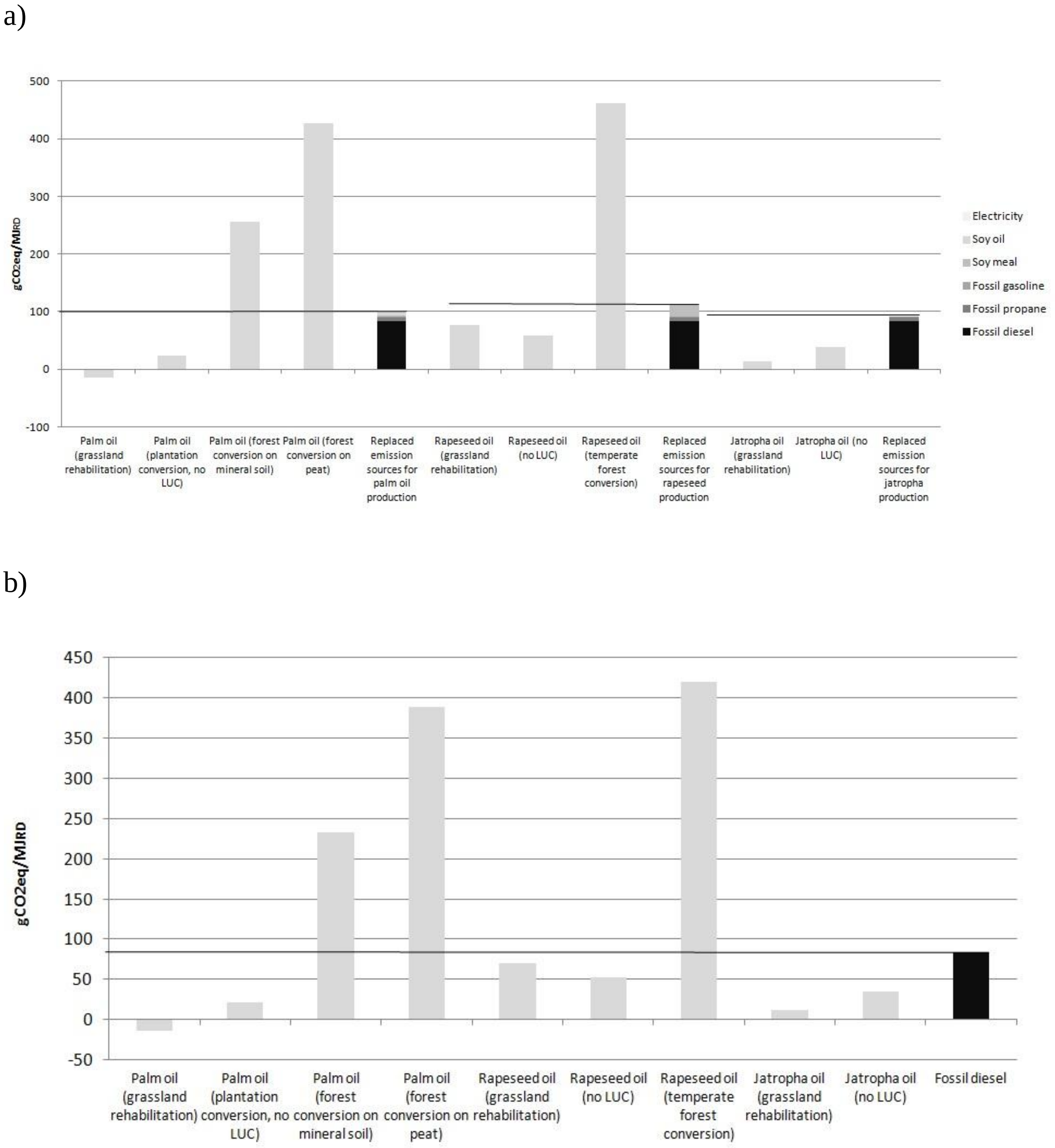

Figure 32. Total GHG emissions compared to production emission replaced by RD production with (a) system expansion and (b) allocation (Figure by Uusitalo V.) (Uusitalo et al., in press).

As can be seen in Figure 32, palm oil and rapeseed plantations seem to release carbon when compared to the forest ecosystem carbon stock levels, and palm oil cultivation in grasslands may even be a GHG sink. Jatropha and palm oil seem to bind carbon when compared to the grassland ecosystem (Figure 31). According to the results, the higher the carbon content of the reference ecosystem is, the higher the carbon emissions are from the land use change to biomass cultivation. This impact is highly dependent also on the biofuel productivity of the feedstock per hectare.

Palm oil cultivation without LUC produces the second lowest emissions. This situation may take place if, for example, rubber tree plantations are replaced by palm oil plantations. GHG emissions from jatropha and rapeseed RD are at the same level if grassland is used for cultivation or there is no LUC. Palm oil and jatropha based RD have higher GHG emissions than fossil fuels if cultivation is carried out by clearing forest ecosystems into cultivation areas. The selection of the allocation procedure between co-product credits and energy allocation did not change the respective order between the feedstocks in terms of GHG emissions. Reasons for this can be found from the same process technology and similar co-product amounts and quality with the similar substitution options. The result also indicates that the energy allocation did take into account the most important co-product flows in terms of comparison of these feedstocks.

4.2 Uncertanties and sensitivity analysis

The modeling of the climate impact of biomass production chains with impacts on ecosystems is a simplified description of complex systems. The LCA addresses only the potential environmental impacts and cannot predict the actual environmental impacts (EN ISO 14040:2006). The accuracy of LCA model is based on the quality of data used in a model. The parameter values and mathematical functions used for the modeling, as the growth rate of forest stand, decomposition of litter, peat layer or forest residues as well as the yield from fields or processes can have a significant impact on the results. The impact assessment, carried out with the GWP method with a 100-year time horizon widens the time span of the impacts, and the timing of emissions may cause changes to the results. For these reasons, the sensitivity analysis is recommended for the key parameters.

The key parameters in the studies presented in Publications I–IV are recognized based on presumptions of the author and located in the chart (Figure 33) based on the uncertainties of the parameters and the contribution to the result. This uncertainty importance analysis (Heijungs, 1996) is used to identify the most important parameters of the four different studies.

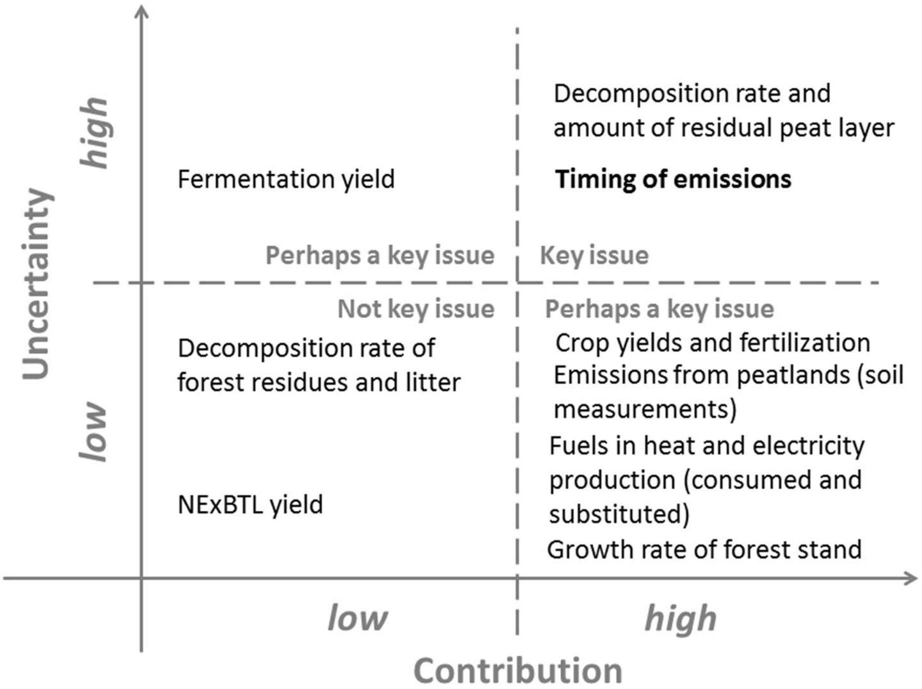

Figure 33. Diagram for finding the key parameters in an uncertainty important analysis (Heijungs, 1996).

In the uncertainty importance analysis (Heijungs, 1996) different parameters are located in the fourfold table based on the size of the uncertainty of the parameter and the size of the contribution to the final result. For example, the uncertainty of fermentation yield in a biorefinery study is high due to the undeveloped situation of lignocellulosic material fermentation technology. On the other hand the impact of yield is low: a 15% change in the initial value would change the GHG emission result only by ±2,2%. Thus, fermentation yield is located into the group “Perhaps a key issue”. In biorefinery and peatland studies the growth of forest stand was modelled with linear growth. Because the forest growth curve is slightly different (see Figure 34), reminding the shape of the letter S, the carbon stock grows with a different rate at different times. When the Fridth-Nilsson growth function is used, in which the carbon stock increases more slowly during the first 10 years but faster after 35 years, the difference between the time averaged carbon stock values is approximately 29%. On the other hand, if dynamic GWP(t) values are used to compare the linear and more realistic growth, a difference of 10% is discovered between these two assumptions. The contribution of the forest growth rate to the results varies between the studies being more significant in the ethanol study and less significant in peat studies where the forest carbon stock contributes 10% and the contribution of the growth rate is thus only 3% of the result.

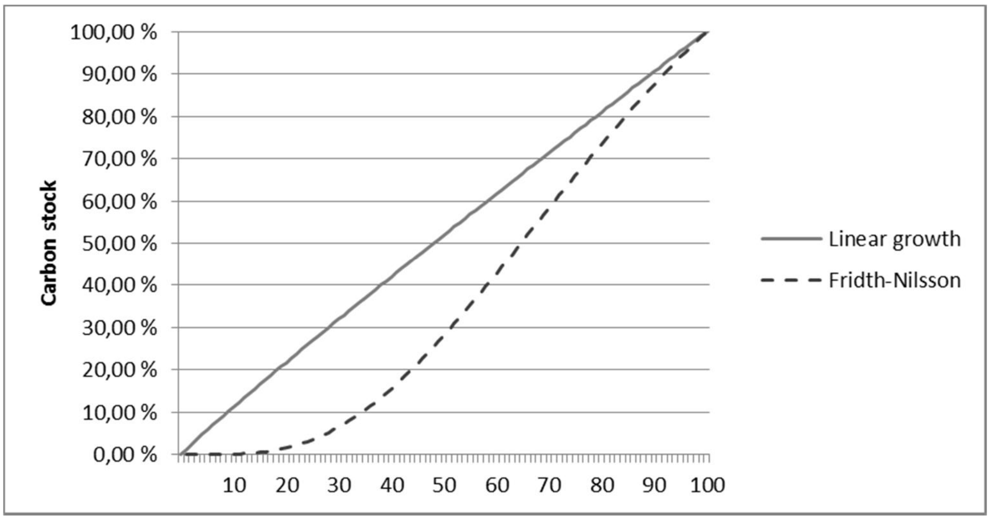

Figure 34. Carbon stock of forest stand: Comparison of linear and Fridth-Nilsson growth functions.

Based on this analysis of uncertainty importancies in the studies presented in Papers I-IV, the most important uncertainties related to the results seem to be the questions related to the residual peat decomposition in peatlands after peat harvesting and the impact of using the static GWP 100 approach in assessing the climate impact of biomass production chains. Because the impact of residual peat layer on results has already been handled in Chapter 4.1.1, the sensitivity analysis is completed to the GWP assessment method.

4.2.1 Sensitivity analysis: Impact of Static Impact Assessment to the results when compared to the Dynamic Assessment Method

In Papers I, II, III and IV the climate impact of peat and biomass derived energy and fuels is calculated based on the carbon balance of different scenarios and by using the GWP method with a 100-year time horizon (GWP(100)) for the impact assessment, when the timing of the emission is not considered as long as the emission occurs during the 100 year time frame. This means that the climate impact has been taken into account during the 100-years impact time after the emission/sink takes place. Due to the fact that GHG emissions and sinks in biomass utilization scenarios are formed more or less in the future the use of the calculation method with GWP(100) values leads to temporally un-explicit results. For example, if the emission or sink actualize in the year 80, with the GWP(100) method the climate impact is calculated for the next 100 years until the year 180. In this case, part of the accounted climate impact is taking place after 100 years from the starting point of the assessment.

The temporally-explicit climate impact for biogenic and fossil carbon flows can be calculated with methods that use for example cumulative radiative forcing as a base. With calculation procedures presented in IPCC (2007c) the GWP values can be calculated as a function of the impact time, and this way, the time-explicit GWP and numerator AGWP can be determined.

In this chapter, the impact of the dynamic LCA approach on the results is assessed by calculating the AGWP (Wm-2, also called Radiative Forcing) of the emissions and sinks as a function of time. Emission profiles and the impact of the time-explicit method for four case examples are presented, and the climate impact is calculated with three methods: first, with time averaged biomass carbon stock and cumulative AGWP(100) values as in Papers I, III and IV; second, with the total biomass carbon stock and cumulative AGWP(100) as in Paper II and finally, with the total biomass carbon stock and cumulative AGWP(t) values where the impact assessment accounts only for the climate impact of the first 100 years starting from the beginning of the assessment.

The emission profile for forestry-drained, myrtillus type (Mtkg) peatland and peat utilization when compared to the unutilization of peat and coal combustion is presented in Figure 35. The cumulative result is presented in Figure 36. In peatland assessment the timing of the impact assessment has a significant impact on the results. When the AGWP(t) method is used, the climatic impact is 47,6% higher than when the AGWP(100) method is used. Difference increases when the time horizon increases being 5,5% with time horizon of 15 years and 22% with the time horizon of 50 years. Figure 35 shows that the emission reductions when coal is changed to peat in this case results evenly during the 100-year reference time. When the GWP(100) values are used in impact assessment with this shape of the balance curve of emission profile of the first 100 years, around a half of the impact can be discovered to reach over the assessment period.

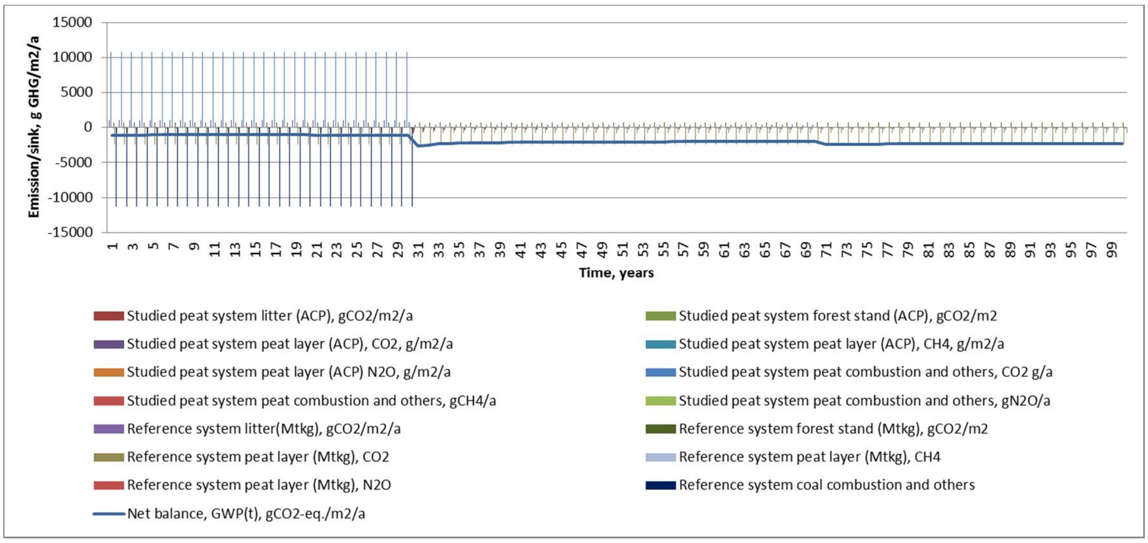

Figure 35. An emission profile of peat utilization: Comparison of GHG emissions of the myrtillus type (Mtkg) peatland with peat utilization with Mtkg-type peatland without peat utilization and using coal for CHP production. Net balance between the systems is presented with the blue line.

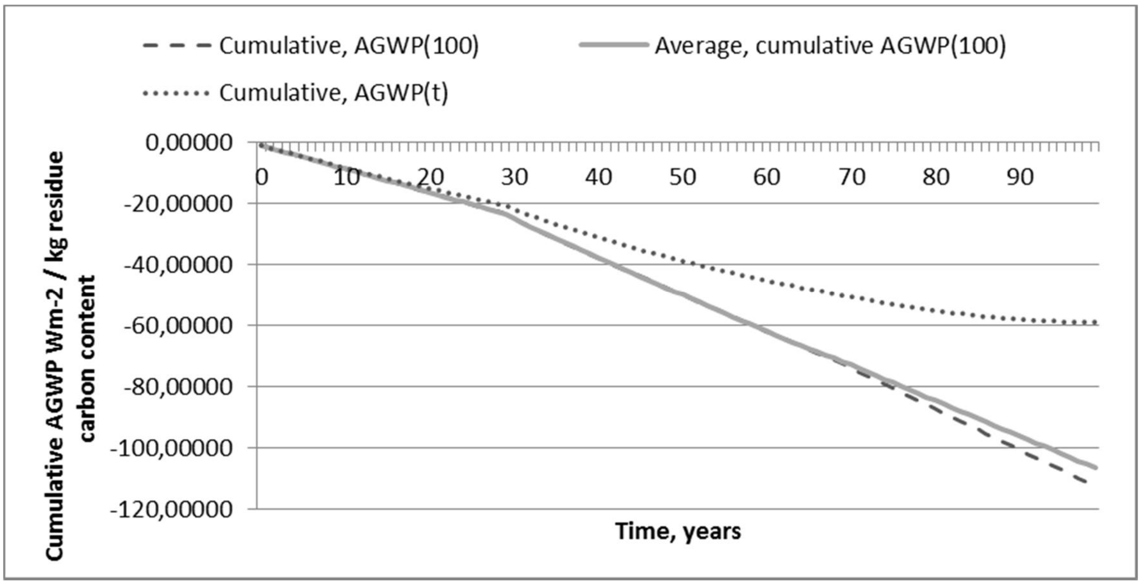

Figure 36. Time dependent, cumulative radiative forcing of peat utilization from the myrtillus type (Mtkg) peatland when compared to the coal use in CHP production.

The emission profile for forest residue utilization and the cumulative AGWP results for forest residue and forest stand utilization are presented in Figures 37, 38 and 39. The emission profiles for these two different types of forest biomass sources are significantly different: when the forest residues emit carbon exponentially during a decomposition when left in the forest, forest stand accumulates carbon during a regrowth phase constantly until felling is repeated. In Paper III, the carbon stock of forest stand and forest residues is accounted by using a time averaged value for carbon stock. Figure 38 shows that the simple carbon balance method with the time average approach is an approximation that gives a similar result as the AGWP(t) method. The difference between these is 7%. The difference in the climate impact of forest stand utilization is also relatively small, 11%, when time averaged values are used (Figure 39).

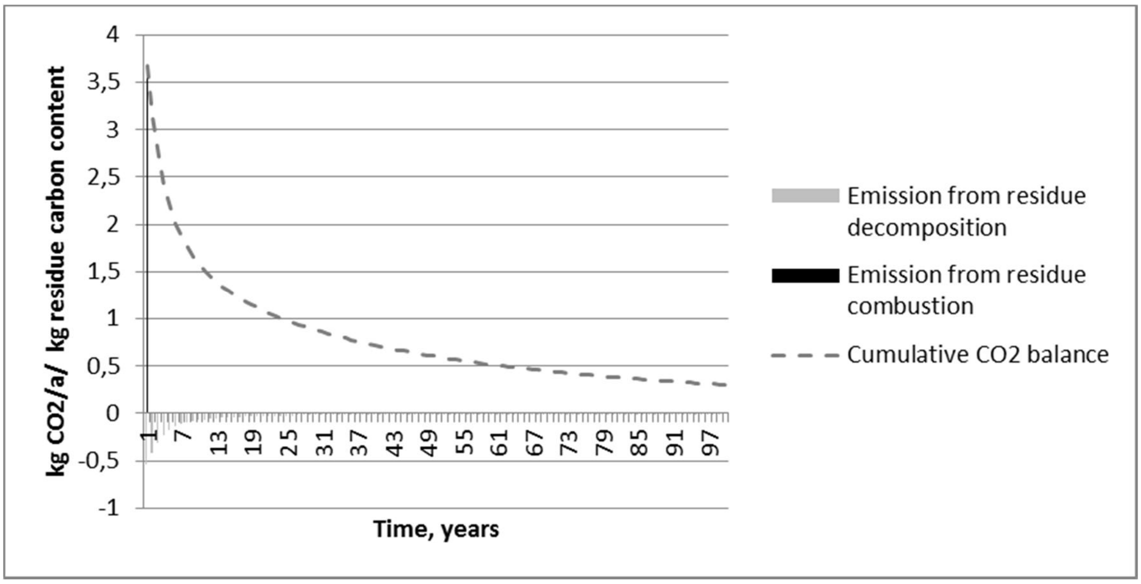

Figure 37. An emission profile of residue utilization. Comparison of GHG emissions of residue combustion to the emissions from residue decomposition in site.

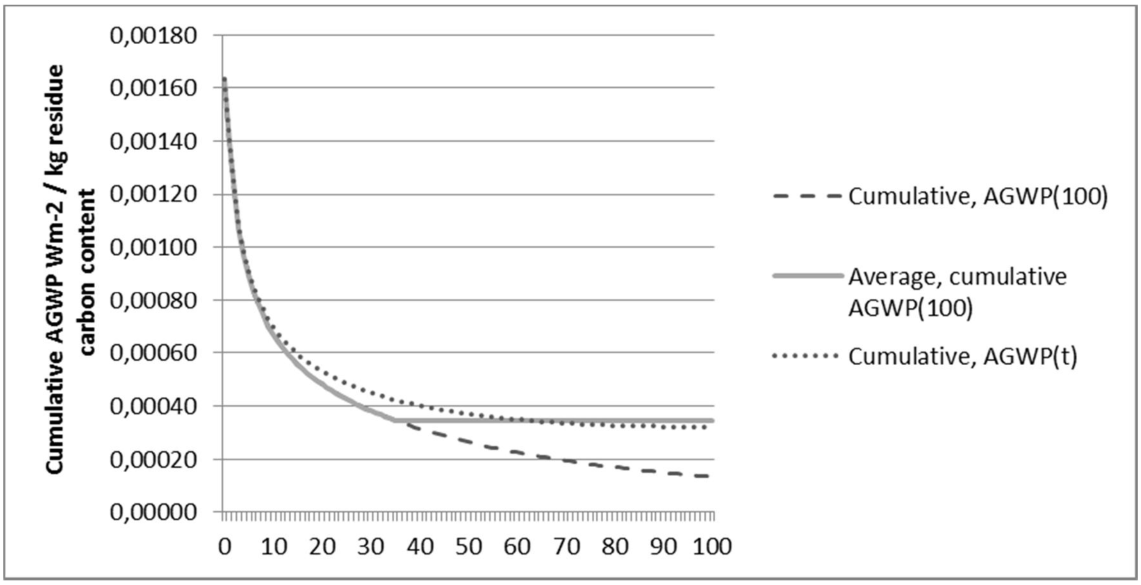

Figure 38. Time dependent, cumulative radiative forcing of forest residue utilization.

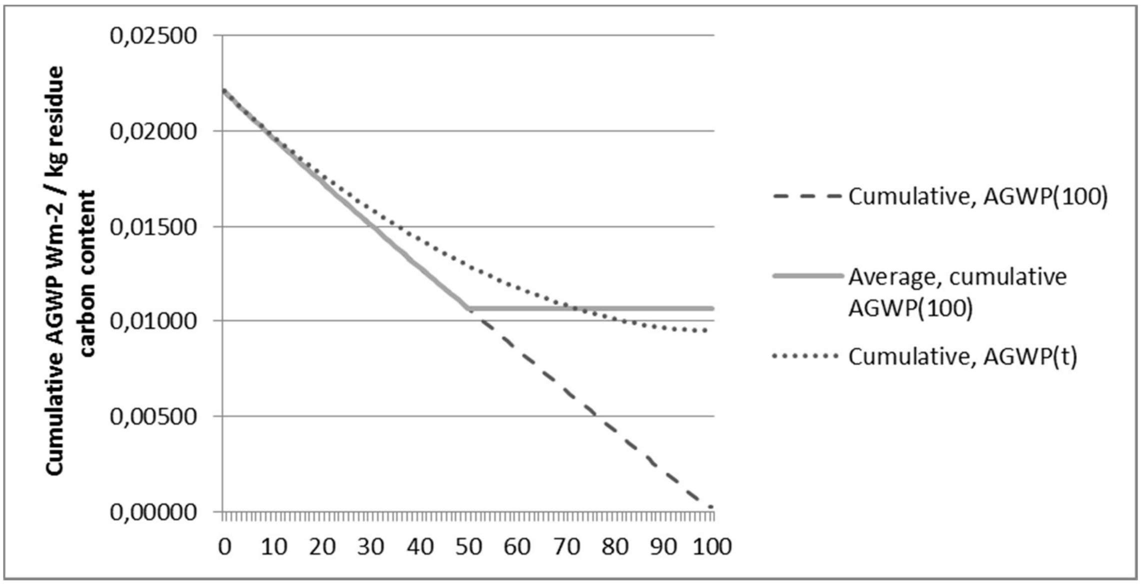

Figure 39. Time dependent, cumulative radiative forcing of forest stand utilization.

The emission profile of LUC of mineral forest soil to palm oil cultivation is presented in Figure 40 and 41 and the cumulative AGWP results in Figure 42. In Paper IV, the time averaged values for palm oil AGB carbon stock were used, and the LUC emissions were assumed to come true during the first 20 years. It can be seen from Figure 42 that the difference between the dynamic and time averaged static method results is 10.6%. If oil palm cultivation is assessed with a 25-year lifetime of oil palm stand and continuous cultivation (see Figure 42), the difference between AGWP(t) and AGWP(100) is 8.8%.

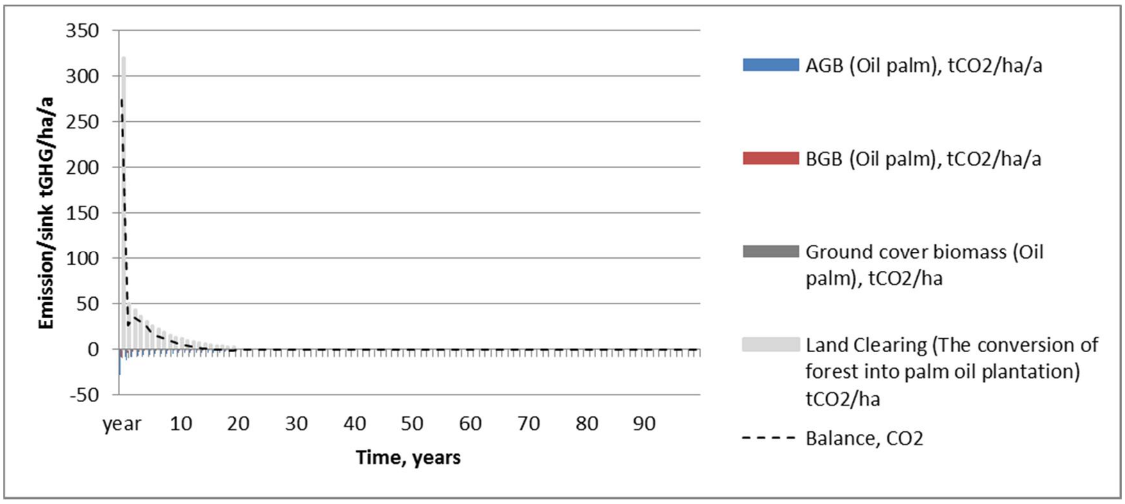

Figure 40. An emission profile of LUC emissions of land clearing and cultivation of Oil palm.

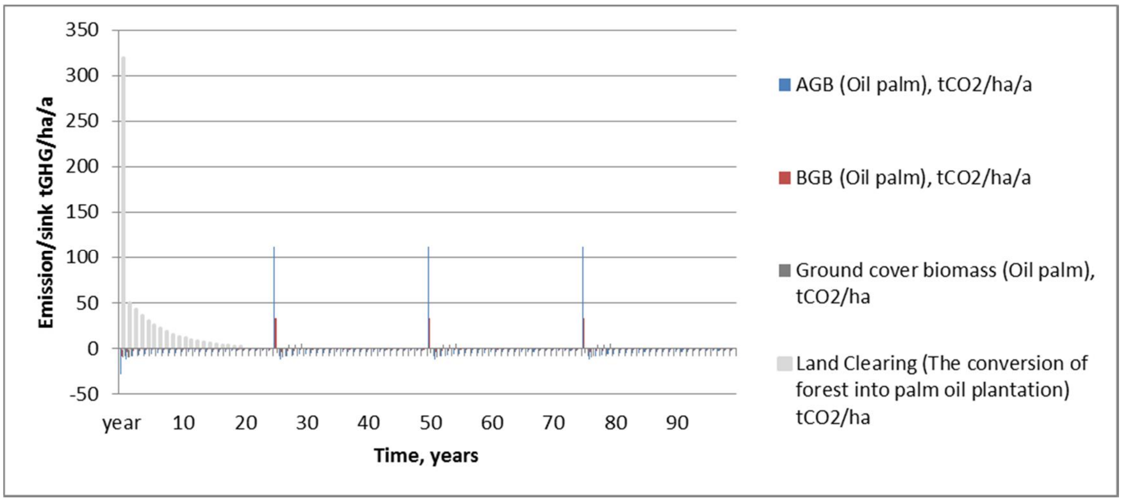

Figure 41. An emission profile of land clearing and cultivation of oil palm when the 25-year continuous cultivation cycle is used.

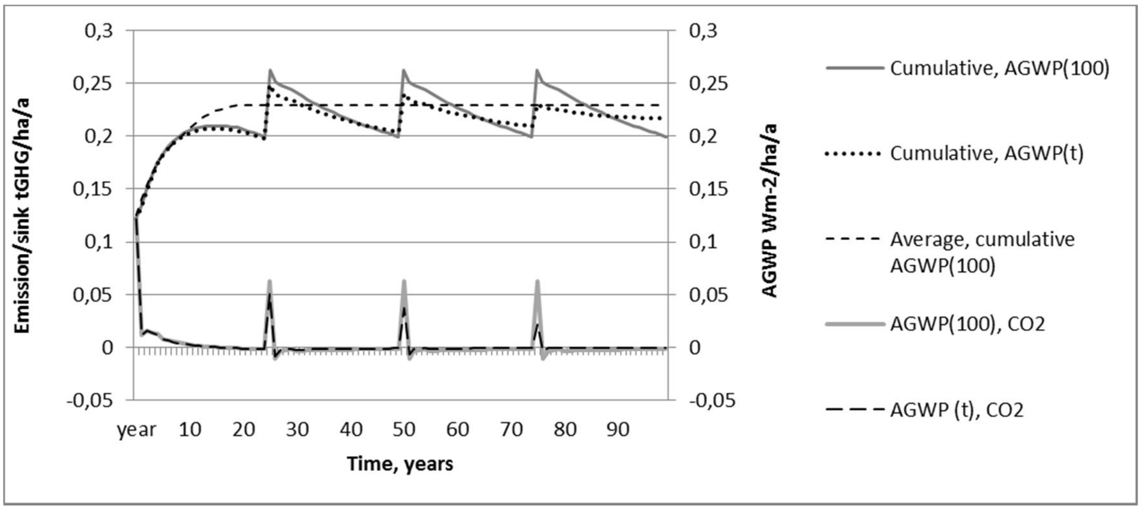

Figure 42. Time dependent, absolute and cumulative radiative forcing of converting mineral forest to palm oil cultivation. Average, cumulative AGWP(100) with single harvest, others with continuous harvest scenario.

The difference between the climate impact results of GWP(100) and time-explicit GWP(t) depends on the shape of the GHG emission profile of the studied biomass chain. The more there are emissions in the beginning of the reference time, the less the difference between these two methods affects the result. Consistently, the more there are emissions taking place at the end of the reference period, the more the results will differ. The difference is significant in the peat fuel chain because the reference peatland causes significant emissions during the entire reference period. If the GWP(100) method is used, nearly half of the global warming impact will actualize after a 100-year reference time (until year 199). Time averaged values for forest carbon stock seem to be an acceptable approximation because the difference to the GWP(t) method was only around 10%.

4.3 Comparison of results to other studies

Life cycle emissions of peat utilization in Finland have been studied recently by Kirkinen et al. (VTT Technical Research Centre of Finland, 2007; 2008; 2010b). The study focused on the GHG impact assessment of peat and peat F-T diesel production from forestry drained and cultivated peatlands when compared to the fossil references as coal and fossil diesel. The assessment uses a 100-year reference time and the dynamic impact assessment with the RRFC approach. The emissions from reference scenario peatland are accounted, and as a result, they have a strong decreasing impact on the net GHG emissions. In the study by Kirkinen et al. (2007), the GHG impact of peat from forestry drained peatlands cause nearly the same GHG impact as coal, and the GHG impact of peat from cultivated peatlands causes lower emissions. The only difference between the peat from forestry drained and cultivated peatlands is in the emissions of the reference peatland scenario. The peatland studies, presented in Papers I and II, confirm these findings that the emissions from the reference situation determine the climate impact of peat. When the parameters for forest stand growth and litter accumulation are used in the peatland model used in Papers I and II, the GWP of peat is close to the value of coal. Thus, it can be assumed that different peatland scenarios can be compared to each other either with a static or dynamic method although the absolute values differ. When the results from Paper II and Kirkinen et al. (2007) are compared, the emissions from reference peatland can affect the GHG balance of peat fuel significantly. This difference is smaller, when the dynamic LCA is used instead of the static approach, but the difference still exists. If the peat fuel emissions would be 72 g/MJ with the static method, the emissions are approximately 90.5 g/MJ when the dynamic approach is used. This means that peat from high emission areas has a GHG impact 18% smaller than coal.

Biogenic carbon impact of the utilization of biomasses for energy has been recently studied for example by Holtsmark (2012; 2013a; 2013b) and Cherubini (2011), both conlcuding that biomasses are not climate neutral sources for bioenergy systems: The climate impact of biomass combustion depends on the rotation length of the biomass species under study. For short rotation crops, the climate impact of combustion is low because the carbon released does not remain in the atmosphere for a long time before it is bound back to the growing biomass. Correspondingly, the climate impact of long rotation forests is significantly stronger, since the average lifetime of CO_2 emitted is longer (Cherubini et al., 2011). The method used by Cherubini et al. (2011) uses GWP_{bio} values, and thus, the results are easy to compare with the results presented in this study. The low importance of jatropha, oilseed rape and palm oil biomass carbon stocks in Paper IV, the medium importance of forest residue carbon stock and the high importance of forest stand biomass carbon stock in Paper III confirm the findings about the impact of the rotation length when only the impact of biomass carbon content on climate is considered.

LUC is noticed to be an important GHG, and in many cases the most important GHG emission source in many recent biofuel LCA studies (Seungdo and Dale, 2005; Hsu et al., 2010; Hennecke et al., 2012; Harsono et al., 2012). Depending on the earlier land use, the new cultivated crop and the soil carbon content, the LUC can increase or decrease the GHG emissions of the biomass utilization (Cherubini and Strømman, 2011; Grönroos et al., 2013; Harsono et al., 2012; Wicke et al., 2008). The highest emissions are released when biomass from organic land areas, e.g. peatlands or mires, is used (Grönroos et al., 2013; Harsono et al., 2012). More favorable results are obtained on degraded lands where the carbon content can be increased with new plantations (Wicke et al., 2008). The results presented in Paper IV are in line with these studies. Actually, the LUC emissions dominated the NExBTL production life cycle emissions in a way that emission reductions are not achieved with this biofuel product with any kind of feedstocks under study, if the cultivation causes forest conversion either on mineral or organic soils despite the low emissions of NExBTL process itself.

4.4 Synthesis

This section synthesizes the main research findings from Papers I-IV presented in section 4.1.

Papers I, II and IV prove that the production area has a significant impact on the GHG emissions of biomass-based fuel production. Land clearing for biomass cultivation releases carbon from vegetation and soil. In the case studies, the change in these carbon stocks caused carbon release unless the area was carbon poor or cleared earlier when the carbon binding increased with new biomass cultivation. The importance of soil emissions is especially high in peatlands, where the situation of the existing peat layer needs to be considered. The peat layer binds large amounts of carbon which potentially strains the GHG balance of biofuel production if released. The impact of peat or biomass-based fuel production on GHG emissions is especially high if the cultivation area is drained due to the peat or biomass production. In contrast, if the peatland has already been drained because of earlier forest management or other cultivation and the peat layer releases significant emissions due to peat decomposition, the peat production might reduce these emissions. The soil emissions from these land areas can be reduced by utilizing the peat layer and replacing the fossil fuels with this peat when new biomass is planted after peat harvesting on top of the reduced peat layer to bind carbon. The ranking of production areas in terms of the land use carbon stock is based on the amount of existing biomass and soil carbon, development of the soil peat layer and the carbon emissions or the carbon accumulation from peat. The GHG impact of cultivation or peat production is affected by the production impact on soil emissions and the biomass amount during the new cultivation, crop yield and need for fertilization. On a local scale, the determination of the most effective GHG emission reduction solution benefits from local, measured values because average values do not reveal the variation and impact of the site selection on the GHG balances. Thus, the local measured values are the key contributor when the locally optimal GHG emission reduction option with biomass based fuels is sought.

The production method and technology vary between the biomass feedstocks. This thesis studies direct combustion with peat, ethanol production from forest biomass and renewable diesel production from oilseed crops. In peat utilization for energy, besides the energy plant efficiency also the production method impacts the GHG emissions. In pristine peatlands, the moisture conditions enable the continuing carbon accumulation and the growth of the peat layer. The decomposition of peat in peatlands accelerates when the peat layer dries and mixes with air. Because of this, the new production method where a smaller peatland area is under production and the peat layer is harvested from the top down with a higher moisture content reduces emissions significantly when compared to the traditional method where peat is harvested with thin layers from the large areas while the sun and wind dry the peat layer until it reaches the target moisture.

With more refined biomass based fuels – renewable diesel and ethanol – GHG emissions can be reduced also from the refinery stages. Lignocellulose biomass feedstocks contain hardly decomposable lignin, and the handling of it either as a feedstock for a biofuel product or separation from the feedstock flow needs an energy consuming pretreatment processes (Paper III). This applies to all biofuel production technologies where lignocellulose material is used. The separated fractions containing lignin can be utilized in heat and electricity production if there is a suitable biomass boiler integrated into the unit (Paper III). With this integration, the heat and electricity produced from combustible fractions of pretreatment can overcome the energy need of pretreatment and produce heat and electricity for other use in the refinery, reducing the use of other fuels or even electricity for sale. Part of the emissions can be attributed to excess electricity production due to allocation rules, and as a result, the GHG emissions of the main product are reduced.

Energy integration is one of the most important factors when biofuel production GHG emissions are minimized. Biofuel production integration to the existing units, e.g. traditional forest industry with pulp production, may have also other benefits due to existing infrastructure, feedstock handling logistics and product transportation logistics.

In addition to energy, pretreatment and the following treatment processes also require chemicals. The recycling or re-use of these chemicals are important in terms of GHG emissions. Heat and electricity production is essential also with GHG emissions of renewable diesel both directly and indirectly in the production of chemicals. These emissions could be significantly reduced through transition to renewable energy utilization in the treatment stages.

Including biogenic carbon in the carbon footprint calculations of biofuels reveals the importance of the timeframe and the efficiency of the utilization of the carbon content of biomass. When the greater share of the carbon content of biomass material ends up in the final product of fuel and in this way in energy, replacing fossil carbon sources, the GHG emission impact is the smaller. Even if the renewable biomass fuels are considered to be better than fossil fuels, as they recapture the carbon content released into the atmosphere during combustion, the emissions caused can exceed the emissions from fossil fuels in the short term if the process is not sufficiently energy efficient. The benefit of a renewable carbon source is wasted with inefficient carbon economy when the rate of carbon recapture to growing biomass is made meaningless through increased carbon consumption and thus greater carbon flow into the atmosphere.

When biomass raw material is refined into biofuel, part of the energy content of biomass is lost to sideflows. In systems studied in Papers III and IV, the side flows are efficiently utilized for heat and electricity production on the site, but a great share of the production is consumed in the process itself (sideflows are used partly as energy inputs in the production). When smaller amounts of the final product and co-products are produced from the raw material, it multiplies the emission impact at the beginning of the life cycle compared to the amount of fuels and electricity produced. Emissions are increased, but the resulting output decreases, leading to a greater carbon footprint. As the GHG emissions occurring at the beginning of the fuel chain are remarkable in all the cases studied, the greatest emission impact is achieved with the most direct and energy efficient form of utilization possible.

LCA methodology itself has an impact on the GHG emission results due to allocation rules, annualization rules, and a selected reference time period and system boundaries. The selection of the allocation procedure has an impact on how great a benefit results from the side products. Depending on the situation, it might be justified to divide emissions based on some physical or economical feature, e.g. energy content or economic value, or replace other corresponding production by subtracting the replaced production emissions from emissions of the main production chain. Through replacement it is possible, in theory, to achieve a result where emission credits of side products overcome the emissions of the main production chain and the GHG impact is overruled in its entirety.

Annualized emissions and the selection of the reference period and system boundary are relevant for emissions related to land use, especially with the slowly renewable biomass feedstocks. The long-term emission impacts of annualization are directed to the feedstock based on the selected time period. Selecting the time period for which the long-term or permanent impacts in the land area carbon stock potential allocated has a great effect on the GHG emission impact of biofuel production. In this thesis, the higher extreme represents peat, which is assessed based on a 100-year reference period. The emission impact of the production and after-treatment of the peat production area during 100 years is divided by the amount of peat which is produced during the same time period from the same land area. The other extreme are the feedstocks of renewable diesel where the land use emissions are spread over 20 years of production based on directive rules. The shorter the time period used for this purpose, the higher the emissions from land use addressed to the unit of the biomass based fuel. Therefore, if the time period is reduced from 100 years, the certainty of achieving better climate mitigation potential than that of fossil fuels is possible only with biomass feedstocks that can increase the carbon binding in the land area or that can be used without impact on the land use. In practice, this applies only to regions where the natural carbon accumulation and stocks are minor or where the intensification of agriculture releases cultivation areas from food production to biomass production. On the other hand, if the reference period is increased, the emissions will be reduced and the GHG emissions of all biomasses can be assumed to fall below the GHG emissions of fossil fuel production. This emission reduction can be achieved at least if low-emission, renewable energy is utilized in the production of biomass-based fuel.

5 Discussion

When the climate impact of biomass energy is discussed, several aspects need to be considered, and the impact on carbon stocks (in organic matter of soils and biomass) compared with the replaced energy source is the key issue. In particular, the carbon emissions of biomass are problematic, and promoting renewable biomass regardless of its biogenic GHG emissions can increase global emissions in the short term. This is a problem even though the sustainable utilization of renewable energy sources is obviously a more climate friendly option than the utilization of fossil resources.

This thesis discusses the role of biogenic carbon emissions originating either from natural decomposition or for from the energy use of biomass. A carbon footprint comprises several technical aspects, and carbon stocks related to soil, forests and products are handled in different ways. The inclusion of carbon stocks in the assessments accounts for an expected gain in terms of emission savings that will be realized at a sooner or later point in time. It should be noted, however, that when biomass is cultivated, harvested and produced for energy, emissions from soils and biomass stocks can offset the emission reductions which may be achieved when fossil resources are replaced with renewables.

This thesis studied the utilization of peat, forest biomass and certain cultivated biomasses in electricity, heat or biofuel production. The aim was to define the size of the impact on the life cycle emissions of peat utilization when the peat production was directed to high-emission peatland areas. High-emission peatlands were selected to demonstrate the significance of the original peatland emission level for the GHG emissions. It is very important to note that all *Herb-rich type* and *Vaccinium Myrtillus* types are not high-emission peatlands. Overall, the results of the thesis suggest that GHG emissions could be reduced through the utilization of peat instead of fossil fuels if the peatlands selected for this purpose feature sufficiently high soil emissions.

According to the results, the carbon storage impact of forests significantly affects the emission values of all of the studied fuels and can offset the emission savings of biofuel products studied in this thesis. It should be noted that the continuing carbon uptake in the forest in the case of non-utilization was not included in the study when the loss of forest carbon was compared with the carbon content of the forest stand before the final felling. In the case of a managed forest, it was assumed that the carbon sequestration did not significantly increase after 100 years and that pristine ecosystems were in a balanced state. This approach constitutes a simplification of reality. Still, it clearly demonstrates the need for a careful consideration of all the aspects related to the use of biomass with the aim of reducing global GHG emissions. The inclusion of biogenic carbon in the scope of the study revealed the importance of the source of the biomass used: residue-based sources, for which carbon would be released in any case within a short time period, have a smaller GHG impact than biomass sources that bind carbon for a longer period of time.

The selection of the boundaries for forest growth dynamics may have significant impacts on the emission dynamics. There are at least two different levels that can be assessed: stand level which is used in this study and a landscape level, in which larger forest areas with multitude stands of different ages exist. On the stand level, the carbon stock will cycle periodically for any reference time, rising due to the regeneration and growth and falling with periodic harvest removals. On the landscape level, only a fraction of these stands is harvested during the selected time period, and the majority of the area is under the growing stage, compensating the carbon loss in other areas, and the carbon balance is fairly stable. Common for both approaches is that the harvest is releasing carbon from the forest stand in similar amounts but the difference is found from the representation. On the stand level, the released carbon is simple to be pointed out because the compensation from near-by areas is not included in the carbon balance. On the other hand on the landscape level, the released carbon is covered with new growth in other stands, when with sustainable forest management the carbon balance between release and growth can be balanced. With the stand level approach it can be estimated, what is the carbon balance impact of harvesting a forest stand. The landscape level approach is valuable, when the renewability of forest management is under focus. In this study, the stand level approach has been used. When the carbon stock cycle is balanced with time averaged values there should not be difference between the stand level and landscape level approach because in both cases, the values present the average carbon stock values of the area under study, and the size of the area should not impact on the result if both are managed with a sustainable manner. If the stand level approach is used without averaging the annual values or taking the timing of release on growth considered with other methods, the carbon stock effect is overestimated when compared to the landscape level because the temporal release during the time period is not taken into account.

The possibility to utilize peat and forest biomass offers at clear benefit for Finland in achieving the energy and emission targets of the European Union. Forest biomass cannot be used for nutritional purposes, and therefore, it is not in direct competition with food crop cultivation in land use. Wood combustion does not cause carbon dioxide emissions accounted for in National Inventories because of the rule of carbon neutrality which states that the effect on the forest carbon stock is not considered as long as stocks are not decreasing at the national level. By using wood-based fuels, significant emission reductions can be achieved through the replacement of fossil fuels.

The GHG emissions of biomass-based fuels are not irrelevant for the biomass business. The climate change mitigation efforts have opened up new business opportunities for companies that can produce low-carbon fuels for the market. Deriving the maximum advantage from the feedstock and energy efficiency is positive for business and there are mutual benefits if processes and biomass cultivation can be developed towards lower emissions. Biofuel operators can refine their business with LCA and decrease the environmental risks related to their products. The demand for low carbon fuels is expected to increase once the mandatory regulations come into effect. Public opinion and evolving legislation keep companies on their guard and far-sighted firms are selecting the feedstocks for production on the basis of sustainability to maximize the chance for production to remain acceptable in the future. An active environmental strategy strives to be a step ahead of that of the competitors. Assessments carried out in the local operational environment may reveal a multitude of options and therefore remarkable development opportunities for business. For example, an assessment of local peatland emissions clarifies the impact of peatland selection. Utilizing LCA helps to reveal the potential risks related to biofuel GHG emissions and to choose the most optimal feedstocks for the production of biofuels – also in the future.

The reduction of GHG emissions with cost effective measures is an essential issue related to climate change mitigation, and research is needed to find these measures. On the one hand, climate mitigation and adaptation causes costs in the short term. On the other hand, it is estimated that the costs of action – reducing GHG emissions to avoid the adverse, long-term consequences of climate change – are lower than the expected costs of climate change in the case no action is taken to mitigate it (Stern Review Report, 2006). In economic terms, it is also important to consider different mitigation options in a wider perspective to find the most cost-effective and politically realistic ways to reduce GHG emissions. To achieve the collective goals, policy tools are needed to steer actions towards a more sustainable direction.

The political decisions can speak for the reduction of GHG emissions. The policy can have an effect on the demand and the availability of biofuels. Electricity, heat and biofuel production from renewables often requires higher investments than from fossil sources, and this price difference needs to be compensated with policy measures that support bioenergy. The transition to renewable fuels results in costs to the community, and emission reductions have a price. More discussion is also needed to assess the true GHG reduction potential what can be achieved with biomass use including the impact of land use.

The use of different types of biomass for electricity, heat and biofuel production is promoted with feed-in tariffs (Germany, France), obligatory shares of bio-based production (electricity in the United States, the United Kingdom, transport in the European Union) and tax exemptions. The ultimate aim of these measures is to reduce production costs by increasing the production volumes.

Companies may also reach added value for business from the reduction of GHG emissions. Increasing environmental consciousness may reflect for example on the taxation policy and consumption behavior, and the public image has become ever more important in trading. Taking into account the environmental attributes of the production field and the life cycle, companies will be able to direct their production towards maximum GHG reduction with minimal costs and reduced risks. Processing biomasses into fuel products instead of direct combustion reduces the energy efficiency of biomass utilization and leads to higher emissions per the unit of energy product produced. Direct biomass combustion for electricity production would be more energy efficient and would thus reduce emissions more than refining biofuels for transport. Unfortunately, there will be no other applicable substitute for fossil fuels in transport in the near future. Wide use of electricity in transport requires the renewal of the car fleet and the further development of rechargeable battery technology and power grids. Also constructing the biofuel production plants in a needed scale takes time, but needed technology exists and the existing distribution network can be utilized. Until the barriers to more efficient transport are tackled, biofuels will continue to play a significant role in the transition from a fossil fuel economy to a more sustainable way of living. However, taking into consideration the prevailing threat of climate change, it is conceivable that biofuels might not yet constitute the final solution for mankind.

6 Conclusion

Despite the uncertainties in carbon stocks and the rates of growth and decay, the largest GHG emissions related to the use of biofuels result from the biomass itself because of the significant amount of carbon it holds. The impact of the biomass carbon stock change depends on how the biomass stock changes during utilization compared to the situation at the beginning. The utilization of forests for biofuel production results in a discharge of carbon stock, the size of the emission depending on how permanent the change is assumed to be. Clearing forests for cultivation releases nearly all of the biomass accumulated in the forest. This is how the largest amounts of carbon are released, in part because tree biomass contains much more carbon than crop biomass. This effect is not only limited to situations in which LUC takes place – even the biomass carbon stock of a forest remaining as a forest may have a significant impact on the balance when the GHG emission impact of the biomass carbon content is assessed (Paper III). When LUC is not the issue, the biomass-related carbon stock reduction is relatively simple to assess on the basis of harvested biomass amounts, the carbon content of these fractions, and the predictions of the time needed to grow a corresponding amount of new biomass. The system becomes much more complex if the ecosystem is adopted for agricultural use or if soil emissions need to be included in the study. In such cases, accurate results are obtainable only with site-specific measurements.

Soil emissions resulting from biomass cultivation and harvesting matter the most in peatlands and other organic lands which contain large amounts of carbon (Papers I, II and IV). The drainage of the peat layer increases the CO_2 emissions from the soil. It is possible to decrease these emissions in areas where the peat layer is already in a draining stage due to forestry use. This assumption is valid only for drained high-emission peatlands – the draining of pristine peatlands generates additional emissions which increase the total emissions attributable to the biofuels produced in these lands. The type of the peatland thus determines the potential to decrease the peat-related emissions. In addition, because the soil emissions during peat production are significant, also the choice of harvesting method can markedly impact the amount of emissions (Paper II).

Even if the land use and the carbon content of biomass stocks are the most important factors in the biofuel GHG balance, other life cycle stages should not be forgotten. GHG aspects need to be integrated into biomass utilization throughout the life cycle of biomass-based fuels. The energy consumption of the biomass chain should be minimized and the production of the main product and co-product maximized. The need for fertilizers and the productivity of different raw materials have an impact on the biofuel GHG balance. These can be optimized by selecting the right plants for the right places to achieve the best biomass or crop yield with minimum effort. The literature review indicates that there also exists a potential for improving the GHG emission performance of biomass conversion processes. In processing, the utilization of sideflows – either internally for heat and electricity production or for producing co-products with credits or allocation benefits – reduces the emissions attributable to the main product. During the use phase, the maximum reduction is achieved by replacing the high-emission fossil energy with sources that have the best efficiency.

The inclusion of biogenic carbon sources and land use emissions increases the importance of efficient biomass use. The traditional grouping of biomass sources into renewable and non-renewable energy sources with the notion that the utilization of the former is carbon neutral may lead to an inefficient use of biomass resources and suboptimal GHG emission mitigation policies. When the biogenic carbon and soil emissions are included, the differences between the emissions of renewable biomass and non-renewable biomass GHG impact decrease. The holistic consideration of all of the relevant aspects may result in a situation where the inefficient conversion of renewable biomass into energy causes higher emissions than that of non-renewable biomass. Therefore, GHG emissions related to biomass-based electricity, heat or biofuel production should always be assessed with life cycle studies which take biogenic carbon and possible LUC emissions into account. Globally, effective climate change mitigation requires additional research to assess and locate the potential LUC impacts of biofuel production and to estimate the sustainable levels of biofuel production.

This thesis consists of four independent research papers which study the GHG emission impact of various biomass-based fuels during their life cycle by applying the principles of LCA methodology. Despite the uncertainties related to biomass carbon stocks, the largest GHG emissions are related to the beginning of the biomass-based fuel production chain: establishing the cultivation and the temporary or longer-lasting decrease of the initial carbon stock level. The effective mitigation of climate change with biomass-based fuels requires that more attention be paid to the origin of the feedstocks for fuel production, with the aim of using feedstocks which have the least impact in terms of GHG emissions. According to the results of this thesis, biomass types with potential for increasing the carbon stocks of the soil have the smallest cultivation and LUC impacts. These are followed by waste and residual biomass, which do not require a land area for production. Biomass types which do not require LUC, i.e. ones growing on existing available cultivated areas or managed forests, are in the third place.

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