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THE EFFECTS OF LOCATION, FEEDSTOCK AVAILABILITY, AND SUPPLY-CHAIN LOGISTICS ON THE GREENHOUSE GAS EMISSIONS OF FOREST-BIOMASS ENERGY UTILIZATION IN FINLAND

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium of Mikkeli University Consortium, Mikkeli, Finland on the 4 th of October, 2013, at noon.

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ABSTRACT

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The effects of location, feedstock availability, and supply-chain logistics on the greenhouse gas emissions of forest-biomass energy utilization in Finland

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Forest biomass represents a geographically distributed feedstock, and geographical location affects the greenhouse gas (GHG) performance of a given forest-bioenergy system in several ways. For example, biomass availability, forest operations, transportation possibilities and the distances involved, biomass end-use possibilities, fossil reference systems, and forest carbon balances all depend to some extent on location. The overall objective of this thesis was to assess the GHG emissions derived from supply and energy-utilization chains of forest biomass in Finland, with a specific focus on the effect of location in relation to forest biomass's availability and the transportation possibilities. Biomass availability and transportation-network assessments were conducted through utilization of geographical information system methods, and the GHG emissions were assessed by means of lifecycle assessment. The thesis is based on four papers in which forest biomass supply on industrial scale was assessed. The feedstocks assessed in this thesis include harvesting residues, small-diameter energy wood and stumps. The principal implication of the findings in this thesis is that in Finland, the location and availability of biomass in the proximity of a given energy-utilization or energy-conversion plant is not a decisive factor in supply-chain GHG emissions or the possible GHG savings to be achieved with forest-biomass energy use. Therefore, for the greatest GHG reductions with limited forest-biomass resources, energy utilization of forest biomass in Finland should be directed to the locations where most GHG savings are achieved through replacement of fossil fuels. Furthermore, one should prioritize the types of forest biomass with the lowest direct supply-chain GHG emissions (e.g., from transport and comminution) and the lowest indirect ones (in particular, soil carbon-stock losses), regardless of location. In this respect, the best combination is to use harvesting residues in combined heat and power production, replacing peat or coal.

Keywords: Geographical Information System (GIS), Life Cycle Assessment (LCA), transportation, Greenhouse Gases (GHGs), logistics

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Mikkeli, September 2013

Eero Jäppinen

ABBREVIATIONS, UNITS, CONVERSION FACTORS AND PREFIXES WITH EXPONENT VALUES

Abbreviations

CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
EC	European Commission
EU	European Union
EW	small-diameter energy wood
GHG	greenhouse gas
GIS	Geographic information systems
GWP	global warming potential
HR	harvesting residues
LCA	Life-cycle assessment
N_2O	nitrous oxide
RED	Renewable Energy Directive of the European Union
ST	stumps

Units

%	percent
h	hours
J	joules
m	meters
m^3	cubic meters
t	metric tons
W	watts
yr (yrs)	year (years)

Conversion Factors

1 Wh = 3600 J

$1m^3_{solid} = 2.5\ m^3_{loose}$ (for comminuted forest biomass)

Prefixes and their exponent values

k	kilo, 10^3
M	mega, 10^6
G	giga, 10^9
T	tera, 10^{12}
P	peta, 10^{15}
E	exa, 10^{18}

LIST OF ORIGINAL ARTICLES

This thesis is based on the original papers listed below, which are referred to in the text by the Roman numerals given here. These papers are reprinted with the permission of the publisher.

I Jäppinen E, Korpinen O-J, Ranta T (2011). Effects of Local Biomass Availability and Road Network Properties on the Greenhouse Gas Emissions of Biomass Supply Chain. ISRN Renewable Energy, Volume 2011, Article ID 189734, 6 p.

II Jäppinen E, Korpinen O-J, Ranta T (2013). The Effects of Local Biomass Availability and Possibilities for Truck and Train Transportation on the Greenhouse Gas Emissions of a Small-Diameter Energy Wood Supply Chain. Bioenergy Research, Volume 6:166–177.

III Jäppinen E, Korpinen O-J, Ranta T (2013). GHG Emissions of Forest-Biomass Supply Chains to Commercial-Scale Liquid-Biofuel Production Plants in Finland (2013). GCB Bioenergy, published online 18 February 2013.

IV Jäppinen E, Korpinen O-J, Laitila J, Ranta T (2013). Greenhouse Gas Emissions of Forest Bioenergy Supply and Utilization in Finland. Manuscript accepted for publication in Renewable & Sustainable Energy Reviews, 24 August 2013.

The author is the main author of the work and fully responsible for the text, calculations, data analyses, and study settings of all papers and this doctoral thesis. Co-author Olli-Jussi Korpinen (papers I–IV) provided expertise for the GIS assessments and created the software geoprocessing model used in the GIS assessments. Co-author Juha Laitila (Paper IV) provided data on forest operations. Co-author Tapio Ranta (papers I–IV) commented on the manuscripts and was the supervisor of the thesis research.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

In 1997, as part of efforts to mitigate anthropogenic climate change, the Kyoto Protocol set binding greenhouse gas (GHG) reduction targets for 37 industrialized countries and the European Community (United Nations 1998). The collective GHG-emission reduction commitment of the European Union (EU) members was 8% by the years 2008–2012 relative to their combined GHG-emission levels in 1990 (United Nations 1998). For Finland, as a member of the EU, the national emission reduction target was 0% relative to the emissions in 1990 (Official Journal of the European Communities 2002). Currently, it seems that both the EU-wide target levels and the national targets of Finland have been reached[1] (European Environment Agency 2012).

After the first GHG-reduction commitment period, 2008–2012, the EU is further committed to reductions in GHG emissions between 2013 and 2020 such that the collective GHG emissions over this eight-year period are, on average, 20% lower than those in 1990 (European Union 2012). Furthermore, the EU is ready to commit to 30% reductions if other major economies reach a comprehensive international agreement on GHG-reduction efforts (European Commission 2010a). In 2009, as a key part of the EU's climate policies, the European Commission (EC) introduced the Renewable Energy Directive (EU RED) (European Commission 2009), which set binding national targets for renewable-energy use by 2020 for each EU member state. For Finland, the target is a 38% share of renewable energy in final consumption and a 10% share in transport, to which Finland is committed through the national Climate and Energy Strategy (Finnish Government 2013a). Finland has even set its own national target of 20%[2] for transportation (Ministry of Employment and the Economy 2011a, 2013a).

With regard to international climate policies, energy produced with biomass-based fuels (i.e., bioenergy) is considered carbon-neutral and renewable (UNFCC 2006), and biomass-based energy is expected to play a key role on international, EU, and national level in climate-

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[1] Final data are not yet available for the full five-year period at the time of writing.

[2] Taking into account double-counting of biofuels produced from waste of various types, residues, nonfood cellulosic material, and lignocellulosic material (European Commission 2009).

change mitigation (IEA 2012, European Commission 2011, Finnish Government 2013a). In Finnish renewable-energy policies, forest-based bioenergy has been identified as the most significant and cost-efficient way of increasing the proportion of renewable energy in Finland (Finnish Government 2013a).

In addition to introducing targets for the share of renewable energy, the EU RED set forth binding criteria for GHG savings with biofuels and bioliquids[3], to ensure that the production and use of biomass-based fuels actually reduces GHG emissions. In 2010, the European Commission further recommended that the Member States introduce requirements in their national sustainability programs for solid and gaseous biomasses[4], as utilized in the power-plant sector, that are similar to those laid down in the EU RED for liquid biofuels (European Commission 2010b). These GHG savings requirements include 35% savings in comparison to EU-wide fossil-fuel comparator[5] values, and they will become stricter, reaching a requirement of 50% in 2017 and 60% savings in 2018 for new installations. The Finnish Government has also proposed that the EU's sustainability requirements be introduced in the national legislation of Finland (Finnish Government 2013b), with the associated national act on sustainability of biofuels and bioliquids due to come into force in July 2013 (Ministry of Employment and the Economy 2013).

1.2 Forest-biomass energy use and potential

In 2010, global primary energy demand was approximately 530 EJ, with bioenergy accounting for approximately 10% of this. The figure includes biomass- and waste-based energy. Traditional noncommercial bioenergy, used mainly for cooking and heating in developing countries, accounted for 59% of total biomass energy use. The proportion of

[3] "Biofuels" refers to liquid or gaseous fuel for transport that is produced from biomass, and "bioliquids" denotes biomass-derived liquid fuel for energy purposes other than for transport, including electricity and heating and cooling (European Commission 2009).

[4] "Solid and gaseous biomasses" refers to raw materials originating from agricultural crops and residues from forestry, the wood-processing industries, and organic waste (European Commission 2010).

[5] Key fossil-fuel EU comparator values relevant for purposes of this thesis are as follows (European Commission 2009 and 2010). Electricity 198 $gCO_2eq\ MJ^{-1}$. Heat produced with solid or gaseous biomasses 87 $gCO_2eq\ MJ^{-1}$. Bioliquids used in heat production 77 $gCO_2eq\ MJ^{-1}$. Biodiesel replacing fossil diesel in transport 83.8 $gCO_2eq\ MJ^{-1}$.

traditional bioenergy use is, however, expected to decline, while demand for bioenergy in other sectors is expected to more than double from the current use of 22 EJ to 50 EJ by 2035, largely driven by international and government renewable-energy policies (IEA 2012).

Various terms, such as "forest energy", "forest biomass", "forest chips", "forest residues", "woodfuel", "fuelwood", "energy wood", "forest bioenergy", "forest fuels", and "modern fuel wood" are used in both the literature and spoken language to describe the same type of biomass feedstock for energy production. In this thesis, the term "forest biomass" means byproducts of forest operations conducted on "forest land remaining forest land[6]" (IPCC 2006), with the main aim being to produce higher-value material – i.e., saw or veneer logs and pulpwood. This represents the current situation in Finland, wherein direct or indirect land-use change is not associated with forest-biomass use and in which forest-biomass supply is integrated with either industrial roundwood procurement or forest-management practices. The categories of forest biomass assessed in this thesis include harvesting residues, stumps, and small-diameter energy wood (HR, ST, and EW, respectively). The types of forest biomass assessed in this thesis can also be categorized as "primary forest residues[7]" (Nabuurs et al. 2007).

The global potential of forest residues generated from forest fellings in 2005 is approximately 5 EJ[8], with the most promising regions being the USA and Canada, Central and Northern Europe, Russia, East Asia, Brazil, and Chile (Anttila et al. 2009a). The use of forest residues is, however, significantly lower than the potential. It has been estimated that annually approximately 1 EJ of energy is generated from forest residues (Sims et al. 2007). This leads to a rough estimate that 0.2% of global primary energy demand is now met with forest residues.

"Realizable" forest residue potential in the EU has been estimated at 0.9 EJ a year; this includes logging residues, stumps, and small-diameter energy wood (Verkerk et al. 2011). This estimate of "realizable" potential, by Verkerk et al. (2011), takes into account several technical,

[6] Forest land remaining forest land means managed forests that have been under forest land for over 20 years, or for over a country specific transition period (IPCC 2006). Land-use change is no t associated with biomass procurement from forest land remaining forest land.

[7] In (Nabuurs et al. 2007) three main categories of forest residues that may be used for energy purposes have been defined: primary residues (available from additional stemwood fellings or as residues (branches) from thinning salvage after natural disturbances or final fellings); secondary residues (available from processing forest products) and tertiary residues (available after end use).

[8] Stumps and small-diameter energy wood were not included in this potential, since their contribution was assumed to be marginal at the global level (Anttila et al. 2009a).

environmental, and social constraints, which makes it more realistic than figures for potential based only on annual forest growth. Another EU-level estimate at this level (0.7 EJ, including felling residues and stumps) has been presented by Asikainen et al. (2008). The actual use of forest residues has been estimated as having accounted for 0.35 EJ in the EU-24 plus Norway in 2006 (Junginger et al. 2010). It should be noted that the global and EU-level estimates stated for forest-residue potentials and use ("forest biomass" in this thesis) are only rough estimates and depend on various assumptions and the estimation methods used (Anttila et al. 2009a, Torén et al. 2011).

In recent years, several estimates of the potential of forest biomass for energy purposes in Finland have been presented (Helynen et al. 2007, Laitila et al. 2008, Kärhä et al. 2010, Salminen et al. 2010). The estimates of potential, falling within the range 0.09–0.15 EJ, depend on the methods used and on various parameters. This range represents the potential that could be utilized in view of various technical, environmental, and economic constraints. In 2012 the total use of forest biomass (harvesting residues, stumps, and small-diameter energy wood) for energy production in Finland was 0.06 EJ (Finnish Forest Research Institute 2013a).

With respect to estimation of forest-biomass potential in general, it should be noted that all estimates involve various and case-dependent assumptions. Four categories of potential can be distinguished: 1) theoretical potential, a maximum value limited by factors such as the physical or biological barriers that, given the current state of science, cannot be altered; 2) technical potential, limited by the technology used and the natural circumstances; 3) economic potential, the technical potential that can be met at economically profitable levels; and 4) ecological potential, which takes into account ecological criteria, such as soil erosion and loss of biodiversity (EUBIA 2012). Most estimates of potential feature characteristics from two or more of these four classes and thus represent "techno-ecological" or "techno-economic" potential – e.g., potential as presented by Kärhä et al. (2010) and Ranta et al. (2007).

1.3 Current and future demand for forest biomass in Finland

In 2011, 87% of the total use of 50 PJ[9] of forest biomass (HR, EW, and ST) in Finland was by power and heating plants and 13% by small-sized dwellings, most of them farms. Most of the forest biomass in Finland is used in combined heat and power (CHP) plants, producing energy for communities or industry, or, in many cases, both (Laitila et al. 2010, Kärhä et al. 2010). The type of forest biomass used most in the power and heating sector was EW, with a 49% share, followed by HR and ST, with 36% and 15%, respectively. Since 2000, Finland's total use of EW, HR, and ST for energy has increased almost sevenfold (Finnish Forest Research Institute 2013a).

In the National Forest Program, the target for forest-biomass energy use in 2015 has been set at 72–86 PJ[10] (Ministry of Agriculture and Forestry 2011), whereas the target set by the Finnish Government is 90 PJ in the heat and power sector by 2020 (Ministry of Employment and the Economy 2010, Finnish Government 2013a). The most significant increase in forest-biomass energy use is expected to come from replacement of peat in multifuel boilers and from substitution for coal in coal-fired boilers (Finnish Government 2013b). In addition to the heat and power sector, the demand for forest biomass in Finland may grow because of production of so-called second-generation liquid biofuels (Heinimö et al. 2011, Ministry of Employment and the Economy 2011b). A commercial-scale liquid-biofuel production plant could consume approximately 14 PJ yr^{-1} of forest biomass (UPM-Kymmene Oyj 2011, Metsäliitto 2011, Stora Enso Oyj 2010). However, because only one such plant in Finland was awarded funding by the EC in 2012, with that plant currently expected to commence operation in late 2016 (European Commission 2012), it can be assumed that the growth in biomass demand over the next few years will come mainly from the heat and power sector. The future is also expected to see significant growth in internationally traded volumes of biomass (Bahadur Magar et al. 2011, Heinimö 2011), which may result in export of forest biomass from Finland and further increase in demand for forest biomass.

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[9] Large and rotten roundwood unsuitable as raw material for the forest industry is not included in this figure, because it is not covered by the assessments in this thesis. Its use by the power and heating sector represented 7% of total forest-biomass use in Finland in 2011 (Finnish Forest Research Institute 2012).

[10] Converted from wood-use volumes on the following assumption: 1 million m^3 = 7.2 PJ.

1.4 The motivation for the work

Given that forest biomass is going to play an increasingly important role in energy production on national, European, and global level, the issues of resource-use efficiency in relation to climate-change mitigation and GHG emissions derived from forest-biomass supply and utilization need to be addressed accordingly. Forest biomass from natural forests represents a geographically distributed feedstock, and geographical location affects the GHG performance of a given forest-bioenergy system in several ways. For example, biomass availability, forest operations, transportation possibilities and the distances involved, biomass end-use possibilities, fossil reference systems, and forest carbon balances all depend to some extent on location. Furthermore, if demand for forest biomass grows as expected, it will lead to growing imbalance between demand points and supply areas on international, national, and even regional level (Tahvanainen and Anttila 2011, Ranta et al. 2007, Korpinen et al. 2012, Ranta 2005, Anttila et al. 2013), which, in turn, will result in longer feedstock transportation distances and more GHG emissions.

Location-specific information has been used in many studies examining forest-biomass availability, supply costs, and logistics in Finland and in the Nordic region, such as the work of Tahvanainen and Anttila (2011), Rørstad et al. (2010), Ranta (2005), Nord-Lasen and Talbot (2004), and Korpinen et al. (2013). Also, the GHG emissions related to forest-biomass supply and energy utilization in Nordic conditions have been addressed in many studies, such as those of Lindholm et al. (2010), Gustavsson et al. (2011), Repo et al. (2012), Valente et al. (2011), and Wihersaari (2005). However, the author of this thesis is not aware of previous published research addressing GHG emissions of forest-biomass supply and utilization in a similar – location-specific – manner in Finland.

The main motivation behind this work was the need for information on how, and to what extent, the location of a demand point, local biomass availability, and transportation possibilities affect the GHG emissions derived from forest-biomass supply and energy-utilization chains in Finland. A further question is how important these emissions are in relation to the GHG savings that may be possible with use of biomass energy. Another motive was desire to introduce a novel way of utilizing geographically specific data in GHG-emission assessment of bioenergy systems.

1.5 Outline of the thesis

1.5.1 Objective

The overall objective of this thesis was to assess the GHG emissions derived from supply and energy-utilization chains of forest biomass in Finland, with a specific focus on the effect of location in relation to forest biomass's availability and the transportation possibilities.
The main research questions of this thesis are these:

1) To what extent does the location of the biomass end user affect the GHG emissions arising from the forest biomass supply chain in Finnish conditions, in terms of gCO_2eq MJ^{-1} of comminuted forest biomass delivered to the end user?
2) What is the effect of any location-dependent differences in GHG emissions of feedstock supply chain to end user locations in Finland on the possible GHG reductions achieved with forest-biomass-based energy production?

The main hypothesis adopted for this thesis project is that there are location-dependent differences in GHG emissions but these differences are not decisive in terms of possible GHG reductions achieved with forest-biomass use. A sub-hypothesis is that the location-dependent differences in emissions generated through forest-biomass supply can be compensated for through logistical choices – for example, utilization of railway transportation from distant supply areas.
The thesis focuses on forest-biomass supply on the scale typical for CHP plants in Finland (in papers I and II) and the possible scale of supply of a commercial-scale liquid-biofuel production plant (in Paper III). The approach of Paper IV is not tied to the scale of supply, but the end-use possibilities assessed in Paper IV represent industrial scale. Therefore, the results stated in this thesis do not accurately represent supply and utilization situations for small-scale users of forest biomass, such as housing or small heating networks, because in smaller-scale applications the supply areas are smaller and the machinery used in the supply chain and energy-production equipment may differ significantly from those on which the assessments in this thesis are based.

1.5.2 The papers included

The thesis is based on four papers, briefly described thus:

Paper I: The Effects of Local Biomass Availability and Road Network Properties on the Greenhouse Gas Emissions of Biomass Supply Chain

Paper I deals with a rather limited forest-biomass supply of 360 TJ yr^{-1} (100 GWh yr^{-1}) and focuses on the method of assessing the effects of local biomass availability along with the effects of road network properties. In Paper I, two case studies of comminuted EW supply to CHP plant locations are presented, one in northern Finland (Rovaniemi) and one in southern Finland (Mikkeli). Since the only transportation method assessed in this study is truck-based transportation, the focus is on the differences in the GHG emissions of transportation between the two case-study locations. The scale of supply represents a large CHP plant.

Research question for Paper I: What are the effects of local biomass availability and road network properties on the GHG emissions of forest-biomass transportation to CHP plants in Northern and Southern Finland when the amount supplied is 360 TJ yr^{-1}?

Paper II: The Effects of Local Biomass Availability and Possibilities for Truck and Train Transportation on the Greenhouse Gas Emissions of a Small-Diameter Energy Wood Supply Chain

Paper II continues on this subject and with the same two locations as Paper I but with a larger supply, of 720 TJ yr^{-1} (200 GWh yr^{-1}). In Paper II, also assessed are the possibilities for using railway transportation from distant supply areas with two possible arrangements of comminution (in roadside storage or at railway loading locations). Similarly to Paper I, Paper II presents a supply scenario for comminuted EW to two CHP plant locations, Mikkeli and Rovaniemi. In addition to the emissions from transportation, the assessments include comminution and loading operations. The scale of supply represents a large CHP plant.

Research questions for Paper II: What are the effects of local biomass availability and road network properties on the GHG emissions of forest-biomass supply to CHP plants in Northern and Southern Finland when the amount supplied is 720 TJ yr^{-1}? Can these emissions be reduced through the use of railway transportation? If transportation by rail is utilized, should the feedstock be chipped at roadside storage locations or, instead, at railway loading locations?

Paper III: GHG Emissions of Forest-Biomass Supply Chains to Commercial-Scale Liquid-Biofuel Production Plants in Finland

Paper III continues on the same topic as papers I and II but considers a greater supply, 7.2 PJ yr^{-1}, and different case-study locations. The case studies assessed in Paper III represent supply situations for three possible commercial-scale liquid-biofuel plants on the Finnish coast: Porvoo and Rauma, in southern Finland, and Kemi, in northern Finland. Possibilities for train transportation are assessed with multiple logistics scenarios. The supply scale represents possible demand for this type of forest biomass from domestic sources for a commercial-scale liquid-biofuel production plant.

Research questions for Paper III: What are the GHG emissions derived from the supply of 7.2 PJ yr^{-1} of biomass to three possible liquid-biofuel plant locations in Finland? How much can these emissions be reduced through railway transportation from distant supply areas?

Paper IV: Greenhouse Gas Emissions of Forest Bioenergy Supply and Utilization in Finland

Paper IV assesses the effects of geographical location on the GHG balance of forest-biomass supply and utilization in a wider context. While the first three papers focus on biomass availability and long-distance transportation by truck (addressed in all three papers) and train (papers II and III), Paper IV covers all parts of the supply chain of forest biomass from forest operations to the comminuted feedstock ready for use for energy purposes. Furthermore, in addition to the GHG emissions of the supply chain, Paper IV assesses various possibilities for utilization of the feedstock in Finland and possible GHG-emission reductions that may be achieved.

Research questions for Paper IV: What are the GHG emissions of the most typical supply chains for HR, ST, and EW in Finland, with all parts of the supply chain taken into account? What GHG reductions, if any, might be achieved with various utilization systems? How do the GHG emissions differ between Northern and Southern Finland?

2. MATERIALS AND METHODS

2.1 Data on forest-biomass potential

2.1.1 Harvesting residues and stumps

The forest-biomass availability assessments in papers I, II, and III are based on municipality-level estimates of technical potential (398 municipalities) of HR, ST, and EW provided by the Finnish Forest Research Institute.

The estimates used for HR and ST in this thesis are derived from annual forest fellings in 2004. The amounts of HR and ST potentially available depend on final fellings; therefore, the potential estimations embody an assumption that the demand for saw and veneer logs in Finland is going to stay at the same level as in 2004. The raw material taken into account in these potential estimates includes spruce and pine HR from final fellings (*Pinus sylvestris and Picea abies*) and spruce ST. The methodology and availability constraints used in the potential estimation for HR and ST are presented by Laitila et al. (2008).

2.1.2 Energy wood

EW is collected from advanced seedling stands and first thinnings either as a separate operation or integrated with procurement of industrial roundwood. so its availability is not tied to industrial roundwood use as directly as that of HR and ST is. The potential of EW is based on the 10th national forest inventory and multi-source national forest inventory conducted by the Finnish Forest Research Institute. The methodology and the constraints applied in the assessment of EW potential are described by Anttila et al. (2009b). Of the three types of forest biomass assessed in this thesis, EW has the greatest potential for growing use in the future (Laitila et al. 2008, Hynynen 2008).

The total potentials for HR, ST, and EW in Finland are 48.6, 19.4, and 46.8 PJ yr^{-1}, respectively, totaling 114.8 PJ yr^{-1}. In 2011, the annual use of the kinds of forest biomass included in this study (HR, ST, and EW) was 57 PJ (Finnish Forest Research Institute 2013a). Accordingly, the current use in Finland corresponds to 50% of the estimated technical potential at national level.

2.2 Theoretical vs. practical forest-biomass availability

For a more realistic assessment of the GHG emissions of the forest-biomass supply chain, the technical potential should be adjusted to reflect the actual availability. One key factor affecting the availability of biomass is whether or not the forest-owners are willing to sell (or give away) forest biomass for energy purposes. However, from survey results and the data available on this matter, no precise figure can be derived for forest-owners' willingness to sell various types of forest biomass for energy purposes that would be representative for the whole country. According to results of surveys conducted in Finland (with varying geographical coverage and questions asked), the percentage of forest-owners who are willing to sell or would consider selling HR, ST, and EW is within the range 18–74%, 45–80%, and 18–87%, respectively (Mynttinen et al. 2013, Rämö et al. 2001 and 2009, Karjalainen 2001, Järvinen et al. 2006.

In addition to forest-owners' attitudes to selling forest biomass for energy purposes, other factors that may limit the availability of forest biomass to any one user include lack of information about suitable harvestable stands and about opportunities to sell EW, prohibitive harvesting and transportation costs arising from remoteness of location, and lack of the subsidies that are often required for economically feasible harvesting and collection – especially of EW (Laitila et al. 2008, Maidell et al. 2008, Kärhä et al. 2010, Karhunen et al. 2011, Rämö et al. 2001, Karjalainen 2001, Ministry of Agriculture and Forestry 2012). In view of all these possible factors limiting forest-biomass availability, the actual potential was estimated to be 50% of the technical potential in papers I, II, and III of this thesis, so the potential of each supply point was adjusted by a factor of 0.5. Given that in 2012 around 50% of the technical potential was used for energy purposes, the 50% limitation can be considered to reflect the current situation in Finland accurately enough for the purpose of assessment of the GHG emissions derived from forest biomass in the supply chains. However, it should be noted, that the potential estimations used in this work reflect the current situation and current raw material procurement practices. In practice this means that, if end users are willing to pay more for the raw material, the amount of potentially available raw material may rise. Also, trees that could also be suitable for pulpwood production may be directed to energy use in the future in increasing quantities.

It should be noted, though, that local competition over the same resources does limit the availability of forest biomass to any one user more in some regions than others (Korpinen et al. 2013, Anttila 2013), with various influencing factors, among them the paying capacity, location, and market share of the competing demand points (i.e., the entities buying the biomass). Possible effects of competition for forest-biomass resources in different regions or parts of the country have not been further evaluated in this thesis or the papers included in it.

2.3 GIS assessments

2.3.1 Spatial allocation of forest-biomass potential

If one is to take local biomass availability into account in the assessment of GHG emissions arising from transportation activities, the spatial distribution assumed for forest-biomass resources should reflect the actual conditions in the relevant location. Therefore, in this thesis project, the municipal-level forest-biomass potential was allocated within a more detail-level grid in the following manner.

In papers I, II, and III, the forest-biomass potential (as described in sections 2.1 and 2.2) was spatially allocated to the geographical reference area, Finland (see Figure 1, pane a). For this purpose, Finland was divided into a geographical grid of 2 × 2 km for papers I and II, and into a grid of 4 × 4 km for Paper III (see Figure 1, pane b). The grid for Paper III was less dense than those for papers I and II because the supply areas covered were significantly larger and a 4 × 4 km grid was assessed as producing accurate enough results for the purpose of that particular paper. In general, it can be stated that the larger the amounts of biomass supplied and the supply areas, the less fine the geographical grid needs to be. Accordingly, the area of each grid square of land was 4 km^2 for papers I and II and 16 km^2 for Paper III. The total sizes of the supply areas ranged roughly from 3,900 to 4,500 km^2 for Paper I, from 7,700 to 9,000 km^2 for Paper II, and from 26,000 to 64,000 km^2 for Paper III.

For each grid square, the share of productive forest land was calculated by means of raster analysis with GIS software. The forest area taken into account in this study was forest land in the growth categories of forestry land as defined by the Finnish Forest Research Institute (2011). By definition, forest land is land area where the average growth of forest is >1 m^3 ha^{-1} yr^{-1}. The method enables the exclusion of unsuitable land areas that do not produce biomass for this specific purpose from the calculations (see Figure 1, panes c and d). These unsuitable areas include, for example, areas covered with water, urban areas, roads, fields, and also forest areas with poorer growing conditions. The land-use categories were based on the

SLICES land-use data, with 10 m × 10 m raster density (National Land Survey of Finland 2011). Also, the center points of the grid squares that did not fall within Finnish territory, along with those completely offshore, were deleted from the grid. The total municipality-level forest-biomass potential was then allocated to the grid-square center points within each municipality in accordance with the amount of productive forest-land area within each square (see Figure 1, pane e).

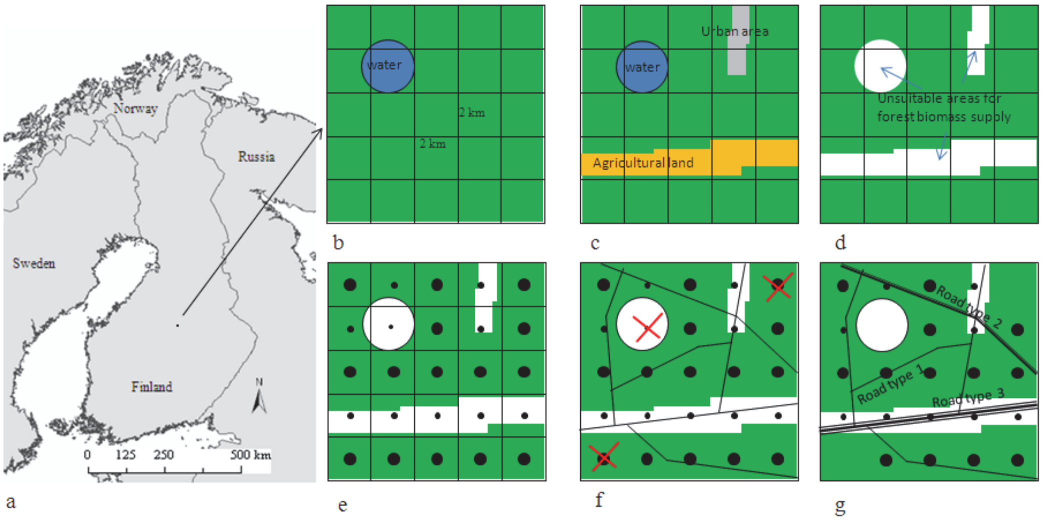

Figure 1. Simplified diagram of the supply-point grid system. a, b: Finland was divided into a geographical grid; c, d: Unsuitable areas for forest-biomass supply were excluded; e: The forest biomass within each grid square was allocated to the grid-square center points; f: Center points further than 1 km from the nearest road were excluded; g: Roads were grouped into three classes in line with the maximum speed limits.

2.3.2 Road network assessment

The first part of the transportation chain for forest biomass from roadside storage to the demand points is practically always truck transportation. In supply areas where the road network density is poorer, longer distances may have to be driven between a roadside storage location and a given demand point than in areas with a denser road network. In addition to road network density, road type affects the GHG emissions of truck transportation, since driving on smaller roads, such as gravel forest roads, consumes more fuel. In order for the

GHG emission calculations to take these factors into account, road network assessment was conducted as described below.

For papers I, II, and III, the forest-biomass supply points (the center points in the geographical grid) were linked directly to the nearest road. Points further than 1 km from the nearest forest road were excluded from the calculations (see Figure 1, pane f). This was done because if a supply point is too far from the nearest road, the forest-transportation distance – i.e., forwarding distance – was assumed to be too long for collection of forest biomass to be economically feasible. For definition of the supply areas around the demand points and railway loading points, the shortest possible route to each point was calculated with GIS software. Then, from the nearest supply point, the supply areas around each demand point were expanded and supply points included in the area until the desired total amounts of biomass were reached. The route calculations were based on the Finnish national road and street database, Digiroad (Finnish Transport Agency 2010). To take the various road types and their effects on the GHG emissions of truck transportation into account, road segments were classified into three distinct road types (see Figure 1, pane g), as used in the life-cycle inventory dataset (Gabi Databases 2013) utilized in the GHG calculations (see Table 1 in Paper II). This classification was based on the maximum speed limit for each road segment as stated in Digiroad (Finnish Transport Agency 2010). According to data provided by VTT Technical Research Centre of Finland (2012), the fuel consumption on roads categorized as urban roads, interurban roads, and motorways in the emission calculations corresponds to fuel consumption on small rural roads, regional roads, and highways, which are typical road types traveled in the transportation of forest biomass from roadside storage to power plants in Finland. For papers I, II, and III of this thesis, if a biomass supply point was inside the supply area(s) around each demand point or loading location, all of its biomass was considered to be collected. This resulted in the total amount of biomass collected being slightly different from the desired total amounts, because supply points were included in the supply areas one by one in order of driving distance from the demand point. Therefore, the amounts supplied were adjusted to be exactly the desired amounts, by means of correcting factors. A value for kilometers per unit energy content was calculated for all three road types in each supply scenario, and the values were then multiplied to yield the distances that would be driven on each road type for supply of exactly the desired amount of biomass.

2.3.3 Assessment of forwarding distances

For Paper IV, to estimate the GHG emissions of forwarding, the distance from harvesting sites to the roadside was assessed as follows. The classification as forest land was conducted as described in Subsection 2.3.1. First, the geographical reference area (Finland) was divided into a grid with 2 km × 2 km density, and the midpoints of these 2 km × 2 km grid squares that were further than 1 km from the nearest road were not taken into account (in line with calculation methods use in previous papers). Second, the 2 km × 2 km grid squares were divided into a more detailed grid with a density of 100 m × 100 m (1 ha). Areas of restricted use (such as protected areas) were excluded (Finland's Environmental Administration 2013). Finally, direct distances from the center points of each 1 ha square of forest land to the nearest suitable roads were calculated. These direct distances were multiplied by a factor of 1.4 to yield an estimation of the actual distances covered by the forwarder (Viitala et al. 2004). Highways were excluded from the assessment, since they are not suitable for roadside operations (storage, comminution, and loading) in forest-biomass supply (Viitala et al. 2004).

2.4 GHG assessments – LCA

2.4.1 LCA as a method

In this thesis, including the four papers, the GHG emissions of forest-biomass supply and utilization are assessed by means of life-cycle assessment (LCA) methods. The ISO 14040 standard defines LCA as a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle (ISO 2006). Because this thesis, including its papers, focuses only on GHG emissions, the assessments can also be defined in "carbon footprint" terms (Weidema et al. 2008). LCA is the method chosen by the European Union for bioenergy sustainability assessments (European Commission 2009 and 2010b).

LCA involves four main phases: 1) the goal and scope definition phase, 2) the inventory analysis phase, 3) the impact assessment phase, and 4) the interpretation phase (ISO 2006). The characteristics of each phase in relation to this thesis are described in the following sections of the chapter.

2.4.2 Goal and scope

The overall goal of this thesis was to assess the GHG emissions stemming from the supply and energy-utilization chains of forest biomass in Finland, with specific focus on the effect of location in relation to forest-biomass availability and transportation possibilities.

The scope of each paper, including system boundaries, is presented in more detail in the included papers (see Chapter 1 of Paper I, Figure 2 in Paper II, Figure 1 in Paper III, and Figure 2 in Paper IV). The scope of Paper I is limited to feedstock transportation, and that of both papers II and III is limited to feedstock transportation and comminution. Therefore, these three assessments can be classified as gate-to-gate assessments, because they focus on only one or a few steps in the process in the full life cycle of the forest-biomass energy-utilization chain (Jiménez-González et al. 2000).

On the other hand, Paper IV represents more comprehensive LCA, or cradle-to-grave assessment, for it includes all relevant parts of the bioenergy production and utilization chain (European Commission Joint Research Centre 2013). In addition to assessing the GHG emissions derived from the bioenergy production and utilization chain, Paper IV takes the assessment a step further by evaluating the possible emission reductions that may be achieved with the selected bioenergy systems in Finland.

In addition to division into, for example, gate-to-gate or cradle-to-grave studies, which is based on the scope and boundaries, LCA studies can be categorized as attributional or consequential studies, on the basis of their approach to a given system and its possible consequences. Attributional studies provide information on the emissions and impacts arising from a certain system or subsystem, while consequential studies also assess the indirect consequences of the functions performed by the (sub)system studied (Ekvall and Weidema 2004, Brander et al. 2009, Finnveden et al. 2009). In this thesis, papers I, II, and III represent attributional studies – they concentrate on the GHG emissions of certain parts of the bioenergy chains – whereas Paper IV represents a consequential study: it evaluates not only the emissions arising from a given bioenergy system itself but also the emissions that, because of certain fossil-energy systems being replaced by the bioenergy system, are not released (i.e., emission savings achieved when forest biomass is used instead of fossil fuels).

A vital part of any LCA study is the definition of the functional unit. The functional unit is the reference unit of the system, and the performance of the system under study is judged in terms of it (ISO 2006). The functional unit should be chosen such that the results provide useful information in view of the goal and scope of the study. In this thesis, the functional units for papers I, II, III were selected to represent the annual demand for biomass in each case: 360 TJ, 720 TJ, and 7.2 PJ of comminuted forest biomass delivered to a demand point, respectively. For Paper IV, the functional unit was 1 MJ of comminuted forest biomass produced and delivered to a demand point. Paper IV also included the energy-production phase, for which the results were presented in terms of 1 MJ final energy produced; therefore, the functional unit for the latter part of the assessment was 1 MJ of final energy produced (heat, electricity, or both, depending on the bioenergy system in question). It should be noted that, even if the results of different studies are given in the same units (for example, in terms of $gCO_2eq\ MJ^{-1}$), the functional unit must be taken into account in the interpretation of the results, as discussed by, for example, Rebitzer et al. (2004). For example, the emissions per unit of comminuted forest biomass delivered to a demand point increase as the amounts supplied grow, because of longer transportation distances, but the results are still given in the same units.

2.4.3 Inventory analysis

The inventory analysis phase is an inventory of the input and output data of the systems studied. In this thesis, special focus was placed on the assessment of geographically dependent emissions, for which the GIS assessment of biomass availability, transportation network, and forwarding distances (as described in Section 2.2) provided site- and location-specific initial data. In the included papers, data from the literature and Life Cycle Inventory (LCI) datasets (GaBi databases 2011, 2012, and 2013) were used (see the references in each paper for details). The GaBi databases are the largest internally consistent databases currently on the market (PE-International 2013, JRC 2013a), with consistent documentation in line with the European Life Cycle Data System conformity rules (JRC 2013b). Data sources of the same quality were used across the various papers, thus enabling drawing of conclusions based on the four papers as a whole. The emissions were calculated with LCA software.

2.4.4 Impact assessment

The potential environmental effects a given system causes are assessed in the impact assessment phase. First, the inputs and outputs of the system, such as the resources used or emissions, are classified into various impact categories on the basis of the potential environmental effects they may produce. For example, gaseous emissions to the air may be classified among, for example, substances that cause global warming or substances that cause photochemical ozone formation. A single substance may be placed into one or more categories. After classification, the emissions are characterized, meaning that each substance is assigned a relative factor, in accordance with the potential of said substance to cause a certain environmental effect. For example, the gases that may cause global warming are characterized (i.e., weighed) for their estimated potential to cause global warming on a given time horizon with respect to, for example, CO_2. This thesis focuses on GHG emissions, meaning that the only potential environmental impact focused on here is anthropogenic climate change – i.e., human-induced global warming. More precisely, only those emissions with potential to cause the actual environmental effect in question are assessed, not the effect itself (i.e., rising of the average global temperature) or the physical climatic responses that the emissions may cause (Forster et al. 2007). GHGs cause radiative forcing, by definition "the change in net (down minus up) irradiance (solarplus longwave; in W m^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values" (Ramaswamy et al. 2001). However, radiative forcing is not assessed in this study; only the three most important gaseous substances that cause it are: carbon dioxide, methane, and dinitrogen oxide (CO_2, CH_4, and N_2O, respectively) (IPCC 2007). This is in line with international climate agreements and with the EU RED methodology, in which the climate-change mitigation activities are associated with the amount of GHGs emitted. For this thesis, emissions were assessed in terms of global warming potential (GWP) on a 100-year time horizon. The GWP value can be used for estimation of the potential future climate impact of individual gases in a relative sense (Ramaswamy et al. 2001), and it forms the basis of, for example, the Kyoto Protocol, the EU RED, and the US Renewable Fuel Standard for long-term emissions (Forster et al. 2007, EEA 2012, Yacobucci and Bramcort 2010).

In papers I and II, the GWP factors relative to CO_2 for CH_4 and N_2O were 25 and 298, and in papers III and IV 23 and 296, respectively. This difference in GWPs arises from the fact that in papers I and II the impact-assessment methodology of CML 2001 (Nov. 2009) was used (Guinée et al. 2001), which applies the same GWP factors recommended by the IPCC (Forster et al. 2007), whereas in papers III and IV the GWP factors specified in the EU RED were used (European Commission 2009). However, the difference in these studies' final results that is due to the use of different GWPs can be deemed negligible. For example, the GHG emissions calculated from the use of diesel fuel with 5.75% bio-components (the fuel assumed to be used in the case studies in the included papers) differ by only 0.03% when the different GWPs for CH_4 and N_2O as presented above are used. This is because the clear majority of GHG emissions from fossil-fuel use take the form of CO_2.

2.4.5 Interpretation

The findings from the inventory analysis and the impact assessment phases are considered together in the interpretation stage, which takes into account the goal and scope of the study. In this thesis, the four papers are organized such that the interpretation phase is a part of the discussion section of each paper. Similarly, the overall interpretation of the results in this thesis is presented in the discussion section (Chapter 4 of this thesis).

2.4.6 EU RED methodology

The EC presents the following calculation procedure for bioenergy life-cycle GHG emission assessments (European Commission 2009 and 2010b):

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee}$$

where E = for liquid biofuels, total emissions from the use of the fuel; for solid and gaseous biofuels, total emissions from the production of the fuel before energy conversion;
e_{ec} = emissions from the extraction or cultivation of raw materials;
e_l = annualized emissions from carbon stock changes caused by land use change;
e_p = emissions from processing;
e_{td} = emissions from transportation and distribution;
e_u = emissions from the fuel in use;
e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;
e_{ccs} = emission savings from carbon capture and geological storage;
e_{ccr} = emission savings from carbon capture and replacement; and
e_{ee} = emission savings from excess electricity from co-generation.

Forest-biomass supply in Finland (as assessed in this thesis) is assumed not to cause direct or indirect land-use changes. Also, in this thesis, it is assumed that the removal of forest biomass follows the recommendations for sustainable forest-management practices (Äijälä et al. 2010) so that future forest growth is not affected. Furthermore, on a nationwide scale, the current annual growth of forests in Finland also clearly exceeds the amount felled, resulting in a net increment of wood volume and carbon stocks in living wood. This trend is expected to continue (Finnish Forest Research Institute 2012). Therefore, the emissions related to carbon-stock changes caused by land-use change were assumed to be zero, in line with IPPC guidelines (IPCC 2006). Also, emission savings from soil carbon accumulation via improved agricultural management, carbon capture, and geological storage or replacement, and from excess electricity generation from co-generation for liquid biofuels, are not relevant for the forest-biomass-based systems addressed in this thesis. Accordingly, the EU RED calculation procedure takes the following form:

$$E = e_{ec} + e_p + e_{td} + e_u$$

In relation to the EU RED methodology, Paper I addresses only the parameter e_{td}, because it deals only with transportation activities. Papers II and III address parameters e_p and e_{td}, with comminution included in addition to transportation. Parameter e_{ec} (emissions from the extraction and cultivation of raw materials) was not addressed in papers I, II or III, because forest operations do not have direct influence on the following operations (e_p and e_{td}). In other words, it was assumed that the material is at the roadside storages in uncomminuted form. This is the current dominant practice in Finland material, i.e. material is not comminuted in the forest before forwarding to the roadside. Paper IV addresses all relevant parameters: e_{ec}, e_p, e_{td}, and e_u, since the extraction of raw materials and the use phase of the forest biomass are included also.

3. RESULTS

In this chapter, only the key results presented in the included papers with respect to the overall objective of this thesis are presented and summarized. Detailed results are presented in the individual papers.

3.1 Paper I

Paper I addresses solely emissions of biomass transportation by truck. Expressed per unit of energy delivered to the plant, the transportation of 360 TJ yr^{-1} of wood chips made of EW to plants in Mikkeli and Rovaniemi produced 0.43 and 0.56 gCO_2eq MJ^{-1}, respectively. Transportation-derived emissions were 31% greater for Rovaniemi than for Mikkeli, even though the total driving distance by truck was only 22% longer. This resulted from the fact that the percentage of driving on small roads is higher, and the density of the road network poorer, around Rovaniemi than near Mikkeli.

3.2 Paper II

Paper II addresses the supply chains for 720 TJ yr^{-1} of EW chips, from roadside storage of EW to chips in the plant yard. The lowest GHG emission figures for both case-study locations – Rovaniemi and Mikkeli – were found for the supply chains that included supply of one trainload of chips per week from the nearest loading places, and in which the material was transported as loose trees to the railway loading locations. In these scenarios, 32% of the total demand was met by railway. The supply-chain emissions (per unit of energy delivered to the plant) came to 1.41 and 1.56 gCO_2eq MJ^{-1} for Mikkeli and Rovaniemi, respectively. These values are based on electric trains running on average Finnish electricity.

In the scenarios in which only truck transportation was used, the supply-chain emissions were 1.53 and 1.69 gCO_2eq MJ^{-1} for Mikkeli and Rovaniemi, respectively. Thus, for both locations, GHG-emission savings of 8% could be achieved if one trainload per week were delivered by train. The total emissions of the least GHG-emitting supply chain were 9% lower for Mikkeli than for Rovaniemi. For both case-study locations, all of the supply chains that included transportation by train from the nearest loading sites produced lower GHG emissions than did the traditional supply chains based on direct truck transportation, regardless of whether diesel or electric trains were used and of the type of electricity used by the electric trains.

3.3 Paper III

In Paper III, similarly to Paper II, the supply-chain emissions from roadside storage to comminuted feedstock at the plants were assessed. The amount supplied was 7.2 PJ yr^{-1}. For all three plant locations – Porvoo, Rauma, and Kemi – the least GHG-emitting supply-chain scenarios were those in which only 33% of the feedstock is delivered to the plants by truck, on the assumption that electric trains powered by hydropower or average Finnish electricity are used.

With a 50% limitation in biomass availability (in line with the assumptions made for papers I and II), the supply-chain emissions of the least GHG-emitting scenarios were 1.91, 1.91, and 2.33 gCO_2eq MJ^{-1} for Porvoo, Rauma, and Kemi, respectively. These values assume electric trains running on average Finnish electricity. Here, the supply-chain emissions were 22% higher for Kemi than for Porvoo or Rauma. If only direct truck transportation were used, the supply-chain emissions for Porvoo, Rauma, and Kemi would be 2.45, 2.59, and 3.37 gCO_2eq MJ^{-1}, respectively.

With a 50% limitation to the availability of biomass (in line with papers I and II), all scenarios assessed that include railway transportation produced lower GHG emissions than did the scenarios in which only direct truck transportation is used, regardless of whether diesel or electric trains are used and regardless of the type of electricity the electric trains use.

3.4 Further work related to the results presented in papers I, II, and III

Assessment of emissions from transportation of EW by truck was part of the work described in papers I, II, and III. To facilitate unbiased comparison of the results in these three papers for EW transportation from the supply areas surrounding the demand points, the following further calculations and revisions were employed: 1) The transportation emissions for the biomass supply cases presented in Paper I were calculated also with 60-ton trucks and the same parameters used in papers II and III (they were originally calculated with 40-ton trucks in Paper I). 2) Unloading of chip trucks and transport of the diesel fuel used by the trucks from the refinery to the plant and loading locations were included in the emission figures for wood-chip transportation presented in Paper II. The transportation emission for the supply cases addressed in Paper II were, therefore, calculated also without these operations. 3) For Paper III, the feedstock was a mix of HR, ST, and EW, and the results were not presented separately for transportation of energy-wood chips. Therefore, the emissions were calculated separately for EW chip-truck transportation for the supply cases of Paper III.

In Figure 2, the truck transportation emissions are presented as a function of the amount of EW chips supplied to the demand points, with account taken of the revised calculations as described above.

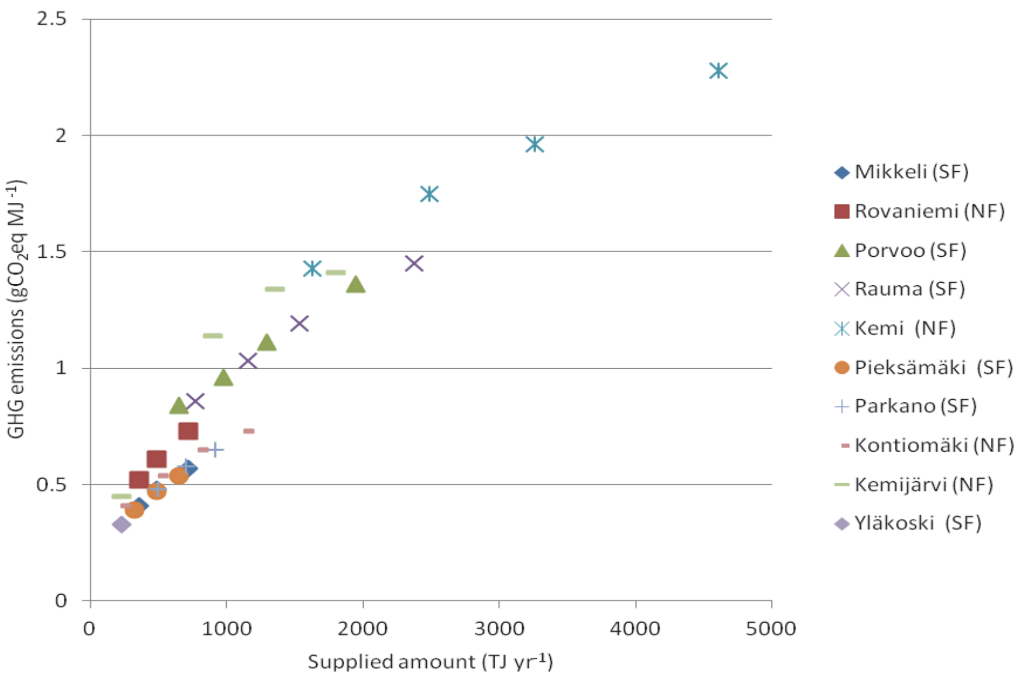

Figure 2. GHG emissions of truck transportation of EW chips as a function of the amount supplied for each supply scenario presented in papers I, II, and III, calculated with 60-ton chip trucks. SF: Southern Finland, NF: Northern Finland.

As illustrated in Figure 2, the GHG emissions of truck transportation per unit of energy content supplied grow with the amounts supplied. However, the increase in emissions is not linear. It should be noted that the emissions per unit of energy delivered as presented in Figure 2 are not directly comparable between locations, because Porvoo, Rauma, and Kemi are coastal, while the other locations are inland. See Figure 3 for the locations of the demand points assessed in papers I, II, and III. Also, the land area which can be reached by driving a certain distance increases exponentially. In theory, the area that can be reached by driving a certain distance from a given location follows the equation $A= \pi r^2$, in which A= area and r=driving distance. However, in practice, roads are winding and local circumstances, such as waterbodies etc., affect the driving distances between two points. Furthermore, with longer distances a larger proportion of the total distance is covered on highways, which consumes less fuel.

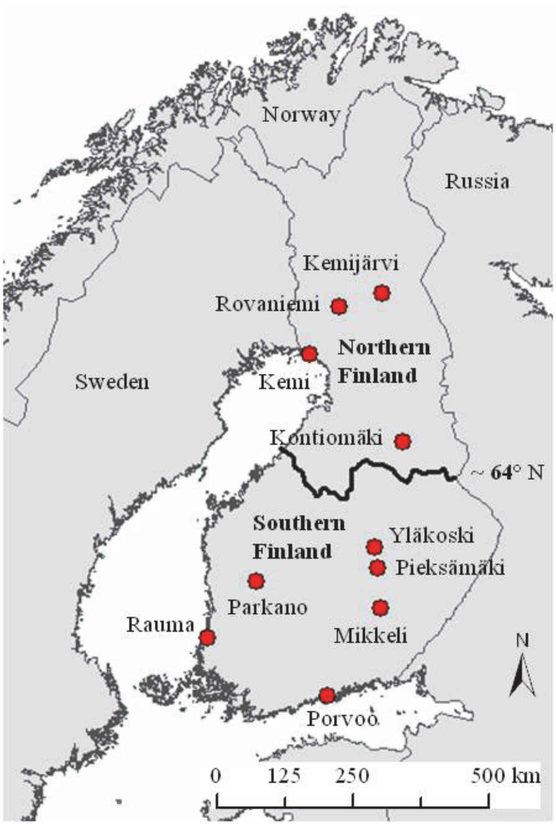

Figure 3. Locations of the demand points and the division of Finland into Southern and Northern Finland.

3.5 Paper IV

In Paper IV, the GHG emissions of forest-biomass supply chains, beginning with forest operations and ending with comminuted feedstock in the plant's yard, were assessed, with possible differences between southern and northern Finland (see Figure 3) taken into account; see Figure 4 for the results.

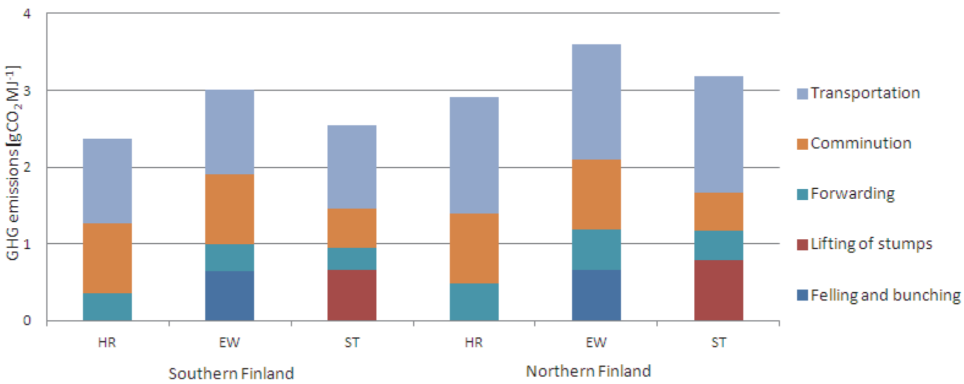

Figure 4. GHG emissions of forest-biomass supply chains. Note: For simplicity, the transportation emissions given in this figure are 1.1 and 1.5 $gCO_2eq\ MJ^{-1}$ for Southern and Northern Finland, respectively, roughly representing the average emissions.

As Figure 4 illustrates, the direct supply-chain emissions are highest for EW, followed by ST and then HR. The emissions of the EW supply chain are the highest because of felling and bunching operations and roadside chipping. The emissions of stump lifting are roughly the same as those for felling and bunching of energy wood, but, because the stumps are comminuted at the plant or terminal, the comminution is more efficient. It should be noted that in Figure 4, the transportation emissions represent roughly the average emissions in northern and southern Finland; in real life, they vary between locations.

When possible fertilization, soil carbon-stock changes, and possible storage of comminuted biomass are accounted for, the emissions related to the supply of HR, EW, and ST are substantially higher than if these are omitted; see Figure 5 for the results. Because the storage of comminuted biomass is not always necessary, and the emissions associated with it are dependent on the duration of storage (among other things, as discussed in Paper IV), the emissions of storage are presented as a range of possible emissions (see Section 2.3 of Paper IV for details).

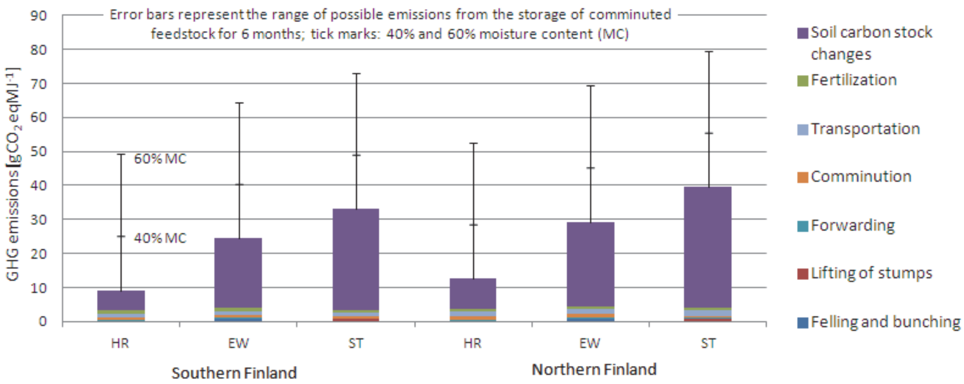

Figure 5. GHG emissions of forest-biomass supply chains, including fertilization and soil carbon-stock changes on a 100-year time horizon. The storage emissions shown represent the emissions possible in six months' storage of comminuted biomass with 40% and 60% moisture content (MC). HR = harvesting residues, EW = small-diameter energy wood, ST = stumps.

As illustrated in Figure 5, on a 100-year time horizon, soil carbon-stock changes constitute the majority of emissions. Furthermore, if comminuted biomass is stored long enough that the decay process begins, the resulting emissions of CH_4 and N_2O may be significant. However, emissions created through storage depend on various factors and occur only if comminuted biomass is stored for a longer period. Therefore, they are stated in terms of an approximate range for the possible emissions over half-year storage. Fertilization may account for approximately 1 $gCO_2eq\ MJ^{-1}$, but most sites in Finland are not fertilized, and, therefore, emissions from fertilization are not included in the basic scenario presented in Figure 4 (see Section 2.3 of Paper IV for details).

Table 1 presents the GHG emissions of the various forest-biomass energy-utilization chains assessed in Paper IV compared to their reference systems in Finland and the EU comparator values. The GHG savings depend on which of the possible sources of GHG emissions along the bioenergy chains are taken into consideration.

Table 1: GHG emissions of forest-biomass-based energy production in comparison to fossil production

	GHG emissions in comparison to reference systems in Finland[a]	GHG emissions in comparison to EU comparator values[b]
Soil carbon-stock changes, fertilization's effects, and storage emissions omitted	CHP and heat: 94–98% savings Electricity: 92–94% savings	CHP and heat: 93–97% savings Electricity: 93–95% savings
Soil carbon stocks and fertilization included	CHP and heat: 48–91% savings Electricity: from 75% savings to 1% increase in emissions	CHP and heat: 40–91% savings Electricity: 20–81% savings
Soil carbon stocks, fertilization, and storage emissions[c] included	CHP and heat: from 57% savings to 2% increase in emissions Electricity: 26–102% increase in emissions	CHP and heat: from 56% savings to 19% increase in emissions Electricity: from 1% reduction to 61% increase

[a] In this column, the possible GHG savings in electricity production are compared to values for average Finnish electricity. See Paper IV for comparison with other types of electricity.

[b] EU comparator values (European Commission 2009 and 2010): Electricity 198 $gCO_2eq\ MJ^{-1}$. Heat produced with solid or gaseous biomasses 87 $gCO_2eq\ MJ^{-1}$. Bioliquids used in heat production 77 $gCO_2eq\ MJ^{-1}$.

[c] Storage emissions represent an estimate of the GHG emissions possible in six-month storage of comminuted biomass (Wihersaari 2005b). Exact and/or empirical data for this issue are not available.

4. DISCUSSION

4.1 Implications

The principal implication of the findings in this thesis is that in Finland, the location and availability of biomass in the proximity of a given energy-utilization facilitiy is not a decisive factor in supply-chain GHG emissions or the possible GHG savings to be achieved with forest-biomass energy use. Therefore, for the greatest GHG reductions with limited forest-biomass resources, energy utilization of forest biomass in Finland should be directed to the locations where most GHG savings are achieved through replacement of fossil fuels and one should prioritize the types of forest biomass with the lowest direct supply-chain GHG emissions (e.g., from transport and comminution) and the lowest indirect ones (in particular, soil carbon-stock losses), regardless of location. In this respect, the best combination is to use harvesting residues in CHP production, replacing peat or coal.

4.2 The effect of location on total GHG emissions of forest-biomass supply

In Finland, the availability of forest biomass is poorer, the road network is less dense, and the proportion of small roads is greater in the northern parts of the country than in the south, as a general rule. These location-related differences lead to longer transportation distances and longer forwarding distances for forest biomass, resulting in higher supply-chain GHG emissions. Also, in northern Finland, the tree density (i.e. amount of biomass available for energy use within a certain land area) is lower than in southern Finland, which increases the emissions of forest biomass extraction, due to lower productivity of forest operations. The total GHG emissions derived from fossil fuel use in different parts of the forest-biomass supply chain – from forest operations to comminuted biomass in the end user's yard – range roughly between 2 and 4 $gCO_2eq\ MJ^{-1}$ of comminuted biomass, depending on location and biomass type (recall Figure 4, in Section 3.5). Location-dependent differences in GHG emissions between forest-biomass supply situations can, however, be effectively reduced – by up to 30% – through utilization of railway transportation, depending on the scale of supply. In general, the larger the supplied amount and the poorer the availability of feedstock is around the demand point, the greater are the GHG reductions that may be gained through the use of railway transportation of feedstock from distant supply areas. The GHG emissions of the railway transportation itself can, in fact, be cut to almost zero level, if hydropower or other electricity with low production GHG emissions is used, further reducing the location-dependent differences in forest-biomass supply-chain emissions between end-user locations. Though relatively large differences in transportation-related GHG emissions can be found between different parts of Finland, the effect of these differences is of minor importance when compared to the total emissions arising from forest-biomass supply chains, and the possible GHG savings that may be achieved through replacement of fossil fuels in energy production with forest biomass. For example, in the case of the supply chain for small-diameter energy-wood chips, the difference in transportation-related emissions between northern and southern Finland may account for as much as approximately 2 $gCO_2eq\ MJ^{-1}$ (including truck-based transportation and forwarding) while the emissions due to soil carbon-stock changes can be estimated to account for roughly 20 $gCO_2eq\ MJ^{-1}$ in southern Finland and 25 $gCO_2eq\ MJ^{-1}$ in northern Finland (on a 100-year time horizon) (Repo et al. 2012). Furthermore, the possible emissions of storage of comminuted biomass at the plant – or at terminals or railway loading locations – may possibly account for up to 40 $gCO_2eq\ MJ^{-1}$ (Wihersaari 2005b), reducing the relative contribution of transportation to the total emissions even more. There are, however, significant uncertainties related to storage emissions, and literature and data regarding GHG emissions (CH_4 and N_2O) of comminuted forest biomass stockpiles are scarce (as discussed in Paper IV).

4.3 Forest-biomass energy utilization and GHG savings

The perceived GHG savings achieved with forest-biomass energy utilization depend on a) which emissions are taken into account, b) the production system that a given bioenergy system is compared to, and c) the time horizon of the assessment, so there is no general answer to the question of how much GHG emissions can be reduced through forest-biomass energy utilization in Finland. When the GHG emissions are calculated according to the EU RED methodology, emission savings in the 93–97% range are achieved when fossil energy production is replaced with forest-biomass-based production (recall Table 1, in Section 3.5), and thus the EU's sustainability criteria of 35% savings currently and 60% savings in 2018 relative to EU-wide fossil comparator values would be met. The GHG savings calculated in this thesis are in the same range as the GHG savings values of 96% for electricity and 98% for heat produced with forest-residue chips in the EU that have been presented by the European Commission (European Commission 2010b). In comparison to the actual reference systems in Finland, which deviate from the EU reference values, GHG savings in the same range are achieved. However, if GHG emissions due to soil carbon-stock changes and the possible emissions released during storage of comminuted biomass are considered, GHG savings are not guaranteed and emissions may even increase significantly (recall Table 1, in Section 3.5). These emissions are not taken into account in the current default savings values presented by the EC (JRC 2013, 2011). The highest reduction in GHG emissions with forest biomass in Finland can be achieved through replacement of peat[11] in CHP production, or via gasification and coal replacement in CHP production. This is due to the high GHG emissions of the fuels replaced but also since utilizable energy content is always lost in preparation and conversion processes – for example, in torrefaction and pelletization processes or in the pyrolysis-oil production process, as discussed in Paper IV. This phenomenon can be explained by the second law of thermodynamics: conversion of energy from one form to another increases entropy (i.e., disorder).

4.4 The effect of feedstock selection on the GHG savings

With respect to feedstock, harvesting-residue supply and energy use produces lower emissions than small-diameter energy wood or stumps, mostly because of the faster natural decay of harvesting residues, leading to lower relative soil carbon-stock losses, but also because of the lower production-chain emissions. Utilization of stumps as feedstock produces lower GHG emissions than utilization of energy wood but only if soil carbon-stock changes are not considered. If these carbon-stock changes are accounted for, stumps are the worst feedstock in terms of GHG emissions, because of the slow natural decay process.

Previous studies addressing Nordic conditions have found the GHG emissions of the forest-biomass supply chain to be in the range 1.0–1.8 $gCO_2eq\ MJ^{-1}$ for harvesting residues (Näslund-Eriksson and Gustavsson 2008, Wihersaari 2005, Lindholm et al. 2010, Kariniemi et

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[11] With respect to the possible GHG savings achieved through peat replacement, it should be noted that the calculations did not take into account the differences possible in initial GHG emissions between individual peat-extraction areas (Silvan et al. 2012).

al. 2009), 1.8–3.6 gCO_2eq MJ^{-1} for stumps (Näslund-Eriksson and Gustavsson 2008, Lindholm et al. 2010, Kariniemi et al. 2009), and 1.5–2.6 gCO_2eq MJ^{-1} for small-diameter energy wood (Näslund-Eriksson and Gustavsson 2008, Kariniemi et al. 2009) (see Table 5 in paper IV). These figures do not include emissions due to soil carbon-stock changes. The relatively large variation in results between studies arises from differences in background data, study boundaries, the assumptions made, and calculation methods. The corresponding supply chain emissions of this current study (recall Figure 4, Section 3.5) are higher than the results of previous studies, especially for HR and EW. The difference is mainly due to the emissions of truck transportation, which are assumed to be higher in this thesis than in the previous studies. The transportation emission figures presented in (Figure 4) are derived from papers I, II and III of this thesis. However, it should be noted that the transportation emission figure used in Figure 4. of this thesis represents a central value from the case studies of papers I, II and III, in which the transported biomass amounts ranged from a rather limited amount of 0.36 PJ $year^{-1}$ to a very large demand of 7.2 PJ $year^{-1}$. Furthermore, direct comparison to other studies is not possible, because, for example, in (Lindholm et al. 2010) and (Eriksson and Gustavsson 2008) the transportation distances have been assumed shorter and the payloads have been assumed to be higher than in papers I, II and III on which the values presented in (Figure 4) are based on. In (Wihersaari 2005) and (Kariniemi et al. 2009) transportation equipment and distances have not been specified in detail. Thus, the results presented in (Figure 4, Section 3.5) do not represent a specific supply situation to a specific location. Previous studies addressing emissions due to soil carbon-stock changes have come to the same conclusion as this thesis work: if soil carbon-stock changes are accounted for, they constitute the majority of emissions (assuming that storage emissions are low) (e.g., Palosuo et al. 2001, Wihersaari 2005, Repo et al. 2012, Lindholm et al. 2011) (recall Figure 5, in Section 3.5). It should be noted that the results pertaining to emissions due to soil carbon-stock changes vary significantly from one study to the next, because they apply different decay models, calculation parameters, and calculation approaches.

4.5 Assumptions and limitations related to GHG assessments and LCA as a method

The results of any LCA study or GHG assessment depend on the system boundaries. Any system can be deemed GHG-efficient if the boundaries are narrow enough (O'Rourke et al.

1996). If the boundaries are set too narrow, problems are shifted from one phase to another or from one region to another (Finnveden et al. 2009). The boundaries selected for this thesis, including the papers, were chosen such that the results, when considered together, provide information on how much the GHG emissions of forest-biomass supply chains depend on the location of the end user in Finnish conditions and on how important any differences in supply-chain emissions between locations are in terms of possible GHG reductions achieved through energy utilization of forest biomass.

Life-cycle assessment is a relative approach for assessing environmental impacts (ISO 2006): the results are relative to the functional unit. The accuracy of an LCA study is also dependent on how well the initial data used represent a given, often highly complex, system in reality. In view of these considerations, it should be noted that the results presented in this thesis do not represent the quantity of GHG emissions emitted into the atmosphere because of forest-biomass energy use with absolute accuracy, but they do, however, reveal the relative differences in GHG emissions between locations and between supply scenarios in a case- and location-specific manner. The results are based on case studies in Finnish conditions, so they cannot be generalized as such to areas where conditions are different. For example, in Northwest Russia the road density is only 80 m km^{-2} while in southern Finland it is 1,500 m km^{-2} (Mönkkönen et al. 2010), so the results having to do with transportation-related emissions cannot be generalized to the former. The conditions in Sweden are more comparable in that sense (World Bank 2013), and the division of Finland into Northern and Southern Finland for Paper IV, roughly along the 64° latitude line, corresponds to the division between northern and central Sweden (Berg and Lindholm 2005).

In addition to the boundaries and initial data used, which limit the scope and representativeness of a given study, the GHG balance of any particular system depends heavily on the time horizon of the assessment, land-use scenarios, and allocation of carbon sequestration. For this thesis, the recommendations of the EU RED and IPCC (European Commission 2009, IPCC 2006) have been followed with respect to these elements: i.e., the time horizon was 100 years, forest-biomass energy use was assumed not to lead to changes in land use, and forest growth is assumed not to be negatively affected. It is debatable whether or not these recommendations and assumptions are adequate in relation to climate-change mitigation over the next few decades, as discussed by, for example, Reijnders and Huijberegts (2003) and Vanhala et al. (2012). The shorter the time horizon, the greater the climate impact of forest-biomass energy use is. This is because carbon is released immediately when biomass or biomass based energy carriers are combusted, but it takes decades for forests in Finland to grow back, for which time the released carbon is sequestered. If the biomass were left in the forests to decay naturally, the carbon would be released slowly, over several years or decades. Over a 20-year time horizon the emissions due to soil carbon-stock changes would be about 2–5 times greater than on a 100-year time horizon, depending on the type of forest biomass and the prevailing conditions (based on decay assessments by Repo et al. 2012). Also, the climate impact of the two other GHGs assessed in this study (CH_4 and N_2O) would differ on a shorter time horizon. For example, on a 20-year time horizon, the climate impact of CH_4 is almost three times higher than on a 100-year time horizon; therefore, the climate impact of possible storage of comminuted biomass would also grow significantly, since emissions during storage consist mainly of CH_4 (Wihersaari 2005b, BTG 2002).

The research for this thesis assessed only CO_2, CH_4, and N_2O, listed as the three most important GHGs by the IPCC (2007). Other GHGs, among them sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons, were not accounted for, but emissions of these gases can be assumed to be negligible in relation to the forest-biomass supply and use chains assessed in this thesis (IPCC 2007). Also aerosols that have a climate-warming effect – in particular, black carbon – are emitted when biomass or biomass-based energy-carriers are combusted. Globally, black carbon may actually be the second most important climate-warming agent after CO_2 (Bond et al. 2013). Black carbon from biomass combustion for energy purposes is, however, due mostly to residential cooking and heating, not to industrial bioenergy systems with more controlled combustion processes as assessed in this thesis (Bond et al. 2013).

The removal of the forest biomass from forests has in some studies also been found to affect forest growth negatively, which may cause indirect climate impacts over time. However, results of studies addressing this issue contradict each other in some cases (Egnell and Valinger 2003, Saarsalmi et al. 2010, Helmisaari et al. 2011), and the long-term impacts over a whole rotation period of, for example, 100 years are not known with accuracy. Further and more detailed evaluation of these elements and their impact at different locations is beyond the scope of this thesis.

It should be noted also that this thesis has not taken into account other emissions or environmental impacts than GHGs and climate change. For example, removal of biomass for energy purposes may have a significant negative impact on the biodiversity of forests (Åström et al. 2005).

4.6 Biomass availability prospects

The availability of harvesting residues and stumps for energy purposes is connected to industrial wood supply. The Finnish forest industry's total demand for pulpwood and saw and veneer logs has been projected to decrease by approximately 12–23% by 2020 from the average level between 2002 and 2011 (Kärhä et al. 2010, Hetemäki and Hänninen 2009, Finnish Forest Research Institute 2013b). A decrease in industrial wood demand and final fellings would directly reduce the amount of potentially available harvesting residues and stumps. However, it must be noted that the availability of harvesting residues and stumps is mostly dependent on demand of saw and veneer logs, and not to that extent on the demand of pulpwood. The demand of saw and veneer will probably not decrease as much as the demand of pulpwood in the near future (Hetemäki et al. 2011).

Another factor that may affect the availability of harvesting residues, stumps, and small-diameter energy wood in the future is the new forest act, currently under preparation. In consequence of possible changes in legislation, the amount of wood that is used for energy purposes may grow, but, on the other hand, the number of clearcuts (final fellings) may fall, decreasing the amount of residues and stumps that can be collected economically (Kostamo et al. 2012).

Another factor that may affect the availability of forest biomass for energy purposes in Finland, increasing it, is climate change itself. Climate change has been assessed as increasing forest growth in Finland, more in the northern parts of the country than in the southern regions (Briceño-Elizondo et al. 2006, Talkkari and Hypén 1996, Ge et al. 2012). Furthermore, toward the south of the country, climate change may even decrease the growth of spruce (*Picea abies*), a major tree species for harvesting residues and the only source of stumps taken into account in this thesis. These effects of climate change would further decrease the differences between southern and northern locations in terms of GHG emissions related to forest-biomass supply. Climate change is also expected to increase forest damage due to more severe and frequent storms and increasing insect outbursts (Gardiner et al. 2010, Lindener et. al 2010). Further assessment of these aspects in terms of forest biomass availability for energy purposes is, however, outside the scope of this thesis.

4.7 The role of transportation

Transportation is a major component in the total supply-chain costs of forest biomass, and its share increases as the amounts supplied and the transportation distances grow (Tahvanainen and Anttila 2011, Ranta 2005, Laitila 2008). If one assumes that forest operations are handled similarly across Finland and that there are no significant differences between locations in terms of unit costs of forest operations or in the stumpage costs (i.e., the prices paid to the forest-owner for the material), because of, for example, local competition, transportation is the only truly location-dependent cost component. Fuel constitutes approximately 80% of the variable costs of road transportation of forest biomass (Ihalainen and Niskanen 2010) and up to 30% of all costs of road transportation (SKAL 2012), and its share of the total transportation costs is rising (Statistics Finland 2013). Accordingly, while location is not a decisive factor in terms of GHG emissions of forest biomass use in Finland, it is a critical factor in terms of supply-chain costs. Cost-efficient feedstock supply is also a key aspect of the international-level commercialization of new bioenergy systems, such as second-generation liquid biofuels (Sims et al. 2010). When one takes into account both aspects of the forest-biomass supply chain, costs and GHG emissions, and in that order from the perspective of a plant utilizing forest biomass, the best locations in terms of supply chain costs are also the best ones in terms of GHG emissions. Furthermore, the results reported in this thesis indicate that, in consideration of GHG emissions, it is feasible to expand the supply area surrounding a given plant and also to use railway transportation from distant supply areas, to reach out for more harvesting residues, instead of using stumps or energy wood available closer to the plant. The lower GHG emissions related to energy utilization of harvesting residues, especially those associated with soil carbon-stock changes, outweigh the increased emissions from transportation. Harvesting residues are currently also the cheapest types of forest biomass in Finland (Kallio et al. 2011), making this practice cost-efficient too. However, use of railways in forest-biomass transportation for energy purposes is very limited in Finland at present, particularly on account of the high fixed costs and the lack of rail connections to biomass-utilizing CHP plants. In Sweden, about 3.6 PJ of forest biomass is transported by rail annually (Routa and Ranta 2012).

The GHG emissions of forest-biomass supply can be cut through railway transportation, given that suitable railway connections and loading locations exist. Railway transportation also reduces costs over longer distances, and the loading locations can act as terminals or buffer storage increasing the security of supply and facilitating improvements in feedstock quality management (Tahvanainen and Anttila 2011, Gronalt and Rauch 2007, Kärhä 2011). However, for cost-efficient use of the transportation equipment, the feedstock must be comminuted before the train arrives, either at the roadside or at the loading location. Once comminuted, the biomass starts decaying more rapidly, possibly resulting in increasing GHG emissions. Therefore, if feedstock is transported by rail, the operations should be arranged so as to ensure that the storage time of comminuted biomass is as short as possible. Otherwise the decrease in emissions from transportation may be offset by increase in storage emissions. In Finland, transportation of loose residues and chipping at the loading location is the most GHG-efficient, and also the most cost-efficient, system with distances under 30–65 km, depending on type of biomass and transportation equipment (Tahvanainen and Anttila 2011). Comminution at the loading location facilitates efficient use of comminution equipment and minimizes the need for storage of comminuted feedstock, and it also facilitates further drying of the uncomminuted feedstock at the loading location, improving its properties as fuel. Another option in long-distance transportation by rail is to transport uncomminuted material with the same railcars that are used for industrial raw wood. In this case, harvesting residues or energy wood should be bundled, or energy wood delimbed. This practice would facilitate efficient comminution at plants and minimize the need for storing comminuted material before railway transport, thus minimizing possible storage emissions at that stage.

A legislative process is currently underway in Finland to increase trucks' maximum weight from 60 to 76 tons and their maximum height from 4.2 to 4.4 m (Ministry of Transport and Communications of Finland 1992, Finnish Government 2012). For transportation of forest biomass, this would mean an increase of roughly 7% in cargo volume[12]. On the assumption that the larger trucks could operate on the small unpaved forest roads typical of forest-biomass transportation, this increase in cargo volume would slightly decrease the differences in supply-chain GHG emissions between locations. However, its effect on total supply- and utilization-chain GHG emissions can be estimated to be minor.

[12] The height of cargo space varies between trucks. This ~7% increase in cargo volume is based on 3m height of current cargo space.

4.8 Policy issues

The results in this thesis indicate that the greatest GHG reductions with forest biomass can be achieved by replacing peat and coal in CHP production. From this point of view, the current, recently updated Finnish legislation (Laki uusiutuvilla…2012 and 2012) is guiding forest-biomass use in the right direction: the feed-in tariff for electricity produced with biomass is tied to the taxation of peat, with the aim being to ensure competitiveness of forest biomass against peat. Gasification of biomass and coal replacement too is currently subsidized through a feed-in tariff. It should be noted that, in the short term, the use of peat facilitates the use of forest biomass at many plants, because it is required as a supporting fuel, on account of the technical characteristics of the boilers. In that respect, ensuring the competitiveness of peat when compared to coal by legislative measures can be seen as a justified measure, although the emissions related to peat production and combustion of peat are similar to, or greater than, the emissions associated with coal.

In Finland, the type of biomass used most, small-diameter energy wood, is currently subsidized with the "Kemera" incentives, grounded in the Sustainable Silviculture Foundation Law (Kestävän metsätalouden...2007). Without these subsidies, production of energy-wood chips and their energy use would in many cases be unprofitable (e.g., Petty and Kärhä 2011). Currently a new national support mechanism for small-diameter energy wood is under preparation, but it is unclear how and to what extent the use of this kind of forest biomass will be supported in the future (Ministry of Agriculture and Forestry 2013). Because small-diameter energy wood currently has the highest supply-chain costs of any type of forest biomass (Kallio et al. 2011, Laitila et al. 2010), the subsidies are critical for its use. If the support level decreases, the availability of this particular type of forest biomass at a feasible price for the users will be reduced. This is sure to affect the feedstock supply for users in northern Finland more than users located in southern parts of the country, because the proportion of small-diameter energy wood, out of the total amount of potentially available forest biomass, is much higher in the north.

The EU has numerous, quite different renewable energy support mechanisms in the Member States, and these are in some cases contradictory in view of the goal of maximal reductions of GHG emissions and reaching of the EU's common GHG emission-reduction targets (Poullikkas et al. 2012, Kautto et al. 2012, Leduc et al. 2012). For example, Leduc et al. (2012) state that the biggest reduction in GHG emissions EU-wide through the use of forest residues is to be found with CHP plants, not in the production of liquid biofuels for the transport sector. Therefore, the EU's targets of 20% overall GHG reductions and 10% biofuel use in transport are in mutual conflict (European Commission 2008 and 2009). Differences in national support policies within the EU may also lead to increasing export of forest biomass or forest-biomass-based energy-carriers such as liquid biofuels from Finland (Heinimö et al. 2011), which, in turn, would make it more difficult to procure enough biomass for local Finnish users economically. This could result in the use of fossil fuels instead of biomass. Transportation by ship is the best alternative for overseas export of forest-biomass-based products in terms of costs and GHG emissions (Hamelinck et al. 2005). This may, however, bring about the issue of emissions from storage of comminuted biomass, because, on account of the high volumes, comminuted feedstock may have to be stored longer before shipping than in road and railway transportation. Therefore, in export situations, the conversion losses in, for example, torrefaction and pyrolysis-oil production may be insignificant when compared to the possible emissions of storage. Conversion to more energy-dense carriers also decreases transportation costs and the GHG emissions of transportation per unit of energy.

4.9 Finnish forest biomass vs. other biomasses

On a global scale, energy crops grown specifically for energy purposes constitute the majority of solid biomass feedstocks for biofuels and power generation. Sugar and starch crops (sugarcane, sugar beet, and corn) and vegetable-oil feedstocks (rapeseed, soybeans, and oil-palm fruit) account for more than 60% of the current feedstocks, while the share of forest residues is under 20%. It is expected that by 2035 the share of these energy crops and that of forest residues will decline to 40% and 10%, respectively. The largest growth is projected to come from the use of agricultural residues, whose percentage should rise from the current 10% to 35% by 2035 (IEA 2012). The GHG performance of the forest-biomass feedstock supply chains assessed in this thesis is superior to that of energy crops[13]. For example, the default GHG emissions defined by the EC for sugarcane, sugar beet, and corn feedstocks are 24, 40, and 43 $gCO_2eq\ MJ^{-1}$, and those for rapeseed, soybeans, and palm oil are 52, 58, and

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[13] The supply chain for energy crops includes cultivation, processing, transport, and distribution.

37–68[14] $gCO_2eq\ MJ^{-1}$, respectively (European Commission 2009). According to the results in this thesis, the GHG emissions arising from forest-biomass supply chains in Finland range roughly between 2 and 4 $gCO_2eq\ MJ^{-1}$. The above values do not include indirect emissions from land-use change or soil carbon-stock changes. If land-use changes and other indirect emissions are included, the GHG emissions of energy crops can be significantly higher, and the GHG emissions of energy-crop-based energy production may be higher than those of fossil fuels (e.g., Searchinger et al. 2009). When soil carbon-stock losses are taken into account in the case of Finnish forest biomasses on a 100-year time horizon, the GHG emissions are in the range 10–40 $gCO_2eq\ MJ^{-1}$ (calculated for single event combustion). In conclusion, even *with* soil carbon-stock losses accounted for, the GHG emissions of Finnish forest-biomass supply chains are lower than the GHG emissions of sugar and starch crops and vegetable oil crops *without* these indirect emissions. However, it should be noted that on a shorter time horizon, the relative GHG performances of biomass feedstocks with shorter rotation (such as energy crops) become better when compared to feedstocks with longer rotation periods (such as Finnish forest biomass) in terms of soil carbon stock changes.

4.10 Need for further research

Key issues that should be addressed in future research are the following:

- What are the actual emissions from biomass storage in each forest-biomass supply situation and logistics scenario? In relation to this, there is also evident need to make the sustainability criteria, calculation procedures, and related legislation clearer in this regard: Are storage emissions included, and, if so, how case-specifically should they be addressed?
- How should indirect GHG emissions, particularly soil carbon-stock changes, be accounted for in sustainability assessments? In relation to this issue, the policies and calculation procedures should be more transparent and unbiased.

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[14] Lower value for a process involving methane capture at oil-mill sites; higher value for an unspecified process (European Commission 2009).

- How can biomass logistics be improved, so as to facilitate cost-efficient supply of feedstock to the users while the emissions of the supply chain – including storage – are kept as low as possible?

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