System analysis and life cycle assessment of forest supply chains with integrated biomass production

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Abstract

Forests are essential suppliers of raw materials for industrial products and renewable energy, which can help mitigate climate change. In Europe, the market for forest bioenergy and other wood products is expected to continue growing in the future. Therefore, new procurement methods and assortments with high energy efficiencies and low greenhouse gas (GHG) emissions are required from a climate change perspective. One alternative to current conventional supply chains is utilizing integrated supply chains where residual forest biomass is harvested and transported together with stemwood. Additionally, mobile production systems, such as small-scale mobile pellet plants that are situated close to the raw material source, could increase the efficiency of residual forest biomass supply chains, especially in regions with long transportation distances to industry. The overall aim of this thesis was to assess the cost, energy use, GHG emissions and other relevant environmental impacts (terrestrial acidification, marine and fresh water eutrophication, photochemical oxidant formation and fossil fuel depletion) of conventional and integrated forest supply chains in Northern Sweden to provide knowledge that could stimulate the development of more efficient supply chains. The assessment included modelling of conventional and integrated forest supply chains in Northern Sweden, a case study in Western Canada, and modelling of a mobile production system for pelletizing logging residues. A life cycle assessment approach was used in the analyses.

The results showed that integrated supply chains have the potential to reduce the supply cost for non-stemwood assortments. Furthermore, the integrated supply chains were more energy efficient than conventional supply chains, and have the potential to reduce GHG emissions by approximately 13%. The reduction in terrestrial acidification, marine and fresh water eutrophication, photochemical oxidant formation, and fossil fuel depletion associated with switching from a conventional to integrated supply chain was 17%, 24%, 17%, 17%, and 13%, respectively. The evaluated Swedish supply chains also showed, on average, better environmental profiles per oven dry tonne than the Canadian supply chains that were assessed. The environmental performance of a small-scale mobile pellet production system operating at forest landing and at forest terminal was similar in both alternatives. However, if the terminal had access to the power grid, then the environmental impacts (with the exception of fresh water eutrophication potential) decreased, and operating at the terminal became a better option from a life cycle assessment perspective.

Keywords: integrated harvest, environmental evaluation, GHG emissions, wood fuel

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Dedication

To Encarni, Fernando and Javi

Nature is not a place to visit. It is home.
Gary Snyder

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This thesis is based on the work contained in the following studies, referred to by Roman numerals in the text:

I Joelsson, J., Di Fulvio, F., De La Fuente, T.*, Bergström, D., Athanassiadis, D. (2016). Integrated supply of stemwood and residual biomass to forest-based biorefineries. *International Journal of Forest Engineering,* 27:115–138.

II De La Fuente, T.*, González-García, S., Athanassiadis, D., Nordfjell, T. (2016). Fuel Consumption and GHG emissions of forest biomass supply chains in Northern Sweden: a comparison analysis between integrated and conventional supply chains. *Scandinavian Journal of Forest Research,* 1-14. DOI: 10.1080/02827581.2016.1259424

III De La Fuente, T.*, Athanassiadis, D., González-García, S. and Nordfjell, T. (2017). Cradle-to-gate life cycle assessment of forest supply chains: Comparison of Canadian and Swedish case studies. *Journal of Cleaner Production*, 143: 866-881.

IV De La Fuente, T.*, Bergström, D., González-García, S., Larsson, S.H. Life cycle assessment of decentralized mobile production systems for pelletizing logging residues under Nordic conditions (manuscript).

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The contribution of Maria Teresa de la Fuente Diez to the studies included in this thesis was as follows:

I Responsible for performing the energy consumption analysis (model building, data collection together with Fulvio Di Fulvio, and calculation of results), some of the writing, and coordinating efforts between authors for publishing.

II Proposer of the original idea; responsible for planning the study, performing the data collection, calculations, analysis of the results, and writing the majority of the manuscript.

III Proposer of the original idea; responsible for planning the study, performing the data collection, calculations, analysis of the results, and writing the majority of the manuscript.

IV Responsible for planning the study together with Dan Bergström, performing the data collection, calculations, analysis of the results, and writing the majority of the manuscript.

Abbreviations

ALCA	Attributional life cycle assessment
BWT	Bundled whole small trees
CH_4	Methane
CLCA	Consequential life cycle assessment
CO_2	Carbon dioxide
CO_2-eq.	CO_2-equivalents
COP	Conference of the Parties
DBH	Diameter at breast height
DLCA	Dynamic life cycle assessment
EIA	Environmental impact assessment
ET	Energy thinning
FDP	Fossil fuel depletion potential
FEP	Fresh water eutrophication potential
FF	Final felling
FT	First thinning
g	Gram
GHG	Greenhouse gas
GWP	Global warming potential
h	Hour
ha	Hectare
kg	Kilogram
km	Kilometer
l	Liter
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LR	Logging residues

LRS	Non-merchantable stems
LT	Long tops
MEP	Marine eutrophication potential
MJ	Megajoule
MODt/yr	Million oven dry tonnes per year
MWh	Megawatt hour
N-eq.	Nitrogen-equivalents
NMVOC	Non-methane volatile organic carbon compound
ODt	Oven dry tonne
Oil-eq.	Oil-equivalents
P-eq.	Phosphorus-equivalents
PCT	Pre-commercial thinning
PL	Pulpwood
PM_{15h}	Productive machine hours including delays shorter than 15 minutes
POFP	Photochemical oxidant formation potential
RS	Rough-delimbed tree sections
SC	Stump core
SL	Sawlogs
SP	Stumps
SOC	Soil organic carbon
SO_2-eq.	Sulfur dioxide
ST	Second thinning
sub	Solid volume under bark
t	Metric tonne
TAP	Terrestrial acidification potential
ToSIA	Tool for sustainability impact assessment
TWh	Terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

1.1 Forestry in Sweden and the world, a brief overview

The global forest area is around 4 billion hectares (ha), and covers about one-third of the total land area. The most forested countries are Russia, Brazil, Canada, the United States and China, which together account for more than half of the total forest area (Swedish Forest Agency, 2014). Canada accounts for nearly 9% of the world's forests, or 347 million ha (Ministry of Natural Resources Canada, 2017a). The forests of Europe amount to 215 million ha, with Northern Europe as the most forested region (Forest Europe, 2015). The total volume of the global growing stock has been estimated to be 527 billion m^3 (Swedish Forest Agency, 2014). Canada's growing stock volume reached 47 billion m^3 in 2016 (Ministry of Natural Resources Canada, 2017b), while the growing stock of European forests amounts to 35 billion m^3 (Forest Europe, 2015). The Swedish growing stock accounts for 9% of the European stock, or 3.1 billion m^3 (Swedish Forest Agency, 2017).

Forests supply the world's population with wood products, which are essential as both materials and an energy source. Energy from wood represents around 40% of the current global renewable energy supply, and plays an especially important role in low-income countries where wood fuel is the main wood product (FAO, 2016). In 2015, forests provided 3714 million m^3 of roundwood (1866 million m^3 wood fuel and 1848 m^3 industrial roundwood), 452 million m^3 of sawnwood, 406 million tonnes of paper and paperboard, 399 million m^3 of wood-based panels, 176 million tonnes of pulpwood, and 28 million tonnes of wood pellets (FAO, 2017a). Among the forest product-exporting countries, Canada and Sweden were the leading exporters of sawnwood in 2015, together with Russia, Finland and Germany. The two countries were also the leading exporters of pulpwood, together with Brazil, USA, Chile, Indonesia and Finland, as well as paper and paperboard, together with Germany, USA and Finland (FAO, 2017b).

The annual roundwood harvest in Europe is about 430-450 million m^3, and the standing volume still increases by about 400 million m^3 per year (Moffat et al., 2015). Approximately 40% of the harvested volume consists of sawlogs, another 33% is industrial pulpwood, and the rest is wood fuel (Finnish Statistical Yearbook of Forestry, 2014). In Sweden, the amount of harvested roundwood has continuously increased since the early twentieth century, with a net felling volume of 70.1 million m^3 reported in 2013 (Swedish Forest Agency, 2014), yet the forest stock has increased during the same time period due to active forest management.

Today, two dominant mechanized harvesting methods, full-tree and cut-to-length, are used worldwide (c.f. Drushka and Konttinen, 1997). In the full-tree harvesting method, trees are felled by feller-bunchers and skidded to the roadside. Delimbing and cross-cutting by a processor then often occurs at the roadside. Branches, tops and low-quality non-merchantable logs are usually piled at the roadside and then burned to reduce the risk of forest fire. In the cut-to-length harvesting method, trees are felled, delimbed and processed by harvesters into sawlogs and pulpwood lengths at the stump site, leaving the tops and branches as residues. Roundwood is then forwarded to the roadside. If residues are recovered, they are transported to the roadside with specially-equipped forwarders and usually chipped before transportation. If the stumps are recovered, they are harvested with excavators that have stump-lifting tools, and specifically equipped forwarders (Berg et al., 2014). Another harvesting method is the tree-length method, in which trees are felled, delimbed and topped (but not crosscut) directly at the stump site, and then skidded to the roadside (Uusitalo, 2010). The full-tree method dominates in the USA and Canada while the cut-to-length method is preferred among the Scandinavian countries. Swedish forestry has developed into an efficient supplier of stemwood to forest industries and its productivity has improved through mechanization and technical development. Generally, coarse, higher-quality logs are supplied to sawmills while small-diameter, low-quality logs are supplied to pulp mills. The logging residues (tops and branches) are recovered separately for the production of heat and power.

1.2 The role of forests in a climate change context

At the 2015 Paris Climate Conference (COP21), parties to the UNFCCC reached a historic agreement to combat climate change, which entered into force on November 2016. The Paris agreement’s central aim is “to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" (UNFCCC, 2017). As of April 2017, 143 of 197 Parties to the Convention have ratified the Agreement (UNFCCC, 2017). The European targets include reducing greenhouse gas (GHG) emissions by at least 40% by 2030 (from 1990 levels), obtaining at least 27% of energy from renewable sources and delivering an improvement of at least 27% in energy efficiency (European Commission, 2015). The Swedish parliament accepted a renewable energy target of 50% for 2020. In 2013, renewables accounted for 52% of Sweden's energy supply, and it has been estimated that this percentage will slightly increase by 2020 (Swedish Energy Agency, 2015).

Forests do not only supply raw materials for industrial products and renewable energy, but are also vital to mitigating climate change. Trees absorb carbon dioxide (CO_2) from the atmosphere during photosynthesis, converting solar energy, CO_2 and water into carbohydrates while releasing oxygen. Therefore, a growing forest constitutes a carbon sink, as the carbon that is absorbed from CO_2 is bound in both the above- and below-ground biomass. Thus, wood products store carbon, which is released back into the atmosphere in the form of CO_2 when the biomass decomposes or is incinerated. Woody biomass from sustainably managed forests can be substituted for more energy-intensive materials and/or non-renewable fossil fuel-based energy carriers to reduce carbon emissions into the atmosphere.

Forest biomass is currently one of the most important energy sources in Sweden. In 2014, biomass provided 130 TWh of energy (Swedish Energy Agency, 2016). Per fuel category, undensified wood fuel, black liquor and densified wood fuel represented 40%, 33%, and 6% of the total biomass used for energy, respectively (Swedish Energy Agency, 2016). Most of the by-products from the Swedish paper, pulp, and timber industries are currently used to generate energy, but additional forest biomass will be needed to satisfy the demands of the bioenergy market, (Eriksson and Gustavsson, 2008; Forsell et al., 2013), future biorefineries, and EU targets for 2020 and 2030.

1.3 The need for highly efficient supply chains

"The supply chain encompasses all activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end user, as well as the associated information flows" (Handfield and Nichols, 1999). In the scope of this thesis, forest supply chains comprise the operations needed to extract forest biomass from the forest and deliver it to the industry.

Conventional supply chains refer to the separated harvesting and transportation of stemwood and residual forest biomass, while integrated supply chains refer to the integrated harvesting of stemwood and residual forest biomass.

The intensity of forest harvesting is expected to increase in order to meet demands for traditional products and bioenergy (Egnell et al., 2011). Furthermore, Gullberg and Johansson (2006) note that if demand increases, then residual forest biomass will have to be harvested from less favorable sites. Thus, the efficiency of forest biomass supply chains must be improved (Berg, 2003; Ghaffariyan et al., 2017; Routa et al., 2013; Thorsén et al., 2010).

Earlier research has identified harvesting methods and forestry machinery that can increase productivity while reducing costs (Ghaffariyan et al., 2017). Jylhä (2004) presented a prototype of a bundler-harvester that can be used to extract pulpwood and residual forest biomass during the first thinning of Scots pine stands. During trials in Finland, the machine demonstrated higher productivity in dense stands with small-diameter trees than in conventional thinning sites, as the pulpwood and residual forest biomass are harvested simultaneously. An updated version of the machine was tested by Nuutinen et al. (2011) and demonstrated productivity increases that ranged from 38–77% depending on stand density and mean tree volume. This improvement in productivity can be explained by an increase in multi-tree cutting and a mechanism that employs the grapple feeding of bunches.

Junginger et al. (2005) suggested that the use of bundling technology in certain assortments, such as long tops, could reduce the costs of wood fuel. Moreover, Sängstuvall et al. (2011) showed that applying multi-tree-handling in boom corridors could increase harvester productivity during the thinning of dense, young stands. Similarly, Nordfjell and Bergström (2010) found corridor thinning to be 10–15% more productive than the conventional thinning method (selective thinning between striproads spaced at ca. 20 m) for such stands. This concept was extended by Bergström and Di Fulvio (2014), who showed that the addition of boom corridor thinning, optimized bundle-harvesters, and load-compression devices to current systems could reduce both costs and energy consumption. Eriksson and Gustavsson (2008) highlighted that multi-tree handling is key to reducing costs during the thinning of small trees. Di Fulvio and Bergström (2011) showed that rough-delimbing and load compression leads to reductions in harvesting cost and increases in bulk density. Asikainen (2004) also reported that the compression of logging residues and rough-delimbing of stems increases productivity and reduces costs. Another innovative technique includes methods for harvesting stump cores (Athanassiadis et al., 2009; Berg, 2014).

However, despite the expected increase in forest biomass demand and development of technologies that noticeably increase harvesting productivity, conventional harvesting continues to be the most commonly applied method in Swedish forestry. Certain adjustments, which facilitate the collection of residual forest biomass, have been made in the harvesting operations to improve productivity and fuel quality throughout the supply chain (Skogforsk, 2010). However, the basic principles of harvesting operations have remained the same over the past 20 years, with the harvesting of residual forest biomass still a secondary operation in conventional harvesting processes (Björheden, 2006). Therefore, the supply of primary wood fuels depends on the intensity of conventional final felling operations. An alternative to the present approach would be to use integrated supply systems in which the residual forest biomass supply chain is integrated with the stemwood supply chain. Such systems were scrutinized during the late 1970s in Sweden, when the global oil crisis motivated the utilization of domestic forest biomass to secure a supply of energy (Whole Tree Utilization 1975–1980). However, the crisis was temporary and even though the single-grip harvester, along with the cut-to-length harvesting method, was introduced in the early 1980s, the extraction of undelimbed wood (tree parts/sections) declined and finally fell out of use by the late 1980s (Nordfjell et al. 2010). The current increase in the demand for forest biomass has resulted in new developments in integrated forest harvesting systems in Sweden and other countries (c.f. Berg et al., 2014; Harril and Han, 2012; Kärhä et al., 2011).

Mobile production systems, which are located close to the raw material, are another promising alternative for increasing the efficiency of residual forest biomass supply chains, especially in regions that are characterized by long transportation distances to industry. Residual forest biomass, such as the logging residues from final fellings in Northern Sweden, show great potential for use in several biorefining processes (Bergström and Matisons, 2015). However, due to the bulky nature of biomass, densification may be required before transportation over long distances (Paulrud, 2004). The development of mobile systems for the decentralized pelletizing of forest-based residual biomass is currently underway (Mobile Flip, 2017). The investigation of how a production system should be designed and managed for high energy efficiency, low environmental impacts and reduced costs underlies the system's success. Thus, decentralized production systems need to be developed to: 1) value the pre-processing of biomaterials close to the raw material source before they are transported to industry and/or 2) produce the final product at/close to the raw material source. High production efficiency, low consumption of energy and materials, and low environmental impact are all essential to ensuring the overall sustainability of such systems.

Forest supply chains usually require fossil fuels for the production, extraction, transport and conversion of biomass to either bioenergy or other final products (e.g. forestry machinery and trucks usually run on fossil diesel). The more fossil fuel input a forest supply chain requires, the less energetically desirable it is and the less climate benefits it provides. Therefore, depending on the biomass procurement and processing requirements, some supply chains will perform better than others from an environmental perspective. Cherubini et al. (2009) presented the GHG emissions per unit of output of various bioenergy production chains. Vehicles running on bioethanol from lignocellulose, although still under development, showed lower emissions/km than bioethanol from agricultural crops and much lower emissions/km than vehicles that used fossil fuels. Regarding electricity and cogeneration, woody biomass showed lower emissions per MJ than fossil fuels, but higher emissions when compared to wind, geothermal or hydro. In terms of heat production, woody biomass showed the lowest emissions per MJ after geothermal. Although the use of forest feedstocks to produce energy or materials can reduce GHG emissions when compared with fossil fuels or other materials, such as concrete, it is important to identify which forest assortments, processes, and supply chains minimize emissions to air, water and soil in order to maximize the environmental benefits of using forest biomass as a material and energy.

1.4 System analysis and life cycle assessment

System analysis can be seen as a bridge between decision makers and the research community (Quade and Miser, 1980). It is a problem-solving activity that decomposes a system into its parts, and then analyzes each part and its interactions. System analysis strives to help decision makers solve problems and make informed decisions by considering various alternatives in terms of, among others, costs, benefits, and environmental impacts. In system analysis, scientific knowledge serves as the base upon which a strong foundation for analysis and its results is built (Quade and Miser 1980). According to Quade and Miser (1980), a complete system analysis should include the following aspects: a critical examination of the aim of the policy or decision that is being considered; an exploration of alternatives that can achieve that aim; an evaluation of the impacts of different alternatives; a comparison of the alternatives; and a presentation of the results to decision makers in a way that will facilitate an informed choice.

Life Cycle Assessment (LCA) is a tool used in system analysis that compiles and evaluates resource consumption and waste generation to estimate the potential environmental impacts of the investigated production system. This methodology helps assess the environmental profile of a product or service throughout its life cycle (ISO 14040, 2006). LCA has been regulated in the ISO 14040 and 14044 standards (ISO 14040, 2006; ISO 14044, 2006), which describe the principles, framework, requirements and guidelines for LCA. Each LCA study has four phases: definition of goal and scope; inventory analysis; impact assessment; and the interpretation phase (Fig. 1). The goal and scope depend on the intended application of the study. However, the product system to be studied, as well as the functional unit and system boundaries, must be clearly defined in every case. The functional unit is a key element of the analysis since it is the reference flow regarding which inputs (e.g. materials and energy) and outputs (e.g. emissions to air, water and soil) will be reported as well as the final environmental results (ISO 14040, 2006). The functional unit must be clearly defined to enable comparative analyses of different systems. Oven dry tonne (ODt) has been used as the functional unit in various LCA studies of woody systems and hence allows comparisons of different forest supply chains (Whittaker et al., 2010; Whittaker et al., 2011; Johnson et al., 2012). This functional unit was also used in the research underlying this thesis. The system boundaries define the processes that will be included in an LCA study. These processes are linked to one another by flows of intermediate products and/or waste. A product system is broken down into its processes to help analyze the inputs and outputs of the whole system. The quality of an LCA study depends on the collected life cycle inventory (LCI) data. This phase of the LCA involves the compilation and quantification of all inputs and outputs of the product or service system. It includes energy, raw material and ancillary inputs, products, co-products and waste, as well as emissions to air, water and soil. These data then need to be related to each unit process and to the functional unit. The impact assessment phase evaluates the potential environmental impacts by defining the environmental impact categories according to the goals and scope of the study, along with the LCI results. Finally, the interpretation phase presents the results and conclusions in an understandable way, and also clarifies the limitations of the study.

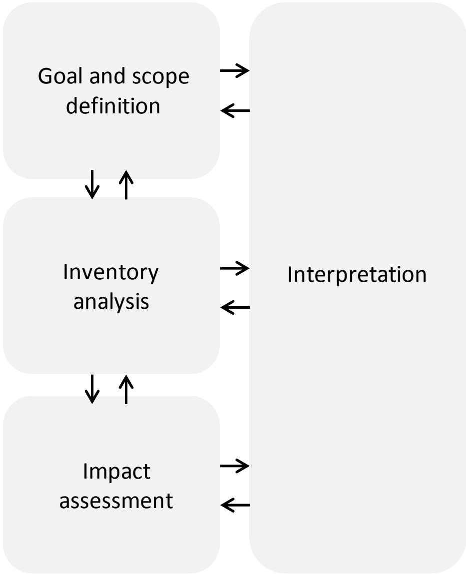


Figure 1. Phases of Life Cycle Assessment (ISO 14044, 2006).

LCA has been widely used to determine the environmental impacts, such as global warming potential (GWP), of bioenergy systems, wood supply chains and woody products (Berg, 1997; Forsberg, 2000; Ghafghazi et al., 2011; González-García et al., 2014; Jungmeier et al., 2003; Lindholm et al., 2010; Lindholm et al., 2011; Murphy et al., 2014; Sikkema et al., 2013; Thakur et al., 2014; Valente et al., 2012; Adams et al., 2015; Fantochi and Buratti, 2010; Hagber et al., 2009; Katers et al., 2012; Laschi et al., 2016; Pa et al., 2011; Porsö and Hansson, 2014; Sikkema et al., 2010). LCA is also used to calculate the GHG emissions arising from biofuels under the EU Renewable Energy Directive (EC, 2009). In addition to evaluating GWP, LCA can be used to analyze how a certain system affects acidification, eutrophication, photochemical oxidant formation or fossil fuel depletion. Moreover, this tool can help improve environmental and operational aspects of forest operations by analyzing and comparing different forest machine configurations, identifying key processes ("hotspots"), and contributing to machine development. Forest managers can then make better system choices by evaluating both the productivity and potential environmental impacts of alternative systems.

1.5 Aim of the thesis and specific objectives

The overarching aim of this thesis is to assess the cost and environmental impacts of conventional and integrated forest supply chains in Northern Sweden to provide knowledge that could be useful in the development of highly efficient supply chains. This thesis draws upon four studies, which had the following specific objectives:

- To assess the costs and energy use associated with supply chains that integrate the harvest of residual forest biomass into the stemwood supply chain in three industrial locations suitable for biorefineries in Northern Sweden (study I).
- To compare integrated and conventional supply chains at three industrial locations in Northern Sweden in terms of fuel consumption and GHG emissions (study II).
- To identify which forest assortments, processes, and supply chains result in the least GHG emissions (study II).
- To investigate and compare the environmental impacts (global warming, terrestrial acidification, marine and fresh water eutrophication, photochemical oxidant formation and fossil fuel depletion) related to the production of different forest assortments (sawlogs and residual forest biomass) from Swedish and Canadian forest supply chains, and to identify the “hotspots” in the supply chains (study III).
- To quantify and compare environmental impacts (global warming, terrestrial acidification, marine and fresh water eutrophication, photochemical oxidant formation and fossil fuel depletion) of a small-scale decentralized mobile production system in Northern Sweden for pelletizing logging residues under two different operating scenarios: landing-based and terminal-based (study IV).
- To provide information on how different processes contributed to total emissions, to identify the key processes within the production system, and to investigate how on-site raw material concentration, transportation distance, pelletizer production capacity, and the use of electricity at the terminal affect the environmental performance of the system (study IV).

2 Materials and methods

The integrated supply chains were compared to conventional supply chains in terms of cost, energy use, GHG emissions and other relevant environmental impacts (terrestrial acidification, marine and fresh water eutrophication, photochemical oxidant formation and fossil fuel depletion). The assessment included the modelling of sawlog and residual forest biomass supply chains in Northern Sweden, a case study in Western Canada, and the modelling of a mobile production system for pelletizing logging residues. An LCA approach was used in the analyses.

2.1 Systems description

2.1.1 Locations

Three sites in Northern Sweden were selected for studies I and II (Fig. 2). Two of these sites, Umeå and Örnsköldsvik, were located on the coast. Both locations have existing biomass-fired combined heat and power plants, as well as large pulp mills and potential locations for new types of biorefineries. The third location, Storuman, is located inland, and is a potential location for either a biorefinery or an industrial-scale hub for feedstock handling and upgrading before further transportation to industries. A circular supply area with a radius of 120 km was set for each site. In study III, Örnsköldsvik was chosen as the Swedish case study area and the Quesnel timber supply area, which lies in the interior of British Columbia in Western Canada, was chosen as the Canadian case study area (Fig. 2). In the study IV, the forest supply area was also located in Örnsköldsvik.

(a)

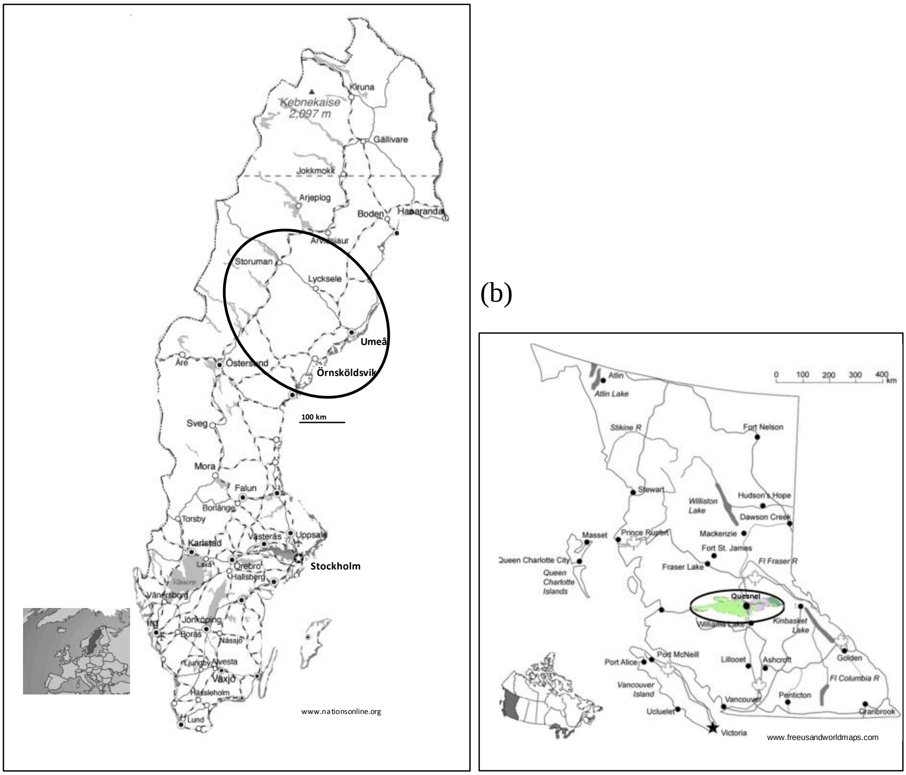


Figure 2. Locations of the studies. a) Örnsköldsvik, Storuman, Umeå - Sweden; b) Quesnel - Canada.

2.1.2 Forestry regimes and forest assortments

The conventional Swedish forest supply chains in studies I, II and III included a forestry regime in which the forest cycle was assumed to comprise pre-commercial thinning (PCT), first thinning (FT), second thinning (ST) and final felling (FF). The main assortments extracted from the forest in the conventional supply chains were sawlogs and pulpwood. Logging residues and stumps were also extracted.

The Swedish integrated supply chains included the same forestry regime, as well as an alternative regime with energy thinning (ET) instead of PCT. During ET, unprocessed tree sections from whole small trees are extracted, whereas the cut trees are left on site during PCT. The whole small trees can be extracted loose or in bundles (BWT). The integrated supply chains extracted the following assortments from the forest: roughly delimbed tree sections (RS), long tops, sawlogs with a stump core (c.f. Berg et al., 2014), and whole small trees, or BWT. The length of a forest cycle was fixed at 95 years for both forestry regimes.

Study III included a Canadian case study in addition to the Swedish case study. The only forestry treatment included in the Canadian supply chains was FF, at year 100. No thinnings took place during the forest cycle; therefore, the Canadian scenarios produced less assortments than the Swedish ones. The conventional Canadian supply chains extracted sawlogs and pulpwood from the forests without any recovery of residual forest biomass. The Canadian biomass dedicated supply chains were similar to the conventional Canadian supply chains with the exception that the biomass dedicated supply chains included the recovery of logging residues and non-merchantable stems (LRS). Study IV only considered logging residues from final felling in Northern Sweden as feedstock for pellet production.

2.1.3 Forest supply chains

Cut-to-length harvesting was applied in all of the Swedish supply chain cases, while full-tree harvesting was the harvesting method used in the Canadian supply chains.

Study I

Three different groups of supply chains were compared in terms of cost and energy consumption: A (conventional supply chains); and B and C (integrated supply chains). In the conventional supply chains (A), stemwood and residual assortments were harvested separately, but these assortments were harvested together in the integrated supply chains (B and C). The integrated supply chains in group B included PCT while the integrated supply chains in group C included ET.

In the conventional supply chains, PCT was carried out manually with a cleaning saw once the stand was 10 years old, and the felled trees remained in the stand. FT was carried out in year 45 using a small harvester followed by a small forwarder. ST, in year 70, followed the same process but utilized a medium harvester and forwarder. FF was carried out in year 95 with a large harvester and forwarder. Pulpwood was extracted during FT, ST and FF. Sawlogs were extracted during ST and FF. Pulpwood and sawlogs were piled at the roadside and then transported by timber truck. Logging residues were collected after the FF harvest by a large forwarder, after which they were chipped by a truck-mounted drum chipper at the roadside and then transported by a wood chip truck. Stumps were removed using an excavator-based stump harvester and large forwarder. Two options were available for the stumps at the roadside: Stumps were either loaded into a shredder by a grapple loader, pre-crushed at the roadside, and then transported by wood chip truck; or the stumps were transported to terminal without pre-crushing.

In the integrated supply chains, residual forest biomass was recovered during all four forestry treatments that occurred within the forest cycle. During ET, which occurred in year 25, whole small trees were felled and bundled by a bundle harvester, after which these bundles were forwarded to the roadside using a small forwarder and then transported by timber truck. FT was carried out in year 50 by a small harvester with an accumulating felling head for rough delimbing, and a small forwarder. Trees were felled and only 50% of the branches were removed. The assortment resulting from this treatment was RS, which were transported by a logging residues truck. ST was carried out in year 75 using a medium harvester and forwarder. Sawlogs and long tops were extracted to the roadside, where a timber truck and a logging residues truck transported the sawlogs and long tops, respectively. FF was carried out in year 95 by a feller puller, which cut the tree and the core of the stump in a single piece. Following this, a harvester processed the logs by separating the sawlogs with stump cores from the long tops and a large forwarder brought the assortments to the roadside. A timber truck transported the sawlogs with stump cores while a logging residues truck transported the long tops.

Study II

The conventional and integrated supply chains (from groups A and C, respectively) from study I were selected for further analysis of their fuel consumption and GHG emissions. Integrated supply chains from group C were selected instead of those from group B since they showed lower cost/ODt. The study included BWT rather than loose whole small trees because study I had shown that the extraction, transportation and processing of BWT during ET cost less, and uses less energy, than that of loose whole trees. The conventional supply chains included pre-crushing stumps to a coarse fraction at the roadside.

Study III

The Swedish conventional and integrated supply chains (from groups A and C, respectively) were compared to Canadian conventional (without recovery of residual forest biomass) and biomass dedicated (with recovery of residual forest biomass) supply chains. Full-tree harvesting was applied to the Canadian supply chains. In the conventional Canadian supply chains, trees were felled in year 100 by a feller-buncher and transported to the roadside by a grapple skidder. A processor was then used to delimb and top the trees, as well as to pile up the processed logs at the roadside. Branches, tops and low quality non-merchantable logs (not suitable for either timber or pulp production) were piled by a grapple loader and then burned at the harvesting site using a drip torch. Sawlogs and pulpwood were transported by timber trucks to industry. Pulpwood was chipped at the industry site by a disc chipper similar to those used at terminals in the Swedish case. In the Canadian biomass dedicated supply chains, in addition to sawlogs and pulpwood extraction, branches, tops and low quality non-merchantable logs were chipped by a horizontal grinder at the roadside and then directly loaded into a wood chip truck.

Study IV

This study concentrated on a further step of the supply chain: the production of pellets from logging residues. Two scenarios were analyzed: a production system located at either the forest site (landing-based scenario); or the forest terminal (terminal-based scenario). The production system was divided into five stages: chipping; fractioning; drying; pelleting; and transportation. The operations of the landing-based scenario were carried out as follows:

- Chipping of logging residues was carried out at the landing using a truck-mounted drum chipper. The wood chips were directly loaded from the chipper to the fractioning machine.
- The fractioning process separated fines from sieved wood chips. A wind-sifter was used to separate contaminants, such as stones and gravel. The chipper, fractioning machine, and wind-sifter worked as one unit. After fractioning, a front wheeled loader piled the fines and sieved wood chips in two different piles.
- The sieved wood chips were dried using two dryer containers with a hot air generator. The same front wheeled loader mentioned above was used to load the drying containers and the boiler. Fine fractions obtained after fractioning were used as fuel for the boiler. Dry wood chips were screw conveyed to the hammer mill.
- The pelleting stage began with the hammer milling of the dry wood chips. The produced wood powder was then screw conveyed to the pelletizer. Produced pellets were belt conveyed to the cooling tower and a vibrating tray, after which they were loaded into truck containers.
- Container trucks and trailers were used to transport pellets from the landing to the terminal. The truck delivered two empty containers when arriving for reloading. The relocation of machinery from one harvesting site to the next harvesting site was performed with trucks, with the exception of the front

wheeled loader, which was able to relocate itself. A passenger car was used for the relocation of workers.

The terminal-based scenario included the same stages described above, with the following exceptions:

- Wood chips were directly loaded into truck containers and transported by container trucks and trailers to the forest terminal where they were unloaded and piled by a front wheeled loader. The truck delivered three empty containers when arriving for reloading.
- The fractioning machine worked independently of the chipper. A front wheeled loader loaded the chips onto the fractioning machine.
- Only chipper and chipper worker relocations were needed.

2.1.4 Available feedstocks

The harvesting of forest biomass at the three Swedish locations was modelled based on data from the Swedish National Forest Inventory (SNFI). The SNFI data were used in SFA (2008) to make long-run forecasts regarding growth, potential harvestable areas and harvesting volumes over years 2010-2019. Each SNFI plot was used as a silvicultural decision unit and contained information regarding geographical coordinates (X, Y), management (FT, ST or FF), and soil characteristics.The annual average amount of feedstock available from harvesting operations was also calculated for each plot. There were 268, 279, and 150 inventory plots within the 120 km radius area for the Umeå, Örnsköldsvik and Storuman sites, respectively. Of these plots, 30 for Umeå, 29 for Örnsköldsvik and 11 for Storuman were excluded because of environmental protection reasons. A separate dataset from the SNFI contained information regarding PCT and early ET stands, and as a result 32, 42, and 30 plots were added to the Umeå, Örnsköldsvik and Storuman sites, respectively.

The available biomass was calculated using the biomass functions presented by Petersson (1999) and Petersson and Ståhl (2006) to estimate the amounts (ODt/ha) of roundwood, bark, branches, needles, tops and stumpwood (including root system) from SNFI data. Stumps from broadleaves were excluded (i.e. it was assumed that they are left on site). The top diameter for sawlogs and pulpwood was fixed at 12 and 5 cm under the bark, respectively. The mass of logging residues resulting from FF in conventional supply chains A was calculated as the sum of the mass of branches and tops. The RS mass was calculated as the sum of the pulpwood, tops, and the respective portion of branch mass. The mass of long tops resulting from ST was calculated as the sum of pulpwood mass and tops, with the addition of branches. The long top mass resulting from FF was calculated as the sum of pulpwood and tops. The annual potential for harvesting whole small trees from ET stands was calculated in plots with an average height between 5.5 m and 8 m and in which biomass removal exceeded 25 ODt/ha. The whole small tree and BWT mass was obtained as the sum of the mass of pulpwood, tops, bark and total branches. Plots with an average height between 2.0 m and 5.5 m and in which biomass removal exceeded 10 ODt/ha were classified as PCT stands. The total stump mass was given in the inventory plots. The stump core mass was calculated by multiplying the total stemwood mass (sawlog, pulpwood, top and bark) by 0.085, according to Berg et al. (2014).

Study III used the Örnsköldsvik supply area as the Swedish case. This translates to a yearly harvesting area of 31,785 ha. This area included 3474 harvesting sites that would undergo FT, ST and FF, as well as 989 harvesting sites that would receive either PCT or ET treatment. The main species in the supply area were Norway spruce (53%), Scots pine (37%) and birch (10%). The Canadian case encompassed a yearly harvesting area of 12,580 ha (FPInnovations, 2015a; FPInnovations, 2015b). It included an average of 254 harvesting sites that would undergo FF. The annual potential available biomass volumes for the Quesnel supply area were calculated from projections based on 20-year harvesting block data (FP Innovations, 2015a; FPInnovations, 2015b). The main species in the studied area were Lodgepole pine (57%), spruce (32%) and Douglas fir (7%) (FP Innovations, 2015a; FPInnovations, 2015b).

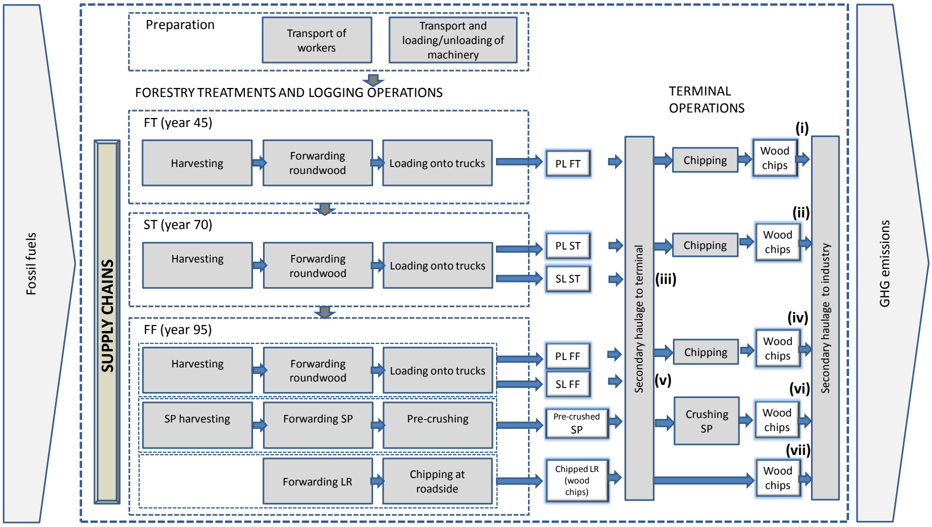
Study IV included only the logging residues from final fellings in Örnsköldsvik as feedstock for pellet production. The average size of a harvesting site in the supply area was 7.5 ha, and the annual production of logging residues from final felling was 34 ODt per ha.

2.1.5 Functional unit and system boundaries

The functional unit in studies I, II and III was one ODt of forest biomass delivered to industry, while the functional unit in study IV was one ODt of pellets stored at the forest terminal.

Studies I and II considered all the processes from harvesting to the delivery biomass to forest industries. In study II, diesel fuel consumption was the main input parameter used to calculate the GHG emissions of different forest supply chains (Figure 3). Processes that were similar in all supply chains, such as cultivation of forest seedlings, soil scarification, tree planting, construction and maintenance of forest roads, production of machinery, as well as production and transportation of diesel, were excluded from the study. Furthermore, changes in emissions resulting from changes in soil carbon stocks and the assimilation of CO_2 by trees were also excluded. The amount of CO_2 that is assimilated during forest biomass growth was considered to be equal to the amount of CO_2 that is released following the oxidation of wood at the end of a tree's life cycle (Dias and Arroja 2012; González-García et al., 2014).

(a)



(b)

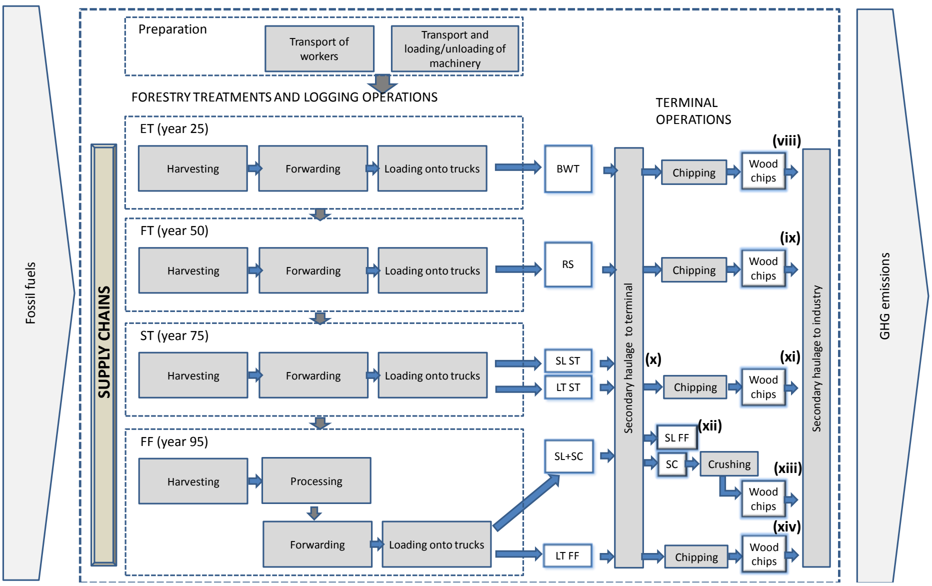
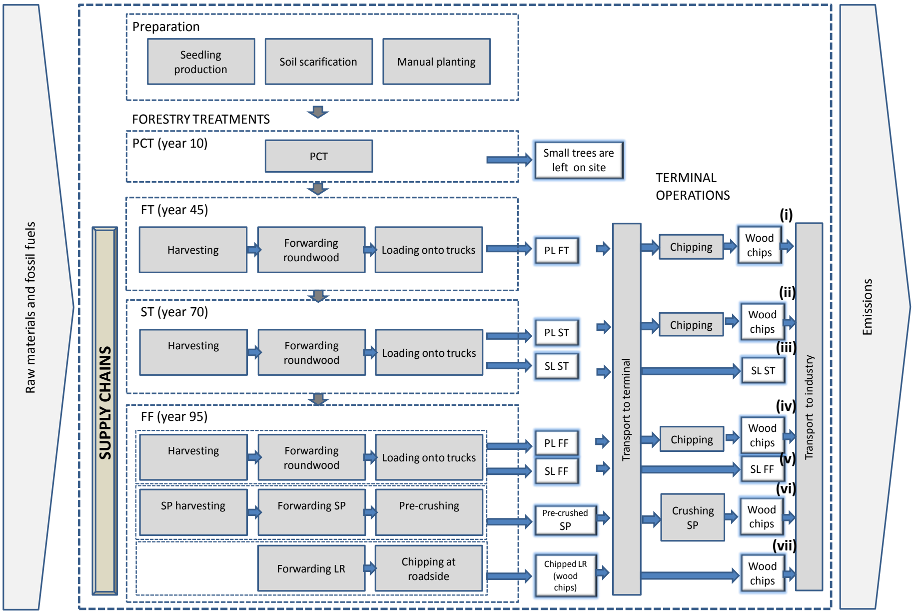


Figure 3. System boundaries of, as well as the operations and assortments included in, the conventional (a) and integrated (b) supply chains examined in study II. Key to supply chains: (i) PL FT, pulpwood from first thinnings; (ii) PL ST, pulpwood from second thinnings; (iii) SL ST, sawlogs from second thinnings; (iv) PL FF, pulpwood from final fellings; (v) SL FF, sawlogs from final fellings; (vi) SP, stumps from final fellings; (vii) LR, logging residues from final fellings; (viii) BWT, bundled whole small trees from energy thinnings; (ix) RS, rough-delimbed tree sections from first thinnings; (x) SL ST, sawlogs from second thinnings; (xi) LT ST, long tops from second thinnings; (xii) SL FF, sawlogs from final fellings; (xiii) SC, stump cores from final fellings; (xiv) LT FF, long tops from final fellings.

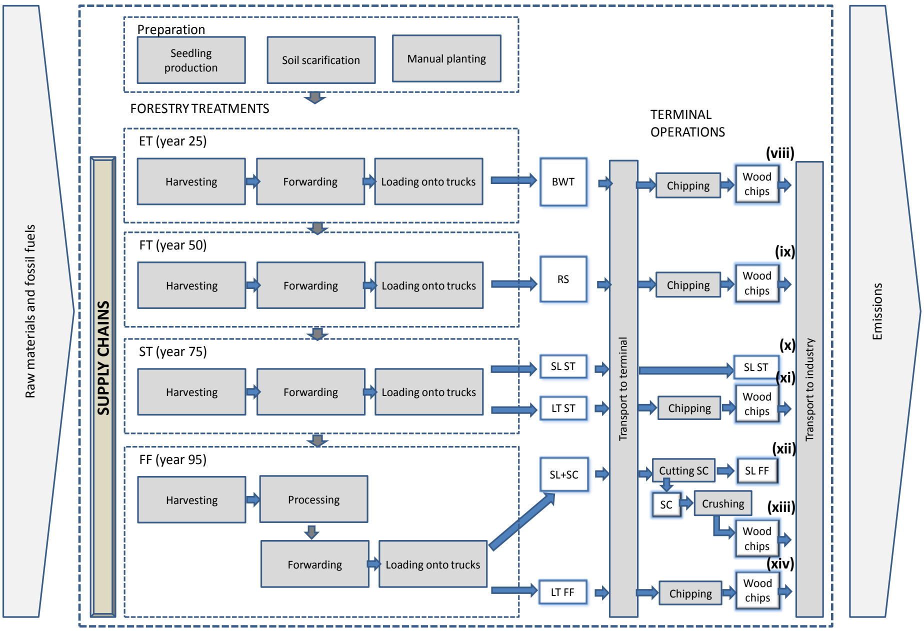
Study III utilized a cradle-to-gate perspective, i.e. from seedling production up to the delivery of forest assortments to the corresponding forest industries, to compare forest supply chains. The operations were classified into four stages: preparation; forestry treatments and logging operations; secondary haulage; and terminal or industry operations. Seedling production was also included in all of the supply chains. The production and maintenance of machinery used in forest operations (harvesters, feller-bunchers, forwarders, skidders, excavators, processors, loaders, shredders and grinders) and terminals (loaders, chippers, grinders and saw blades), as well as the production and maintenance of trucks used in the transportation of the forest assortments (timber trucks, wood chip trucks, and logging residue trucks) were included within the system boundaries (Figures 4 and 5). The production of other inputs, such as fossil fuels (diesel and gasoline), lubricants and electricity, was also included within the system boundaries. The transportation of workers and machinery to and from the harvesting sites was excluded from the system boundaries since their expected contributions to the global environmental profiles were considered to be negligible (Berg and Karjalainen, 2003). Emissions resulting from changes in soil carbon stocks and the assimilation of CO_2 by trees were also excluded from the system boundaries. Activities related to the construction and maintenance of roads were also excluded from the analysis since, according to Dias and Arroja (2012), these activities have a negligible impact on the global environmental profile.

(a)



Raw materials and fossil fuels
SUPPLY CHAINS
Preparation
Seedling production
Soil scarification
Manual planting
FORESTRY TREATMENTS
PCT (year 10)
PCT
Small trees are left on site
FT (year 45)
Harvesting
Forwarding roundwood
Loading onto trucks
ST (year 70)
FF (year 95)
SP harvesting
Forwarding SP
Pre-crushing
Forwarding LR
Chipping at roadside
PL FT
PL ST
SL ST
PL FF
SL FF
Pre-crushed SP
Chipped LR (wood chips)
Transport to terminal
TERMINAL OPERATIONS
Chipping
Crushing SP
Wood chips
(i)
(ii)
(iii)
(iv)
(v)
(vi)
(vii)
Transport to industry
Emissions

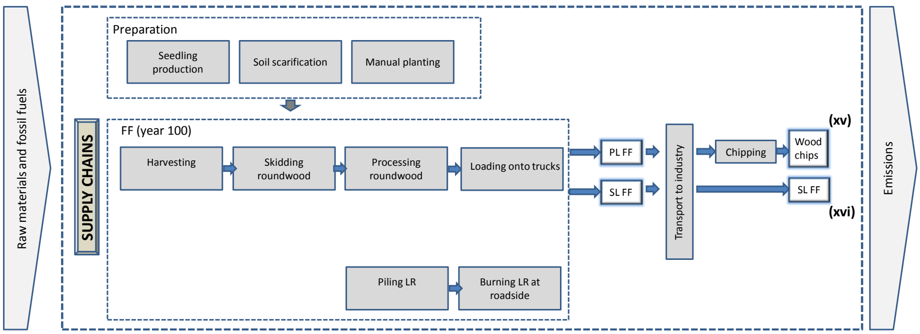
(b)



Raw materials and fossil fuels
SUPPLY CHAINS
Preparation
Seedling production
Soil scarification
Manual planting
FORESTRY TREATMENTS
ET (year 25)
Harvesting
Forwarding
Loading onto trucks
FT (year 50)
ST (year 75)
FF (year 95)
Processing
BWT
RS
SL ST
LT ST
SL+SC
LT FF
Transport to terminal
TERMINAL OPERATIONS
Chipping
Cutting SC
SC
Crushing
SL FF
Wood chips
(viii)
(ix)
(x)
(xi)
(xii)
(xiii)
(xiv)
Transport to industry
Emissions

Figure 4. System boundaries of, as well as the operations and assortments included in, the Swedish conventional (a) and integrated (b) supply chains investigated in study III. Key to supply chains: (i) PL FT, pulpwood from first thinnings; (ii) PL ST, pulpwood from second thinnings; (iii) SL ST, sawlogs from second thinnings; (iv) PL FF, pulpwood from final fellings; (v) SL FF, sawlogs from final fellings; (vi) SP, stumps from final fellings; (vii) LR, logging residues from final fellings; (viii) BWT, bundled whole small trees from energy thinnings; (ix) RS, rough-delimbed tree sections from first thinnings; (x) SL ST, sawlogs from second thinnings; (xi) LT ST, long tops from second thinnings; (xii) SL FF, sawlogs from final fellings; (xiii) SC, stump cores from final fellings; (xiv) LT FF, long tops from final fellings.

(a)



(b)

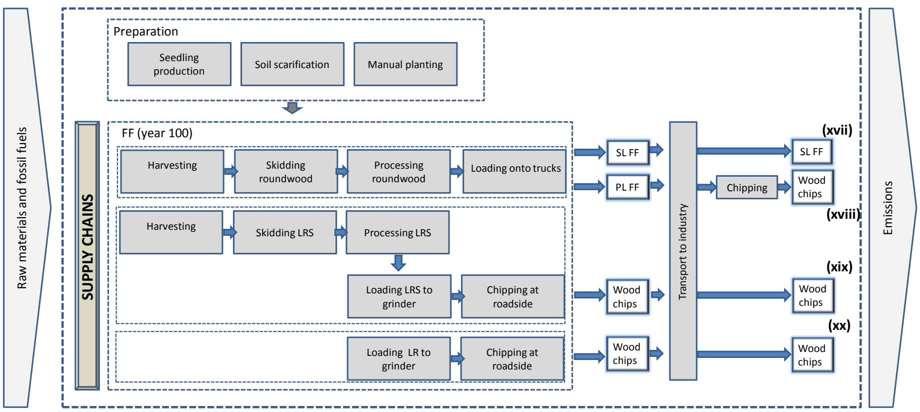
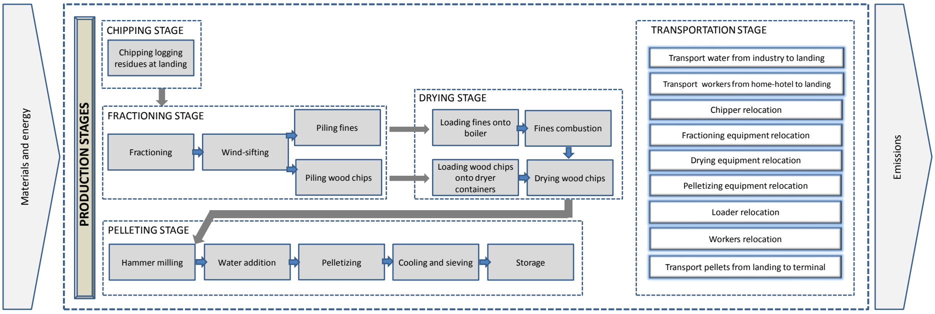


Figure 5. System boundaries of, and the operations and assortments included in, the Canadian conventional (a) and biomass dedicated (b) supply chains investigated in study III. Key to supply chains: (xv) PL FF, pulpwood from final felling; (xvi) and (xvii) SL FF, sawlogs from final fellings; (xviii) Chipped PL, chipped pulpwood from final felling; (xix) Chipped LR, chipped logging residues; (xx) Chipped LRS , chipped non-merchantable logs.

In study IV, the pellet production system started with the roadside chipping of logging residues and ended with the storage of pellets at the terminal. The system included the following stages: chipping; fractioning; drying; pelleting; and transportation (Figure 6). The production and maintenance of machinery, as well as the production and maintenance of the trucks used for the transportation of wood chips, pellets, equipment and workers, were included within the system boundaries of each scenario. The production of other inputs, such as diesel fuel and lubricants, was also included within the system boundaries.

(a)



(b)

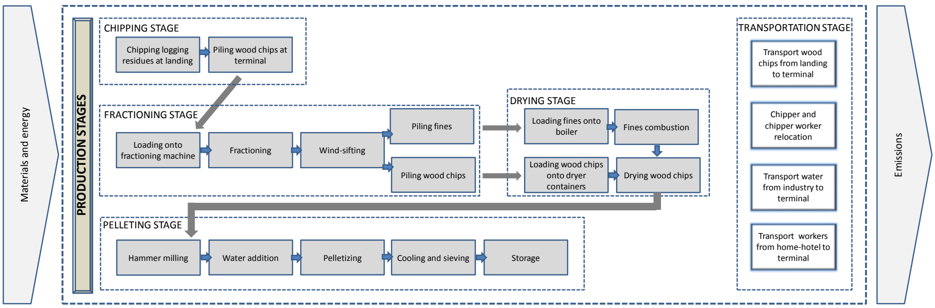


Figure 6. System boundaries of the landing-based (a) and terminal-based (b) scenarios examined in study IV.

2.2 Cost and fuel consumption functions

In study I, the cost functions of conventional and integrated supply chains included costs associated with harvesting, forwarding, landing operations, transportation by truck, terminals, land owner compensation, and overhead. The compensation per biomass unit (ODt) to landowners (i.e. the stumpage price for the stand) during FT, ST or FF was based on local prices (Norra skogsägarna pers. comm., October 2013). The land owner was assumed to receive compensation for the removal of logging residues, but not for stump removal, as is the current status quo. The compensation land owners received for pulpwood from thinnings was lower than that for pulpwood from FF due to the limited profitability of thinning operations. The time that each machine and operation consumed was expressed as PM_{15h}/ODt (PM_{15h}=productive machine hours including delays shorter than 15 minutes). The time consumption was calculated using functions from the literature (Berg et al.,2014; Brunberg, 1997; Brunberg, 2004; Brunberg, 2007; Danielsson and Liss, 2010; Laitila et al., 2007; Laitila et al., 2008; Laitila et al., 2009; Laitila and Väätäinen, 2012; Larsson, 2011; Ligné et al., 2005; Lindberg, 2008; Liss and Johansson, 2006; Nurmi, 2007; Nurminen and Heinonen, 2007; Sängstuvall et al., 2011; Von Hofsten and Granlund, 2010). A storage period of one month in the terminal before re-loading and transportation to the end user was assumed for all assortments.

The total energy needed to extract and transport the different assortments from the forest to industry was calculated in study I by separately modeling all of the processes involved and then taking the sum of these models. The following equation describes the total energy consumption as a function of machinery time consumption (PM_{15h}/ODt), machinery fuel and lubricant consumption (l/PM_{15h} or l/km for trucks), and the dry matter losses:

$$\mathrm{E} = \mathrm{Tw} + \mathrm{Tm} + \mathrm{Lm} + \mathrm{Ha} + \mathrm{Hafp} + \mathrm{Fo} + \mathrm{Ex} + \mathrm{Cc} + \mathrm{Ls} + \mathrm{Ch} + \mathrm{Tr} + \mathrm{To} \quad (1.)$$

Where:

- E: total fuel consumption within the system boundaries (l/ODt)
- Tw: Fuel consumption due to the transportation of workers to and from the harvesting site (l/ODt), obtained from:

  $$\mathrm{Tw} = (\mathrm{Dw} \times \mathrm{pfc} \times \mathrm{Wd} \times \mathrm{Nhs})/\mathrm{m} \quad (2.)$$

  where Dw is the daily average distance for transporting workers to and from the harvesting site (km), pfc is the fuel consumption of a pick-up truck (l/km), Wd is the number of working days needed for harvesting (rounded up to the closest integer), Nhs is the number of annual harvesting sites, and m is the annual forest assortment mass, taking into account total material losses (ODt).
- Tm: Fuel consumption due to the transportation of machinery to and from the harvesting site (l/ODt), obtained from:

  $$\mathrm{Tm} = (\mathrm{Dm} \times \mathrm{tfc} \times \mathrm{Nhs})/\mathrm{m} \quad (3.)$$

where Dm is the average distance between harvesting sites (km) and tfc is the fuel consumption of a truck transporting forest machinery (l/km). Nhs and m are the same as in Equation 2.

- Lm: Fuel consumption due to the loading and unloading of transported machine (l/ODt), obtained from:

$$\mathrm{Lm} = (2 \times \mathrm{t} \times \mathrm{mfc} \times \mathrm{Nhs})/\mathrm{m} \tag{4.}$$

where t is the time required to load/unload the machine from the truck (h) and mfc is the transported machine fuel consumption (l/h). Nhs and m are the same as in Equation 2

- The fuel consumption (l/ODt) for harvesting and processing with a harvester (Ha), harvesting with a feller-puller (Hafp), forwarding (Fo), stump harvesting (Ex), coarse crushing (Cc), loading stumps into a shredder (Ls), and chipping (Ch) was obtained by multiplying the operational time consumption (PM_{15h}/ODt) by the respective hourly fuel consumption (l/ PM_{15h}). For example, the equation for the fuel consumption by a harvester is:

$$\mathrm{Ha} = \mathrm{hp} \times \mathrm{hfc} \tag{5.}$$

where Ha is the fuel consumption of harvesting and processing a certain assortment with a harvester (l/ODt), hp is the time it takes the harvester to harvest and process the assortment (PM_{15h}/ODt), and hfc is the harvester's hourly fuel consumption (l/PM_{15h}).

- Tr: fuel consumption of transporting each assortment from forest roadside to terminal (l/ODt), obtained from:

$$\mathrm{Tr} = [(2 \times \mathrm{Trdist} \times \mathrm{tfc} + \mathrm{ltfc} \times \mathrm{Tt}) \times \mathrm{n} \times \mathrm{Nhs}]/\mathrm{m} \tag{6.}$$

where Trdist is the transportation distance from the harvesting site to the terminal (km), tfc is the fuel consumption of a truck while driving (l/km), ltfc is the fuel consumption of loading and unloading a truck (l), Tt is the time the truck spends at the terminal (h/loading, unloading and complementary activities), and n is the number of trucks needed to transport the assortments from the harvesting site. Nhs and m are the same as in Equation 2.

- To: fuel consumption for terminal operations, which include:
Chipping pulpwood, BWT, RS, and long tops; pre-crushing and crushing stump cores; crushing stumps; loading materials onto trucks; and transportation from terminal to industry.

The fuel and lubricant consumption was obtained from the literature (Berg and Lindholm, 2005; Brunberg, 2006; Eliasson and Granlund, 2010; Eliasson et al., 2012; Jylhä, 2011; Karlsson, 2010; Kons and Läspä, 2013; Nurminen et al., 2009; Skogforsk, 2010; Von Hofsten, 2011; Von Hofsten and Grandlund, 2010;), along with personal communication with “DIMEC srl”, “Domsjo Fiber AB” and “OP System AB” in Sweden.

In study I, the energy consumption of each supply chain was expressed as a percentage of the energy content of the delivered material, which was calculated on a lower heating value basis.

2.3 Data inventory

Time consumption functions and figures from the literature were used to calculate the time consumption of machinery, the hourly cost, fuel and lubricant consumption of machinery and trucks, as well as road transportation cost in the Swedish supply chains. Purchase prices for forest machines were obtained from machine dealers in Sweden, while the truck and trailer unit purchase prices were based on information from contractor companies. In study III, the primary data regarding the time and fuel consumption of the grapple loader, feller-buncher, skidder and trucks in the Canadian supply chains were retrieved from FPInterface, which had been applied to the Quesnel supply area. FPInterface is a software tool that was designed by FPInnovations to simulate the processes in forest supply chains (FPInnovations, 2015c). Secondary data from the ecoinvent 3.01. 2014 database ® (Dones et al., 2007; Nemecek and Käggi, 2007) were applied to processes associated with machinery, fossil fuel, electricity and seedling production. The ecoinvent processes considered in the study were modified to reflect the specific characteristics of the activities involved (fossil fuel consumption, weight and lifespan of the machinery and trucks used, and seedlings required per scenario). In study IV, the data concerning the foreground system (processes related specifically to the pellet production) were collected from the following sources: the time and fuel consumption of the loader, chipper and trucks were taken directly from study I, whereas the time and fuel consumption of the fractioning machine, as well as wind-sifter data, were provided by Norditek AB (personal communication with Eric Johansson, Norditek, Sävar, Sweden). Data regarding the time and energy consumption of the generators, along with dryer and pelletizer units, were obtained from the manufacturers’ webpages. Appropriate distances for the relocation of machinery and workers were provided by Norra Skogsägarna (personal communication with Håkan Lageson, Norra Skogsägarna, Umeå, Sweden). Data from the ecoinvent 3.01.

2014 database ® were used for processes associated with the machinery and fossil fuel production.

2.4 Allocation procedure for costs and resource use

Several of the operations analyzed in the presented research yielded two or more products. Thus, to accurately determine the production cost and resources used for each of the products, the costs and consumption of resources must be appropriately divided between the products. In study I, costs in the integrated supply chains B and C were calculated for the whole supply chains and allocated between the products based on the change in costs compared to a reference case (supply chains A).For example, based on a comparison to separate roundwood harvest, only the additional cost of the integrated operations were allocated to the residual forest biomass in the integrated supply chain B. The cost and energy consumption allocated to stemwood was identical in all three alternative supply systems. In the conventional supply chains A, no harvester costs or energy consumption were allocated to the stumps and logging residues. Since stemwood is considered to be the main product, the felling and delimbing process is carried out in essentially the same way irrespective of whether the stumps and logging residues are recovered.

The ISO standard for LCA (ISO 14040, 2006) recommends avoiding allocation. In the presented research, the harvesting of each assortment required specific amounts of harvester and forwarder work; therefore, allocation of fuel consumption for these operations was not necessary because the time consumption was calculated for each assortment.

If allocation cannot be avoided, ISO 14044 (2006) recommends the use of physical relationships or economic values. Mass allocation was used in studies I and II for the following processes: transportation of workers, harvesters and forwarders to and from harvesting sites; loading and unloading of harvesters and forwarders from and onto trucks. In study II, mass allocation was also used for operations involving the harvesting, forwarding and transportation of the sawlogs with stump cores.

In addition, the mass allocation approach was used in study III to appropriately divide seedling production, soil preparation, and manual planting between assortments. This approach is in agreement with other LCA studies of biomass systems (Kilpeläinen et al., 2011; Neupane et al., 2011; Routa et al., 2011). The energy and material flows corresponding to PCT were also assigned on the basis of mass allocation between all the assortments included in the Swedish conventional supply chains. Harvesting, skidding and processing of non-merchantable logs in Canadian conventional supply chains were allocated to pulpwood and sawlogs. However, these processes were allocated only to LRS when the Canadian biomass dedicated supply chains recovered LRS.

In study IV, two products were produced, sieved wood chips (main product) and fines (by-product), after the fractioning process. The fines were used as input fuel in the drying process. Therefore, this by-product represented an alternative to other fuels on the market. It was assumed that the fines replaced wood chips from logging residues, which means that the production of wood chips was avoided. For this reason, allocation was avoided. The system was then expanded to include all the processes involved in wood chip production (value taken from De La Fuente et al., 2017), after which the total emissions associated with drying pellets were determined by subtracting the emissions associated with the avoided wood chip production from the emissions associated with pellets and fines production.

2.5 Environmental assessment

Study II assessed global warming potential (GWP) over a 100-year time horizon. The gases CO_2, CH_4 and N_2O were included in the assessment because they are the main GHG that contribute to radiative forcing (the difference between the energy in sunlight absorbed by the Earth and energy radiated back) (IPCC, 2013). These gases are released into the environment during forest fuel supply chain processes through the combustion of fossil fuels, with diesel as the most commonly used fuel. The emissions factors reported by Lindholm et al. (2010) were used to calculate the total emissions arising from diesel combustion in forest machinery and trucks. GWP characterization factors, which enable the conversion of results from life cycle inventory data into equivalent CO_2 emissions, were taken from IPCC (2013).

The Life Cycle Impact Assessment (LCIA) in studies III and IV was conducted according to the characterization factors reported in the ReCiPe (H) midpoint method v.10. (Goedkoop et al., 2009). The potential impacts assessed were GWP (kg CO_2-eq.), terrestrial acidification potential (TAP) (g SO_2-eq.), marine eutrophication potential (MEP) (g N-eq.), fresh water eutrophication potential (FEP) (g P-eq.), photochemical oxidant formation potential (POFP) (g NMVOC), and fossil fuel depletion potential (FDP) (kg oil-eq.). Special attention was paid to GWP due to its relevance in a climate change context. In addition, an increase or decrease in GWP implied a similar pattern in other environmental impacts affected by fossil fuel combustion, such as TAP, POFP and FDP. SimaPro 8.0.3 software (PRé-sustainability, 2014) was used for inventory data implementation and the estimation of environmental impacts.

3 Results

3.1 Swedish conventional and integrated forest supply chains (studies I and II)

The three Swedish locations differed mainly in the total feedstock amount that could be produced by conventional supply chains: 1.3 MODt/yr for Storuman; 2.1 MODt/yr for Umeå; and 2.3 MODt/yr for Örnsköldsvik. The average distribution of assortments produced by the conventional supply chains (group A) was 41% sawlogs, 25% pulpwood, 12% logging residues and 20% stumps. This distribution differed by only a few percentage points between locations. The supply of logging residues via integrated supply chains (group B) increased the amount of residues compared to conventional supply chains (group A) by 25%, 15%, and 34% in Örnsköldsvik, Umeå, and Storuman, respectively. The harvest of small trees during energy thinnings in the group C integrated supply chains added 84000 ODt/yr, 77000 ODt/yr, and 86000 ODt/yr for Örnsköldsvik, Umeå, and Storuman, respectively. The harvesting of stump cores in integrated supply chains delivered only about 20% of the stump biomass that conventional supply chains are able to harvest.

The assortments with the highest supply cost were stumps and stump cores, which, on average, had supply costs that were 12% and 10% higher than that of pulpwood, respectively. In contrast, the supply cost of logging residues was, on average, 12% lower than that for pulpwood. RS and long tops demonstrated average supply costs that were 7% and 15%, respectively, lower than the supply cost of pulpwood in conventional supply chains. The cost of procuring whole small trees was similar to that for RS or long tops, as it was 5% less than the cost of procuring pulpwood. The supply cost of BWT was 15% lower than that of pulpwood.

The supply cost for chipped feedstock was mainly within the 75-110 €/ODt range (Figure 7). The supply curves for B and C were below the curve for A since the integrated supply chains (B and C) had lower supply costs per ODt biomass than the conventional supply chains (A). This means that more feedstock can be supplied at a given cost level.

Therefore, the integrated harvesting of tops and branches with stemwood assortments, combined with whole-tree harvesting during early thinnings, shows significant potential to reduce the supply cost for non-stemwood assortments. The energy use analysis shows that the energy input of integrated supply chains is relatively small when compared to the energy content of the harvested feedstock. The amount of energy used corresponds to approximately 2-4% of the energy content of the delivered wood feedstock, when all assortments (except sawlogs) are chipped without prior separation. For the conventional supply chains these percentages vary from 2% to 6%.

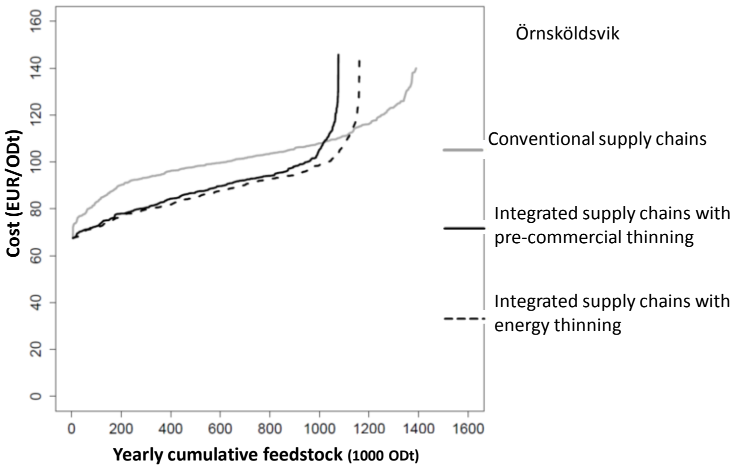


Figure 7. Aggregated supply cost curve for all the assortments produced by different supply chains (excluding sawlogs) in Örnsköldsvik (study I).

At all three locations, the GHG emissions arising from supply chains producing different assortments followed a similar pattern (Fig. 8). The integrated supply chains showed lower estimated total fuel consumption and GHG emissions (kg CO_2-eq.) than the conventional supply chains. The weighted average for GHG emissions of all the assortments varied between 37 and 38 kg CO_2-eq./ODt for the integrated supply chains, and between 43 and

45 kg CO_2-eq./ODt for the conventional supply chains (excluding sawlogs). Thus, switching from conventional supply chains to integrated supply chains should, on average, cut GHG emissions by 13%.

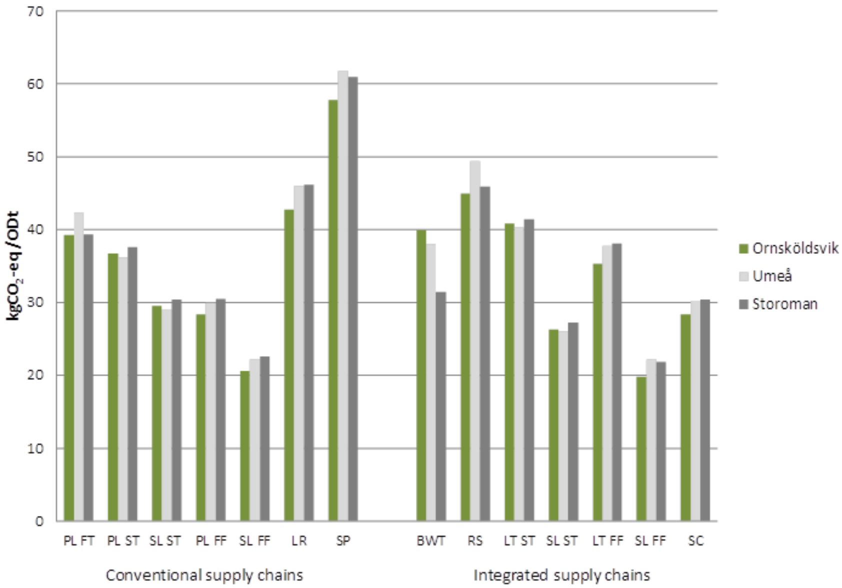


Figure 8. The GHG emissions associated with supply chains that produce the indicated assortments at three study site locations (study II). Key: PL FT, pulpwood from first thinnings; PL ST, pulpwood from second thinnings; SL ST, sawlogs from second thinnings; PL FF, pulpwood from final fellings; SL FF, sawlogs from final fellings; LR, logging residues from final fellings; SP, stumps from final fellings (conventional supply chains) and BWT, bundled whole small trees from energy thinnings; RS, rough-delimbed tree sections from first thinnings; LT ST, long tops from second thinnings; SL ST, sawlogs from second thinnings; LT FF, long tops from final fellings ; SL FF, sawlogs from final fellings; SC, stump cores from final fellings (integrated supply chains).

The key contributors to GHG emissions in both conventional and integrated supply chains were transportation, forwarding, harvesting, and chipping. Stump harvesting was another relevant contributor in the conventional supply chains.

3.2 Swedish and Canadian forest supply chains (study III)

There were large differences between the Swedish and Canadian scenarios in all of the considered environmental impact categories (Table 1 and Fig. 9).

When all of the forest assortments in each scenario were considered, the Swedish integrated supply chains (Scenario B) exhibited the lowest average emissions, followed by the Swedish conventional supply chains (Scenario A), the Canadian biomass dedicated supply chains (Scenario D), and the Canadian conventional supply chains (Scenario C).

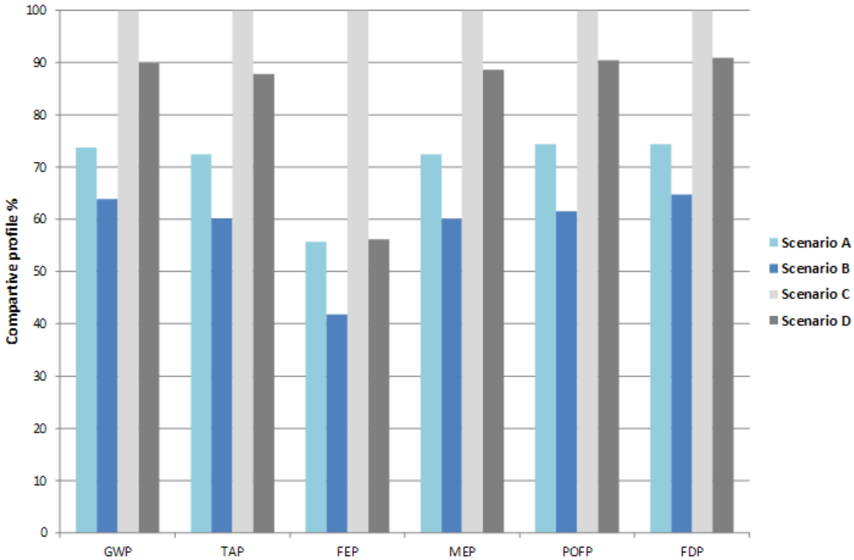


Figure 9. Comparative environmental impacts of the evaluated scenarios (study III). Acronyms: A, Swedish conventional supply chains; B, Swedish integrated supply chains; C, Canadian conventional supply chains; D, Canadian biomass dedicated supply chains.

In terms of GWP, Scenario B generated 48.8 kg CO_2-eq./ODt, which involved an equivalent emission rate around 13% lower than Scenario A, 30% lower than Scenario D, and 38% lower than Scenario C. The GHG emissions mainly arose from fossil fuel combustion by the forest machinery and trucks. The production of machinery, fossil fuels and electricity only had minor contributions to the global GHG emissions. The Swedish integrated and the Canadian biomass dedicated supply chains (Scenarios B and D, respectively) had lower environmental impacts than the respective conventional supply chains in each country (Scenarios A and C).

Table 1. *Characterization results per functional unit (1 ODt of forest biomass) of the different supply chain scenarios in Sweden and Canada (study III). Acronyms: A, Swedish conventional supply chains; B, Swedish integrated supply chains; C, Canadian conventional supply chains; D, Canadian biomass dedicated supply chains; SL, sawlogs; GWP, global warming potential; TAP, terrestrial acidification potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; FDP, fossil fuel depletion potential.*

Impact category	Unit	Scenario A			Scenario B			Scenario C			Scenario D		
		SL	Wood chips	Average	SL	Wood chips	Average	SL	Wood chips	Average	SL	Wood chips	Average
GWP	kg CO_2-eq	36.5	70.4	56.3	35.2	60.4	48.8	74.6	86.0	78.2	62.8	75.4	69.8
TAP	g SO_2-eq	238	481	380	228	391	316	512	589	540	431	495	470
FEP	g P-eq	4.8	10.2	7.9	4.5	7.2	6.0	14.0	15.6	14.3	7.9	8.1	8.0
MEP	g N-eq	14.2	28.7	22.6	13.5	23.2	18.8	30.5	35.0	32.2	25.9	29.7	28.2
POFP	g NMVOC	400	810	639	379	655	528	838	967	888	724	838	794
FDP	kg oil-eq	12.6	23.6	19.0	12.1	20.4	16.6	25.0	28.7	26.2	21.5	25.5	23.7

When all of the supply chains were analyzed, the results identified the key processes (environmental hotspots) to be harvesting, forwarding, skidding, chipping, crushing, and transportation from forest to industry. In terms of GHG emissions, transportation was the process that resulted in the highest emissions, contributing between 30% and 58% of the total emissions depending on which assortment and supply chain was considered.

3.3 Small-scale decentralized mobile pellet production system (study IV)

The landing-based scenario showed slightly lower emissions than the terminal-based scenario for all the impact categories (Table 2). The GWP of the landing-based scenario was 269 kg CO_2-eq. whereas the GWP of the terminal-based scenario was 272 kg CO_2-eq. The GWP, TAP, MEP, POFP and FDP of the two systems varied by about 1%, while there was a 6% difference in FEP.

Table 2. *Characterization results per functional unit (1 ODt of pellets stored at the terminal) of landing- and terminal-based scenarios (study IV). Acronyms: GWP, global warming potential; TAP, terrestrial acidification potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; FDP, fossil fuel depletion potential.*

Impact category	Landing -based scenario	Terminal-based scenario
GWP (kg CO_2-eq.)	269	272
TAP (kg SO_2-eq.)	2.32	2.33
FEP (g P-eq.)	18.4	19.5
MEP (g N-eq.)	146	147
POFP (kg NMVOC)	4.16	4.18
FDP (kg oil-eq.)	87.3	88.1

When all of the production stages were considered, pelleting exhibited the highest emissions, followed by transportation, drying, chipping and fractioning (Table 3).

The influence of different factors was studied through a sensitivity analysis. The results showed that long transportation distances for the wood chips or pellets increased the differences between scenarios. The landing-based scenario showed a lower environmental profile in the transportation stage. The biomass concentration at the landing had a larger effect on the landing-based scenario than on the terminal-based scenario. An increase in pelletizer capacity decreased emissions by between 22% and 25% (depending on the environmental impact considered) in both landing- and terminal-based scenarios. Using electricity from the power grid instead of a diesel generator at the terminal reduced GWP, TA, ME, POF and FD by 68%, 78%, 80%, 83% and 71%, respectively. The drying and pelleting stages showed the highest emission reductions. Finally, a decrease in the productivity of the landing-based scenario caused increases in all of the environmental impact categories, with drying the stage of production that was most affected.

Table 3. *Characterization results per functional unit (1 ODt of pellets stored at the terminal) corresponding to each production stage in landing- based and terminal-based scenarios. Acronyms: GWP, global warming potential; TAP, terrestrial acidification potential; FEP, fresh water eutrophication potential; MEP, marine eutrophication potential; POFP, photochemical oxidant formation potential; FDP, fossil fuel depletion potential.*

Impact category	Landing-based scenario					Terminal-based scenario				
	Chipping	Fractioning	Drying	Pelleting	Transportation	Chipping	Fractioning	Drying	Pelleting	Transportation
GWP (kg CO_2-eq.)	16.2	11.1	31.1	172	38.2	18.5	10.9	31.1	172	38.7
TAP (g SO_2-eq.)	119	78.8	402	1602	117	136	75.2	402	1602	117
FEP (g P-eq.)	0.9	1.8	1.7	7.8	6.3	1.4	2.4	1.7	7.8	6.2
MEP (g N-eq.)	7.2	4.6	26.0	103	5.3	8.2	4.2	26.0	103	5.3
POFP (kg NMVOC)	0.21	0.13	0.72	3.0	0.15	0.24	0.12	0.72	3.0	0.15
FDP (kg oil-eq.)	5.4	3.5	9.6	56.1	12.7	6.1	3.4	9.6	56.1	12.8

4 Discussion

4.1 Key processes and productivity parameters in the supply chain

Road transportation, harvesting and forwarding were the costliest processes in the Swedish supply chains. In terms of energy use and GHG emissions, the same processes were found to be environmental hotspots in the supply chains, as had been previously suggested by Berg and Karjalainen (2003), Berg and Lindholm (2005), and Sambo (2002). Chipping logging residues at the roadside, crushing stumps, chipping RS and long tops at terminal, and skidding were also found to be energy intensive processes.

For a specific forest machine, the fuel consumption per hour of use is often relatively constant (Nordfjell et al., 2003). Therefore, the fuel consumption and most of the GHG emissions per ODt depend heavily on the productivity of the machine. To understand which parameters influence the most the productivity of forestry machinery and trucks is essential to develop efficient forest supply chains.

The time consumption equations used for the harvesters in study I show that the number of trees harvested per ha and the volume of removed stems are key parameters in determining the time spent harvesting. Proper matching of harvesting heads, the power and speed of the crane, terrain conditions and operator training also influence productivity. In fact, well-educated operators can lead to a 10% decrease in energy consumption (Forsberg and Löfroth, 2002). Similar factors influence the productivity of a feller-buncher, since time consumption is mainly affected by tree size and trees per ha. The feller-buncher felling head can cut trees of different sizes in approximately the same time (Akay et al., 2004). Moreover, the speed of moving, cutting and accumulating trees increases when the number of trees/ha increases (Akay et al., 2004). Therefore, large trees and dense harvesting sites decrease the time consumed per ODt by a feller-buncher.

For forwarders, the cycle time includes travel time, loading and unloading time, as well as other delays. Travel time depends on the forwarding distance, machine horsepower, vehicle speed and load weight (Akay et al., 2004). According to Manner et al. (2013) the loading work, on average, accounts for 78-82% of the total forwarding time consumption for forwarding distances of 200-300 m (one way). In addition, Nordfjell et al. (2003) found that loading accounts for most (40-60%) of the total fuel consumption. Log concentration, expressed as volume per unit distance on the strip road, is a key factor that influences forwarding time consumption (Manner et al., 2013); hence, time consumption decrease as log concentration increases. Skidding distance is the most important variable in skidding cycle time (Akay et al., 2004). The load size, including number of logs grappled, volume per turn, and the number of bunches grappled per turn also affect how much time is taken up by skidding (Akay et al., 2004).

Regarding transportation by trucks, maximizing payload is essential to improving efficiency and reducing costs (Canadian Institute of Forestry, 2016). Increased efficiency translates to a reduction in fuel consumption and GHG emissions (Canadian Institute of Forestry, 2016). In British Columbia (Canada), the maximum gross vehicle weight of a B-train truck is 63.5 tonnes (Ministry of Transportation and Infrastructure, 2006). Since 2015, the maximum gross vehicle weight of a logging truck and trailer in Sweden is 64 tonnes. New vehicles that are longer and heavier (load capacities of 90 tonnes and 66 tonnes) have been tested in Sweden (Skogforsk, 2012). These new trucks can reduce fuel consumption and transportation costs by around 20% (Skogforsk, 2012). Therefore, greater payloads can improve transportation efficiency and reduce GHG emissions associated with fuel consumption. However, evaluations of possible damages to the road network, the load-bearing capacity of bridges, and the road geometry requirements for these new trucks need to be considered before the trucks are introduced (Canadian Institute of Forestry, 2016).

In addition to increasing the physical load capacity of trucks, reducing the volume of forest assortments is also important to improving transportation efficiency. Pre-crushing, chipping and bundling all increase payload. In the case of assortments that have to be transported with branches, a good practice would be to transport this biomass after natural drying. This is because reducing the moisture content from 50% to 35% will increase the payload, and therefore, the transportation efficiency. The pre-treatment of biomass becomes increasingly important as the distances from forest/terminal to industry grow. The comparison analysis of integrated and conventional supply chains demonstrated that forest assortments that were not delimbed required more energy during transportation since their volume/mass ratio was higher and the truck load was smaller. However, bundling (producing BWT) reduced the volume/mass ratio and thus, fuel consumption per ODt during transportation.

Within the harvesting process, extracting pulpwood during first thinning and BWT assortments required the most energy. This can be explained by harvesters being less productive in young forests dominated by small-diameter trees. A comparison of the harvesting of RS during FT and long tops during ST with pulpwood during FT and ST showed that fuel consumption during FT and ST was 34% and 50% lower, respectively, when the harvester did not delimb all the branches. Thus, harvesting RS and long tops rather than pulpwood assortments was more productive during both FT and ST. Within the forwarding process, stump and logging residues extraction required the most energy. However, the integrated supply chains used less energy per ODt in the forwarding process than conventional supply chains of logging residues and stumps due to higher stemwood contents of the BWT, RS and sawlog with stump core assortments.

The extraction of stump cores showed low fuel consumption because stump cores were harvested while attached to sawlogs, which increased both the productivity of machinery and truck payload. In contrast, conventional stump extraction caused the most emissions due to the energy intensive excavating and forwarding processes.

The harvesting process of the Canadian scenarios had a better environmental profile than the harvesting process of the Swedish scenarios. This can be explained by the feller-buncher requiring less time to finish the operations than the harvester (0.05 h/ODt compared to 0.08 h/ODt). However, harvesters cut and processed trees at the stump. The Canadian full-tree harvesting system requires machinery at the roadside to further process the trees. This increased the emissions per ODt by around 8.8 kg CO_2-eq. In addition, the forwarders used in final felling have shorter cycle times than skidders (0.10 h/ODt compared to 0.13 h/ODt). All of these factors make the cut-to-length method more energy efficient than the full-tree method, as also shown by Sambo (2002).

Another important aspect in the comparison analysis of Swedish and Canadian supply chains was the amount of forest biomass available. Final fellings in the Swedish scenarios A and B delivered 173 and 136 ODt/ha, respectively, whereas Canadian final felling operations delivered 44 and 68 ODt/ha for scenarios C and D, respectively (study III). In addition, Canadian forest biomass was only harvested during final felling; in contrast, the Swedish supply chains harvested biomass four times throughout the whole forest cycle.

The application of the Swedish cut-to-length harvesting method to the Quesnel supply area would probably result in harvester and forwarder productivities that are lower than the corresponding productivities in Northern Sweden because the volume per ha is lower in the Quesnel supply area. As mentioned above, two of the key parameters affecting harvester productivity are the amount of trees per ha and the stem volume. In addition, log concentration was identified to be a key parameter in forwarder productivity.

4.2 Comparison with related studies

Differences in system boundaries, inventory data quality, background data, study assumptions, allocation methods, characterization factors, and the considered technology make comparison with other LCA studies difficult. Moreover, previous LCA studies of forest supply chains in Nordic conditions have been based on the conventional system (Berg and Lindholm, 2005; Wihersaari, 2005; Eriksson and Gustavsson, 2008; Eriksson and Gustavsson, 2010; Lindholm et al., 2010; Jäppinen et al., 2014), although the harvesting of small trees was included by Jäppinen et al. (2014); Eriksson and Gustavsson (2008); Eriksson and Gustavsson (2010).

In terms of total energy consumed by the supply chains, 2-6% of the energy content of the delivered wood feedstock was use in the conventional supply chains according to study I. This energy ratio agrees with results from Ireland regarding the extraction of logging residues and stumps with similar conventional supply chains (Murphy et al., 2014). The corresponding energy ratio for integrated supply chains, in which all material is chipped without prior separation, was about 2-4%. These results are relatively close to what other studies of supply chain energy use have reported (De Jong et al., 2014).

Previous studies of the emissions generated by the supply chains of specific assortments have reported that 200 MJ of energy is required to produce 1 m^3sub (solid volume under bark) of timber wood in Northern Sweden, which is equivalent to emissions of 36.6 kg CO_2-eq./ODt (assuming that the density of roundwood is 399 ODkg/m^3 as in the cited study) (Berg and Lindholm, 2005). A similar value was calculated for the emissions from pulpwood from ST in study II (36.2 to 37.6 kg CO_2-eq./ODt, depending on location), yet the previously suggested value was higher than the emissions calculated for pulpwood from FF (28.4 to 30.5 kg CO_2-eq./ODt) and sawlogs from FF (20.6 to 22.6 kg CO_2-eq./ODt). These lower values may have resulted from the exclusion of seedling production and silvicultural processes in study II. However, the emissions from sawlogs FF (35.2 kg CO_2-eq./ODt) in study III, which included all the processes from a cradle-to-gate perspective, were similar to those reported by Berg and Lindholm (2005). Berg and Lindholm (2005) also found that final felling requires less energy than thinning, which studies II and III confirmed, as harvesters and forwarders were used less on site as diameter at breast height (DBH) increased. The BWT supply chain emissions presented in study II are similar to estimates by Eriksson and Gustavsson (2008) and (2010), but lower than those reported by Jäppinen et al. (2014). The stump supply chain emissions were similar to values reported for Northern Finland by Jäppinen et al. (2014) and Northern Sweden by Lindholm et al. (2010). However, the logging residues supply chain emission values from study II (42.7 to 46.2 kg CO_2-eq./ODt, depending on the location) were lower than previously reported values for Northern Finland (55.7 kg CO_2-eq./ODt) and Northern Sweden (59.5 kg CO_2-eq./ODt) by Jäppinen et al. (2014) and Lindholm et al. (2010), respectively. The higher emissions presented by Jäppinen et al. (2014) may have resulted from a longer average forwarding distance (470 m) and different transportation processes (for which average distances were not specified). On the other hand, residues were not transported as wood chips in the study by Lindholm et al. (2010), and this would increase fuel consumption during transportation.

Berg et al. (2014) found total fuel consumption for the stump supply chain, 10 l/ODt, to be noticeably lower than what was estimated in study II, 22.1 to 23.6 l/ODt. The lower calculated consumption could be due to differences in the study assumptions, such as shorter forwarding distances (200 m compared to 300 m in study II), lower excavator-based stump harvester fuel consumption (12 l/h compared to 16l/h), shorter transportation distances (50 km), and comminution to chips before transportation compared to comminution at the terminal. However, the estimates of Berg et al. (2014) for the fuel consumption of the stump core supply chain (20 l/ODt) are higher than what was calculated in study II. This difference may be due to a higher fuel consumption of the feller puller (41 l/ PM_{15h} instead of 20) and lower payload of timber trucks (the cited authors assumed that sawlogs with stump cores would be bulkier than sawlogs) in their calculations.

In relation to the results from study IV, no direct comparison with similar studies could be made since other studies identified in the literature were based on stationary industrial plants (centralized production systems). However, it is still relevant to compare the results from a small-scale mobile production system to stationary industrial-scale production. Conventional pellet production chains from sawdust, cutterdust and roundwood were previously analyzed by Hagber et al. (2009). The authors applied a cradle-to-gate approach to centralized systems in Sweden. Their results showed emissions ranging from 56-74 kg CO_2-eq. per ODt of pellets for all three types of raw materials. These values are in agreement with Sikkema et al. (2010), who reported that the production of pellets in a pellet plant in Sweden using sawdust as a feedstock results in GHG emissions of around 50 kg CO_2-eq. per t of pellets. These results are much lower than those reported in other published pellet production studies. For example, Laschi et al. (2016) showed that the production of 1 t of packed pellets results in 400 kg CO_2-eq. in Italy. The production of the electricity required by the system was identified as the most important factor in pellet production, as it caused 93% of the emissions. In fact, Hagber et al. (2009) showed that if electricity from coal instead of the Swedish electricity mix had been used in their study, then the GHG emissions would have been between five and six times greater. The GHG emissions in study IV were around 270 kg CO_2-eq. per ODt of pellets. However, when the Swedish electricity mix was used instead of diesel fuel, the GHG emissions reduced to 87 kg CO_2-eq. per ODt. In terms of the ratio between the energy spent to produce pellets and their energy content, Laschi et al. (2016) reported an energy ratio of 0.15. However, this ratio, as well as the GHG emissions, can vary depending on industrial scale, machinery efficiency, feedstock used and the considered system boundaries (Laschi et al. 2016). Results from study IV showed that this ratio was 0.23 for the scenarios analyzed. However, the ratio decreased to 0.15 if the electricity at the terminal was provided by the power grid rather than generated by a traditional diesel generator. Therefore, from an LCA perspective, the only way small-scale mobile pellets plants can compete with industrial-scale production is by using electricity at terminals.

4.3 Advantages and disadvantages of integrated supply chains

4.3.1 Cost

The integrated harvest of stemwood with tree tops and branches, when compared to separate harvests, has the potential to decrease the supply cost of forest biomass. In addition, ET could replace PCT fully or partially, and this would provide the additional benefit of avoiding PCT costs (this was not included in the calculations, but could make energy thinning even more attractive from a cost perspective). Stump cores were transported to industrial sites still attached to the butt-logs. In this way, sawlogs could be extended 1-2 decimeters, up to the point where the fibers start to change angle (Jonsson,1985 in Berg, 2014). This added length could have higher value than wood fuel and, in turn, make the utilization of these extended sawlogs economically viable (Berg, 2014).

In study I, the costs of sawlogs and pulpwood were kept constant. This gives a good idea of the benefits (and costs) of the new practices, but it does not take into account how changes in costs could affect the market prices of different assortments. A reduced total cost could, depending on the market situation, be absorbed by entrepreneurs as increased profit, lead to lower saw timber prices, or decrease the prices of feedstock for biorefinery or energy industries.

4.3.2 Biomass amount

The total potential biomass production of the integrated supply chains was lower than that of conventional supply chains because stump cores only account for about 20% of the stump biomass recovered during conventional stump harvest. However, residual forest biomass was harvested during thinning operations and final felling in the integrated supply chains, whereas it was only recovered during final harvest in conventional supply chains. If no stump harvesting occurs, then the integrated supply chains could, depending on the location, provide between 16% and 26% more biomass than the conventional supply chains.

4.3.3 GHG emissions

Study II showed that integrated supply chains have the potential to reduce fuel consumption and GHG emissions associated with the combustion of fossil fuels by around 13% relative to conventional supply chains when all three locations in Northern Sweden were considered. Regarding the emissions arising from wood chip storage, Wihersaari (2005) reported that chip storage may generate 5-10 kg CO_2-eq./MWh/month. According to Jirjis (1995), storage of chipped woody biomass for a few months can lead to microbial decay and significant losses (10-15%) of dry matter. However, Afzal et al. (2010) argue that the emissions arising from uncomminuted biomass during storage can be considered insignificant compared to the emissions arising from wood chip storage. This represents an advantage for integrated supply chains because all the assortments are uncomminuted upon arrival at terminals, which reduces possible emissions from biomass storage. However, the emissions arising from storage depend on how, and for how long, the unchipped residues are stored at terminals. Routa et al. (2015) found that the dry matter losses of unchipped logging residues can vary by up to 3% per month. Carbon emissions from forest soils can also increase after soil disturbances due to increased decomposition rates (Berg, 2014). It is expected that the extraction of stump cores instead of conventional stumps reduces soil disturbances and therefore leads to lower GHG emissions.

4.3.4 Nutrient loss, water pollution and soil compaction

In boreal forests, nitrogen is generally the limiting nutrient for tree growth (Hyvönen et al., 2007). Furthermore, foliage may account for up to 50% of a tree's nutrient content (Pelkonen et al., 2014). Therefore, foliage extraction could reduce nutrient availability in the soil. It has been observed for sensitive areas (eg. pine stands on mineral soils), the removal of logging residues may be followed by a decline in productivity (Egnell and Valinger, 2003).

In addition, it has been suggested that ET could affect the yield of FT (Karlsson, 2013). The actual effect on the yield will, however, depend on stand characteristics (no yield reductions in subsequent harvesting operations were taken into account in the research underlying this thesis). The integrated supply chains extract tops and branches during thinning operations rather than only during final felling, as is the case in conventional supply chains. Therefore, a potential disadvantage of integrated supply chains is the loss of nutrients and possible negative effects on tree growth. On the contrary, the extraction of stump cores instead of stumps would leave the root system intact, and thereby mitigate nutrient depletion and soil disturbance (Berg et al., 2014). Although coarse roots have lower nutrient contents than foliage, they have higher nutrient content than stemwood (Hellsten et al., 2013). Furthermore, soil disturbances can also affect water quality. The concentration of methylated mercury, a toxic compound, in soil water increases after soil disturbance and may reach aquatic systems (Munthe and Hultberg, 2004). It is expected that stump core harvest would have less of an impact on water quality than stump harvest. Finally, the simultaneous extraction of stemwood and residual forest biomass could reduce the total amount of driving over the terrain, and therefore soil compaction, when compared to methods with separate extraction (Walmsley and Godbold, 2010).

4.3.5 Flexibility of the supply chains and biomass quality

Different parts of a tree have different properties, so it may be desirable to separate these various parts. In conventional supply chains, the separation of logs and residual assortments happens during harvest. Separate supply chains provide greater flexibility in terms of supply, as the demand for different assortments may vary over time. For example, in some Swedish regions, the demand for energy assortments is presently met by processing residues from pulp mills and sawmills, and there is little demand for wood fuels such as logging residues. In this way, it is more attractive to harvest residues in other locations. In integrated supply chains, separation may be performed at an intermediate terminal or at the receiving industry. The potential disadvantages of integrated supply chains are that valuable and less valuable components are not separated early in the chain, and that there are fewer opportunities to pass different fractions directly from harvest to different users. However, the advantages of an integrated supply chain include easier handling with lower risk for the contamination of residual assortments, better control over comminution and separation if undertaken at a large-scale or at the destination industry, and potentially more efficient comminution and separation when performed at a large-scale at the terminal or industry site. Even though stump cores can be expected to be much cleaner than stumps, which are typically contaminated with dirt, sand and stones (Laitila et al., 2008; Athanassiadis et al., 2011), Berg (2014) mentioned that soil contamination of stump cores can still be problematic for the processing industries.

Although the application of an integrated supply chain is associated with the potential for cost reduction, a change in practices is likely to require a steady demand for the residual assortments. This demand could be created by expanding the biomass-based heat and power generation or biorefinery industries that produce, for example, advanced transportation fuels. An integrated supply of stemwood and residues appears to be an attractive option for industrial sites that accept unsorted feedstock components. In addition, forest terminals may act as important hubs for receiving integrated assortments and separating them for different users (Kons et al., 2014).

4.4 Advantages and disadvantages of small-scale decentralized systems

Study I showed that transportation was the most costly process in the supply chains analyzed. In addition, studies II and III identified transportation as the process that contributes the most GHG emissions. Therefore, reducing emissions in transportation will have a large effect on the total emissions of the supply chains. This could be achieved by reducing transportation distances, increasing the load capacity of trucks, or increasing the energy density of biomass. Therefore, both compaction and densification are considered to be crucial for an efficient biomass supply (Eubia, 2017a). A small-scale decentralized production system, such as a mobile pellet plant, could be part of the conventional or integrated forest supply chains. This small-scale production system could contribute to reducing GHG emissions, improving the transportation efficiency of biomass, reducing biomass degradability, and producing a high value, homogeneous product.

4.4.1 Main barriers affecting decentralized renewable energy systems

High operational costs and low efficiency have been identified as some of the most critical barriers to the development of decentralized energy systems (Mangoyana and Smith, 2011; Yaqoot et al., 2016). Technology design, installation and performance are technical barriers that affect efficiency. In fact, Mangoyana and Smith (2011) claimed that economic factors play a more pivotal role in driving the development of small-scale decentralized bioenergy systems than environmental factors. This means that production efficiency is essential to ensuring the overall sustainability of such systems, and efficiency could be improved by: 1) implementing closed loop models where waste materials from one process are used for the production of other products; or 2) seeking linkages in the biofuel production chain for small scale producers, i.e. raw material procurement, refining, distribution and marketing. In addition, Yaqoot et al. (2016) identified policies that favor conventional energy technologies as another important barrier.

However, the decentralized systems also have several strengths, such as the creation of economic opportunities and the reduction of transportation distances, which could reduce transportation costs and emissions. These strengths are enhanced by the local availability of raw materials and local markets for bioenergy (Mangoyana and Smith, 2011). Mangoyana and Smith (2011) pointed out that community participation in providing markets and feedstock is critical for the sustainability of decentralized bioenergy systems.

Different studies have stressed how difficult it is for small-scale decentralized systems to compete with large-scale production systems. For example, Bernesson et al. (2004) compared the small- and large-scale production of rape methyl ester under Swedish conditions. The authors showed that the high efficiency of large-scale production outweighed the environmental impacts of longer transportation distances. Daianova et al. (2012) showed that the cost of supplying a regional passenger car fleet with transport fuel can be decreased by up to 31% when the ethanol production is integrated in a CHP plant when compared to standalone plants. According to the authors, the higher profitability of the integrated system resulted from better process efficiency and the additional revenue that will come from using residuals and/or byproducts within the system. Braimakis et al. (2014) compared the intermediate conversion of biomass to bio-oil (through fast pyrolysis process), along with bio-oil transportation to a central bio-refinery unit, to the alternative option of transporting biomass directly to the same unit. The authors concluded that the reduction in transportation costs cannot make up for the increased capital and operational costs related to the fast pyrolysis process for a range of distances between 100 and 500km. In contrast, Kimming et al. (2015) concluded that a farm cluster in Sweden could produce heat with a lower total climate impact (3 kg CO_2-eq/GJ heat) than a system with production based on regionally-sourced biofuels (13–14 kg CO_2-eq/GJ heat). Compared with the large-scale biomass-based system, the production costs and subsequent heat prices for consumers were lower in the farm cluster system. This was mainly due to the use of unconventional agricultural fuels, but was also influenced by shorter transportation distance, lower overhead costs and the lower profit requirement of small energy producers.

The final outcome of the tradeoff between shorter transportation distances in small-scale decentralized systems and the production efficiency in centralized systems largely depends on the contextual distances, feedstocks used and energy yields (Mangoyana and Smith, 2011).

4.4.2 The mobile wood chip production case

Processes like chipping logging residues are commonly carried out at the landing in Sweden. In fact, wood chip production at the landing is currently the predominant chipping option, covering approximately 75-80% of all chipping operations (Eubia, 2017b). Kettunen (2014) stated that chipping at landing, terminal or plant presents different advantages: the biggest advantage of chipping at the landing is the increase in transportation efficiency, since wood chips provide higher payloads than loose logging residues; while the terminal chipping is advantageous if the terminal is located near the harvesting sites. The wood chips can then be delivered from terminal to different customers with homogenous transportation density. Kettunen found the main advantages of chipping at the plant to be self-controlled logistics, higher capacities and lower chipping costs. Stationary chippers do not have restrictions in design, e.g. weight, whereas the mobile chippers have certain limitations because of their required mobility. Mobile chipper investment costs are typically lower, but the chipping cost per MWh is higher because of the shorter lifetime of the chipper, higher maintenance costs and higher fuel costs. Chipping at the plant becomes more advantageous as the biomass flow increases. Kettunen (2014) also mentioned that the lower operating costs of a stationary chipper offset the investment costs and make the stationary chipper a preferred choice for medium and large power plants that produce more than 10MWe. However, Kanzian et al. (2009) argued that chipping at the plant complicates logistics and increases handling costs, and is often not viable due to high dust and noise emissions.

Nevertheless, chipping closer to the harvesting site becomes advantageous as the transportation distance to industry grows and the biomass density before chipping decreases.

4.4.3 The mobile pellet production case

The results and sensitivity analysis of study IV confirm that the decentralized landing-based scenario is more beneficial in terms of transportation than the terminal-based scenario, and that pelletizer capacity and the energy source used in the system have a strong influence on total emissions. In fact, when the Swedish electricity mix was used instead of diesel fuel, operating at terminal becomes a better option, from a LCA perspective, than operating at landing.

When the transportation distances between landing and terminal increased from 38 km to 200 km, the difference in the GHG emissions arising from the transportation stage between the scenarios increased from 1.4% to 11.1%. This difference was due to better truck payloads in the landing-based scenario, as pellets are denser and have lower moisture content than wood chips. In fact, the maximum weight (and not volume) is the limiting factor for pellet transportation. Thus, scenarios will differ greatly if the transportation distances are large and bigger truck payloads are used.

An increase in pelletizer capacity requires powerful machinery; however, an increase in capacity will reduce the pellet production time, and therefore, reduce the environmental impacts per functional unit. Another key influential factor was the energy source used in the production system. The environmental impacts of the pelletizing and drying stages were reduced when using electricity from the power grid instead of a diesel generator (this option was only possible in terminal-based scenario). Finally, a decrease in the productivity of the landing-based scenario increased all of the environmental impacts. These results showed that an electrified mobile pellet production system situated at a forest terminal close to the harvesting site could, from an LCA point of view, be an interesting option for pelletizing logging residues, especially in regions with long transportation distances to industry. However, since high operational costs were identified as a main barrier to developing decentralized energy systems, it is necessary to analyze the costs in order to evaluate if a mobile option can compete with stationary pellets plants.

Besides chipping, the fractioning process could be an interesting option for landing-based operations. Fractioning improves the quality of wood chips, reduces the fine fractions which have higher moisture, nutrient and ash contents, and eliminates possible contamination by stones or oversize materials. Therefore, this process could improve transportation efficiency since only high-quality wood chips would be transported. In addition, since the fine fraction has high nutrient content it could be distributed over the original stand when transported back from the landing. However, some logistic aspects should be taken into account. In the landing-based scenario, the chipper, fractioning machine and wind-sifter work as one unit. Therefore, the slowest machine determines the productivity of the entire unit, and in the case of landing-based operations, the chipper slowed down the fractioning machine. Thus, the three machines should have similar time consumption figures to improve fractioning efficiency.

4.5 Methodological considerations

4.5.1 Methodologies applied in studies I to IV

Each of the presented studies adopted an LCA perspective to analyze the energy use and other relevant environmental impacts of the systems. In addition, study I included a cost analysis. The results of study I helped define more efficient integrated supply chains that were then evaluated in study II (e.g. bundles instead of whole small trees, crushed stumps at landing, and ET instead of PCT). Study II analyzed fuel consumption in more detail, and presented the weighted average results for conventional and integrated supply chains as well as the fuel consumption by each forest assortment and process. Study II also provided the GHG emissions associated with fossil fuel consumption. In study III, the system boundaries were expanded and the LCA was conducted from a cradle-to gate perspective, i.e. from raw material production to delivery to industry. In addition, the production of machinery and energy was included within the system boundaries. The results from studies I, II and III showed how the contribution of transportation process to the total emissions of supply chains justifies the design of a mobile pellet plant close to the raw material. The system boundaries of study IV also included the production of machinery and energy. Although study IV utilized a gate-to-gate perspective, it would be easy to change to a cradle-to-gate perspective since the raw material used in this study was previously analyzed in study III. The GHG emissions increase by approximately 30 kg CO_2-eq./ODt of pellets produced when the extraction of logging residues to the landing area is considered.

4.5.2 Key factors affecting the quality of the LCA studies

A high-quality LCA study will consider the following aspects:

- System boundaries

The selection of the processes that will be modelled to accomplish the goal of the study will influence confidence in the results of the study (ISO 14040, 2006).

The main objective of studies I and II was to compare the integrated and conventional supply chains in Northern Sweden. For this reason, processes that were similar in all supply chains were excluded from the study. However, study III compared forest supply chains from a cradle-to-gate perspective, i.e. from seedling production up to the delivery of forest assortments to the corresponding forest industries, since Canadian and Swedish supply chains differed also in the preparation stage.

The differences in the GWP of Swedish supply chains between studies II and III clearly show the influence of system boundaries. On average, the GWP results of the supply chains in study II represent around 61% of the GWP results obtained from study III. However, the GWP difference between the two Swedish scenarios was the same in both studies, which indicates that fuel consumption is a good indicator to compare different chains.

Emissions due to changes in soil carbon stocks, the decay of biomass, and the assimilation of CO_2 by trees were excluded from the system boundaries. The uptake of CO_2 during tree growth was considered to be equal to the amount of CO_2 released during the oxidation of wood at the end of its life cycle (Dias and Arroja, 2012; González-García et al., 2014). Although emissions from burning fines in the boiler were included in the calculations of study IV, the ReCiPe method used in calculations ignores the biotic carbon uptake and release. The assumption of carbon neutrality, as well as the decision of how to consider emissions arising from changes in soil carbon stocks, are important aspects that will affect the final climate benefits of using forest biomass.

There are three main CO_2 fluxes in forest ecosystems: CO_2 uptake by plants through photosynthesis; carbon capture in biomass (above and below vegetation, dead wood and litter) and soil; and soil respiration (CO_2 release into the atmosphere as result of organic material decomposition) (De Jong et al., 2014). The balance between growing new biomass and soil respiration determines if the forest is a carbon source or sink in relation to the atmosphere (De Jong et al., 2014). Forestry affects the fluxes mentioned above by harvesting biomass and impacting the soil. Moreover, how the harvested biomass is used determines the timing of emissions (e.g. if biomass is used as fuel, the carbon stored in the biomass is released immediately into the atmosphere, but if natural biomass decomposition takes place the emissions are slowly released), which is important for the overall GHG performance of a biofuel system (Höglund et al., 2013).

The climate impact of biogenic CO_2 emissions from temporary changes in carbon pools is often excluded from environmental impact assessments due to the assumption of carbon neutrality (the carbon is recaptured by new vegetation within the given rotation period, therefore the radiative forcing effects due to these emissions are assumed to be negligible). If the carbon balance is assessed at landscape level instead of at stand level, then the direct carbon emissions from forest fuels can be compensated by the capture of carbon in intensive growth phase stands and by avoided decomposition (De Jong et al., 2014). In fact, Clarke et al. (2015) pointed out that the harvesting effects on the aggregated carbon balance at landscape level may be less dramatic than those for individual stands.

However, as Cherubini et al. (2011) and Michelsen et al. (2012) pointed out, it is important to realize that carbon neutrality is not the same as climate neutrality. The CO_2 that is released into the atmosphere causes radiative forcing and therefore contributes to climate change (Michelsen et al. 2012). From a forest stand perspective, there is a time delay between emissions and sequestration. This time difference is the main reason why bioenergy obtained from sustainably managed biomass has been questioned (Guest et al., 2013); (Michelsen et al. 2012); (Wiloso and Heijungs, 2013). Wiloso and Heijungs (2013) have also mentioned that methane (CH_4), which is a much stronger GHG than CO_2, can be released when biomass burning is incomplete or anaerobic decomposition takes place.

In addition, CO_2 release from forest soils can increase due to soil disturbances after the harvesting of logging residues and stumps (De Jong et al., 2014); (Zabowski et al., 2008); (Walmsley and Godbold, 2010), and this removal might decrease the carbon storage in forest litter and soil pools. (Cherubini et al., 2009). Lindholm et al. (2011) found that the harvesting of stumps and residues, when compared to a reference scenario in which neither residues nor stumps were harvested, decreases the soil organic carbon (SOC) at the beginning of each rotation period. However, the authors noted that the differences in SOC stocks between these scenarios were small at the end of the rotation period. On the other hand, the increase in the decomposition rate could increase nutrient availability and therefore stimulate vegetation growth (De Jong et al., 2014; Clarke et al., 2015).

In the systems analyzed in the research underlying this thesis, the "carbon debt" that exists between biomass combustion and the time it takes to regrow the same amount of biomass (Höglund et al., 2013) will vary for different forest assortment analyzed. Stumps are an example of slow biomass, while tops, branches and small whole trees will "pay back" faster. The final use of the extracted biomass will also affect the climate impact. For example, the stump cores could be used as material instead of energy, and would therefore store carbon for a longer time period. Regarding soil disturbances, the integrated supply chains are expected to reduce the impacts on soil by leaving the root systems of stumps in the ground and reducing soil compaction due to less heavy machinery movement in the stand. However, more biomass will be extracted during thinning, which could decrease the carbon storage in forest litter and soil.

- Input data

"The levels of cut-off criteria and the maximum permissible uncertainty are together with the achieved technical, geographical and time-related representativeness as well as method consistency - the key measure for the overall quality (i.e. accuracy, completeness, and precision) of the outcomes of the LCI/LCA study" (EU-JRC-IES, 2010).

Data quality is another key factor that influences the confidence in the LCA results. According to EU-JRC-IES (2010) the representativeness (and accuracy) of the LCI data "addresses how well the collected data represents the true inventory of the process for which they are collected regarding technology, geography and time". The appropriateness refers to "the degree to which a process data set that is used in the system model actually represents the true process on the analyzed system". Since the technology used in a system strongly influences the LCA results, it is important that the inventory data represents the true technological characteristics of the system. The geographical representativeness refers to how well the data represent the system with respect to location (EU-JRC-IES, 2010). This is also relevant for the background data. Temporal representativeness is closely linked to technological representativeness since technology changes over time. Other important components of data quality are completeness and precision. Completeness refers to how well the inventory data covers all relevant impact categories. Precision is defined in ISO 14044 (2006) as the "measure of the variability of the data values for each data expressed".

In the research underlying this thesis, data for the foreground system (processes related specifically to the system under consideration) and background system (processes associated with machinery, fossil fuels and electricity production) were obtained according to section 2.3. Data from published literature, from machine dealers, contractor companies, as well as data from FPInterface (in the Canadian case) correspond to the specific technology used in each analyzed system in the region under study. Furthermore, data from the national forest inventory regarding available biomass and road transportation distances based on GIS were used for calculations. Particular attention was given to ensuring the representativeness and appropriateness of the inventory data. However, some assumptions were needed, and this increased the uncertainty on the results. Sensitivity analysis was performed in the uncertain parameters. For example, in study II, the differences in estimates of fuel consumption required for extracting stump cores presented there and by Berg et al. (2014), along with uncertainties of stump core as a new assortment that is obtained using technology in a concept stage (feller-puller), resulted in a sensitivity analysis in which the fuel consumption of the stump core supply chain was increased to 20 l/ODt, as Berg et al. (2014) reported. In study III, there were important differences between the Canadian and Swedish scenarios in terms of the origin of the data. Most of the Swedish data (specifically regarding machinery time and fuel consumption, and harvested volumes) were obtained from calculations and models from the literature, while the Canadian data were directly obtained from field measurements by FPInnovations and then introduced to FPInterface. Therefore, a sensitivity analysis using machine productivity data reported by Erikson and Lindroos (2014) - data based on records from the Swedish forestry company SCA operating in Scots pine and Norway spruce forests in Northern Sweden - was conducted to overcome this limitation. Furthermore, the time consumption of the skidder and grinder in the Canadian scenarios were tested by means of a sensitivity analysis since these values differed from those found in literature describing the same region. A sensitivity analysis was also used to test the effects of a 20% decrease in fuel consumption by Canadian machinery (feller-buncher, skidder, processor and horizontal grinder) since fuel consumption is expected to decrease as diesel power technology evolves (Timothy, 2010). When this reduction in fuel consumption was combined with the reduction in grinder and skidder time consumption, the environmental impacts decreased 15 to 24% depending on the supply chain and impact considered, with the exception of FEP, which only decreased by around 1%. This result demonstrates how representativeness of inventory data regarding time can affect research; old data of machinery fuel consumption may not represent the current situation. Study IV utilized a sensitivity analysis carried to show how key parameters affect the results. Specifically the use of electricity from the power grid instead of fossil diesel drastically changed the results.

Data completeness is greatly influenced by the definition of system boundaries. In the presented research, as was mentioned above, emissions due to changes in soil carbon stocks and the decay of biomass have been excluded from the analysis. The consideration, or exclusion, of biotic carbon uptake and release will also influence results. Finally, the applied LCI methods need to be in line with the goal and scope of the studies (methodological appropriateness) and need to be consistently applied across all processes. These factors will also influence the accuracy of the data. The scenarios in the different studies presented in this thesis were harmonized in terms of functional unit and methodological assumptions (system boundaries, database used for secondary data, and impact assessment method) in order to carry out a valid comparison.

➢ Allocation

When allocation cannot be avoided, the input and output flows have to be divided between products according to physical relationships (ex. mass, volume, energy) or economic values (ISO 14040, 2006). Allocation based on energy content can be problematic if all of the co-products are not used for energy production (Ahlgren et al., 2015). Allocation by market price, on the other hand, is complicated by the high variability of forest product prices over time (Karjalainen et al., 2001). System expansion is a method for avoiding allocation in which the product system is expanded to include the additional functions related to the co-products (ISO 14044, 2006). According to EU-JRC-IES (2010), this method is only applicable in attributional LCA when the assessment includes interaction with another system.

Different allocation methods will have different influences on the results. Sandin et al. (2015) explored how different allocation methods affected the climate impact assessment of some biorefinery products. For the main product, economic allocation and allocation based on exergy yielded similar results since the main product dominated both in physical and economic terms. However, when these allocation methods were applied to by-products, the results were very different. Therefore, the choice of the allocation method is more relevant for a non-dominant product (Sandin et al., 2015).

The research presented in this thesis avoided allocation as much as possible by increasing the level of detail in the modelling of key processes such as harvesting and forwarding (specific values were calculated per each assortment). However, allocation was necessary in certain processes (see section 2.4). Most of these processes had a small contribution to the total environmental impacts. Therefore, the influence of different allocation methods on the presented results is expected to be low.

- Impact categories and characterization methods

The assignment of the LCI results to the selected impact categories (classification) and calculation of impact category indicator results (characterization) are mandatory steps of LCIA (ISO 14044, 2006). The selection of the impact categories and characterization model should be consistent with the goal and scope of the LCA study (ISO 14044, 2006). To provide a comprehensive environmental analysis, and avoid drawing the wrong conclusions, it is important to take into account that processes with positive GWP effects can perhaps have negative effects in other impact categories (Klein et al., 2015). Therefore, additional environmental impact categories should be considered. GWP was chosen in the research underlying this thesis because of its relevance in a climate change context. The other impact categories (TAP, MEP, FEP, POFP, NMVOC and FDP) were chosen because they are common categories reported in LCAs of forest systems (Klein et al., 2015; Cherubini and Stromman, 2011), and therefore provide a good basis for comparisons. Björkman and Börjesson (2014) identified five main environmental impact categories while focusing on forest residue recovery: climate change; acidification; eutrophication; biodiversity; and forest productivity. The three first categories were analyzed in the research underlying this thesis. The last two categories were not included in the presented calculations, but their implications were discussed in sections 4.3.4 and 4.5.4.

Characterization models describe the relationship between LCI results and impact category indicators. They are used to derive the characterization factors and should be scientifically and technically valid (ISO 14040, 2006). Different models have been developed by various research teams, yet these models are in different stages of development, which can add uncertainty to the LCIA phase (ISO 14040, 2006). There are additional methodological characteristics that are important to take into account when choosing the characterization models: midpoint or endpoint levels, world regions where the models are valid, and time perspective of the characterization factors. The ISO standard allows LCA practitioners to use impact category indicators that are between the inventory result (i.e. emission) and the "endpoint" (areas of protection: human health, natural environmental and natural resources). These indicators are referred to as "midpoint level" indicators. These indicators generally have lower uncertainty (Goedkoop et al., 2016). Concerning the regional dimension, some environmental impacts have a global scope (i.e. GWP) whereas others have adopted a regional perspective (i.e. acidification and eutrophication). Most methods have been developed to reflect the conditions in Northern and middle Europe, the USA and Japan (Goedkoop et al., 2016). In relation to the time horizon selected, this will affect the LCA results since time influences the relative importance of different types of emissions (Røyne, 2016).

ReCiPe midpoint with a 100-year time horizon was chosen for studies III and IV. The ReCiPe midpoint is a common model used in LCA studies of forest production (Klein et al., 2015), and a 100-year time horizon is one of the most commonly used characterization factors for potential climate impact in LCA studies (Ahlgren et al., 2015; Finnveden et al, 2009). The developers of this method have often used European-scale models to evaluate impacts such as acidification and eutrophication. They have also tried to generalize the models so that they would be relevant for all developed countries in temperate regions (Goedkoop et al., 2009). This means that the validity of the ReCiPe method is limited to developed temperate regions.

4.5.3 Different LCA approaches and other environmental impact assessment tools

Attributional LCA (ALCA) has been applied in the research underlying this thesis. However, two other LCA approaches, consequential (CLCA) and dynamic LCA (DLCA), exist. ALCA and CLCA use different methods and system boundaries to answer different questions. In general, CLCA aims to assess the consequences of changing demands, whereas ALCA is used to assess the environmental burden of a product assuming a status-quo situation. (Thomassen et al., 2008). Since different systems are modeled, the results from CLCA and ALCA also differ (Brander et al., 2008). ALCA provides information about the impacts of the processes that are used to produce a product. This is a more straightforward approach for emission accounting and the level of uncertainty is expected to be lower than in CLCA (Brander et al., 2008). However, ALCA does not consider the market effects of the production and consumption of the product, which is part of CLCA (Brander et al., 2008).

On the other hand, DLCA considers the temporal profile of emissions, which is not considered in ALCA or CLCA. DLCA is a methodology for evaluating systems of which the consequences are distributed over time (Dyckhoff and Kasah, 2014). DLCA results are sensitive to the end-of-life scenario assumed for the product analyzed, the timing of forest growth and the time horizon for global warming potential (Peñaloza et al. 2016).

The research underlying this thesis compared different forest supply chains and systems from either a gate-to-gate or cradle-to-gate perspective. The final industrial products produced from the biomass delivered to industry, as well as and their intended use, were not included in the system boundaries. Therefore, a DLCA approach would have been incomplete since the final products, their uses, and end-of-life scenarios were outside of the system boundaries. Differences in emissions between the analyzed assortments and processes were the key result of the presented studies. No markets effects were included. Therefore, ALCA was the most appropriate approach to fulfill the goals and scopes of the studies presented in this thesis.

There are other environmental tools than LCA for assessing the environmental impacts of processes and systems. Björkman and Börjesson (2014) briefly described several of these tools and discussed their applicability to the environmental assessment of forest residue recovery. The authors concluded that Environmental Impact Assessment (EIA) and LCA, as part of the EIA approach, are suitable tools for this purpose. EIA is site-specific and allows a researcher to assess the impacts of biodiversity, acidification and eutrophication at the stand level (Björkman and Börjesson, 2014).

Another tool is ToSIA (Tool for Sustainability Impact Assessment). ToSIA analyses the three dimensions of sustainability (economic, environmental and social) in forest-wood production chains from the forest to the end-of-life of final products. The tool allows different production chains to be compared in terms of sustainability impacts (European Forest Institute, 2014a). All processes of a specific chain are calculated as if they were simultaneous because the impact assessment for the whole chain is calculated for one specific time reference, usually one year. Different studies have chosen ToSIA as the method for sustainability impact assessment (Lindner et al. 2011; Den Herder et al. 2012; Werhahm-Mees et al. 2010; European Forest Institute, 2014b). This tool could have been used in the research underlying this thesis. In that case, data related to the social aspects of the forest supply chains would have been needed. However, LCA - although limited only to environmental assessment – is more commonly used in wood production and bioenergy system analysis, and this facilitates comparison between studies. EIA is a broader tool that not only assesses the environmental impacts of projects, processes and/or systems, but also includes measures to avoid, reduce or compensate those impacts, which is outside the scope of this thesis.

4.5.4 Other environmental considerations

Although the use of wood fuels can be considered environmentally beneficial in terms of reducing GHG emissions compared to fossil fuels, this application can have other negative environmental implications such as changes in soil nutrient content and structure, along with their possible effects on forest productivity, changes in water quality, and the reduction of deadwood with the associated adverse consequences for biodiversity (Ferranti 2014). These negative aspects were not included in the presented analyses. It is important to mention that the chosen midpoint environmental impact indicators were relevant for the goals and scopes of the presented studies. Therefore, the final effect of resource consumption on forest ecosystems was not included, but it is expected that the higher values of midpoint indicators will translate to higher values of endpoint indicators. Nevertheless, the negative impacts mentioned above are important factors to consider when assessing the sustainability of the forest supply chains. Long-term field experiments should be continued to provide further knowledge of the long-term effects of increasing biomass recovery (Björkman and Börjesson, 2014).

5 Conclusions

The research underlying this thesis assessed the costs and environmental impacts of conventional and integrated forest supply chains in Northern Sweden, as well as a case study in Canada, from a life cycle perspective. The results presented here improve knowledge about forest supply chains, and they can stimulate the development of more efficient supply chains that will be characterized by reduced environmental impacts such as GHG emissions. The main conclusions of the presented research were:

- The energy input in the supply chains was relatively small compared to the energy content of the harvested assortments in both roundwood and residual forest biomass assortments. The amount of energy used corresponded to approximately 2-6% of the energy content of the delivered assortments. When producing pellets from residual forest biomass, the amount of non-renewable energy used corresponded to approximately 23% of the energy content of the produced pellets. This energy input was reduced to 15% when using electricity from the power grid instead of a diesel generator at the terminal. Therefore, from a LCA perspective, upgrading forest biomass close to the raw material source to a final product, such as pellets, will be a better option than producing wood chips depending on the contextual distances to final user and depending on the handling and storage processes. Operational and system management costs should also be considered before making any decisions.

- Integrated supply chains, when compared to conventional supply chains, have the potential to reduce the supply cost of non-stemwood assortments. In addition, the integrated supply chains were more energy efficient than conventional supply chains, and have the potential to reduce GHG emissions by approximately 13%. The reduction in TAP, FEP, MEP, POFP and FDP was 17%, 24%, 17%, 17%, and 13%, respectively. The supply of conventional stumps remained the most expensive supply chain, and also generated the highest GHG emissions per ODt. Therefore, the conventional stump supply chain is the least desirable supply chain from a LCA and economic perspective. When stump harvesting was excluded from the analysis, the integrated supply chains were shown to consume approximately 6% more energy than the conventional supply chains, yet provide 16 to 26% more biomass.

- Transportation processes accounted for the largest share of energy consumption in both conventional and integrated supply chains. Assortments that were not delimbed required more energy during transportation because they were bulkier. However, bundling whole small trees (producing BWT) reduced the volume of this assortment and thus, fuel consumption per ODt. The results from study IV showed that the transportation of pellets instead of wood chips reduced GHG emissions due to a better truck payload. This is because pellets are denser and have lower moisture content than wood chips. This difference in GHG emissions will be more noticeable as the transportation distances grows and if larger truck payloads are used.

- Other processes that largely contributed to GHG emissions were forwarding, harvesting, and chipping. In the forwarding process, stump and logging residues required the most energy. However, the integrated supply chains used less energy during forwarding due to higher stemwood contents of the BWT, RS and sawlog with stump core assortments. Harvesting RS and long tops rather than pulpwood assortments was more productive during both first and second thinning since the harvester did not delimb all the branches. The extraction of stump cores consumes little fuel since stump cores were harvested when attached to sawlogs, which increased machinery productivity and truck payload. However, the supply of this assortment was the least studied and it is particularly sensitive to uncertainties in the assumptions.

- The Swedish supply chains showed a better environmental profile, on average, per ODt than the Canadian supply chains in the regions studied. In terms of GWP, the Swedish integrated supply chains had 30% and 38% lower values than the Canadian biomass dedicated and conventional supply chains, respectively. In terms of TAP, FEP, MEP, POFP and FDP, these reductions were 42%, 58%, 42%, 41% and 37% lower, respectively, than the Canadian conventional supply chains and 33%, 25%, 33%, 33% and

30% lower, respectively, than the Canadian biomass dedicated supply chains. This emission reduction was due to lower fuel consumption in key processes within the supply chain, i.e. transportation to industry, forwarding versus skidding, chipping at terminal versus grinding at roadside, and harvesting with harvester versus feller-buncher plus processor operating at landing.

- The difference in environmental impacts (climate change, terrestrial acidification, marine and fresh water eutrophication, photochemical oxidant formation and fossil fuel depletion) between the mobile pellet production system operating at a forest landing and a forest terminal was around 1%. Therefore, both alternatives can be considered almost equal. However, if the Swedish electricity mix was used at the terminal, the environmental impacts (with the exception of fresh water eutrophication potential) decreased, and operating at the terminal became a better option from a LCA perspective. The production stages that consumed the most energy and largely contributed to the environmental impacts (hotspots in the system) were pelleting, transportation and drying. Therefore, improvements in these stages would improve the environmental profile of the system. In fact, a key influential factor in the studied system was, other than the use of electricity at terminals, the pelletizer capacity. An increase in capacity would reduce pellet production time, and therefore, the environmental impacts per ODt. Transportation distances was another factor influencing how the systems operating at either forest landing or forest terminal performed in terms terms of GHG emissions. The system operating at the forest landing became more advantageous as the transportation distance grew. In contrast, the biomass concentration at the landing had a small influence on the environmental profiles. The emission reduction obtained when transporting pellets from the landing to terminal instead of wood chips (with a 200 km transportation distance) was lower than the emission reduction obtained when changing the source of energy at the terminal. When considering all of these factors, an electrified mobile pellet production system with high operational efficiency that is situated at a terminal close to the harvesting sites becomes a better option, from a LCA perspective, than a mobile system situated at the landing. This approach could be interesting for the pelletizing of Nordic logging residues, especially in regions with long transportation distances to industry.

6 Future research

In order to reduce the dependency on fossil fuels and fulfil the EU targets on GHG emission reductions, an increase in demand of forest biomass is expected. Therefore, it is essential to ensure the sustainability of forest supply chains. This thesis has assessed several issues related to sustainability of conventional and integrated forest biomass supply chains, for example, costs and environmental impacts of the consumption of both energy and materials. However, the following aspects could be addressed in further studies to increase knowledge, and make informed decisions, about the design of forest supply chains:

- The negative environmental impacts of new harvesting practices that increase the extraction of forest biomass, such as changes in soil nutrient content and subsequent effects on forest productivity, changes in water quality, reduction of deadwood with the associated adverse consequences for biodiversity, and soil compaction (the implementation of integrated supply chains is expected to reduce this environmental impact because there will be less driving over the terrain than in cases characterized by separate extraction of residual biomass).

- The amount of GHG emissions arising from soil disturbances and changes in soil organic carbon due to increased harvesting of residual forest biomass.

- How does the decay rate affect GHG emissions, and what quality losses over time can be expected for the different residual forest assortments? This type of study would be especially relevant from a management perspective, as managers need to deliver different assortments to different industries while maintaining specific quality standards. In addition, this information would have applications for situations where residual forest biomass is left on the harvesting site for a period to leave needles, i.e. a high percentage of nutrients.

- Full-scale field trials to verify the results regarding integrated supply chains and mobile pellet production plants. This is especially relevant when new machinery is used and when new assortments are extracted, i.e. stump cores. Study IV assumed that the bio-boiler utilized to generate heat and dry the wood chips would only run on fuel from the fine fractions (by-product) from the fractioning process. However, to improve combustion in the bio-boiler, maybe a mixture with wood chips would be needed. Another assumption was the linear relation between time and moisture content in the drying process. Both assumptions should be tested on the field.

- A characterization of the future demand for the integrated supply chains' assortments. Integrated supply chains would seem most interesting to industrial sites with the capacity to process both stemwood and residual assortments. It would be relevant to analyze whether current forest industries would have possible difficulties in handling and processing sawlogs with stump cores, and also future possibilities due to utilization of new forest biomass components.

- Operational and system management costs of the mobile pellet production system analyzed in study IV. The operational costs of forest operations are generally strongly correlated to the operational consumption of diesel fuel, and thus strongly correlated to productivity and to the degree of technical utilization. The system management cost is strongly correlated to the size and complexity of the system. Thus, an additional analysis of the systems that considers operational and management costs could be an important part of the decision-making process.

- Development of terminal logistics. Forest terminals may act as hubs that receive integrated assortments, separate these for different users, and even process biomass to the final products, i.e. pellets.

- Positive social aspects. Forest terminals and small-scale decentralized bioenergy systems could provide economic development opportunities in rural areas.

- The timing of GHG emission by considering the whole life cycle of different final industrial products. This approach would give a complete picture of the GWP generated by the utilization of forest biomass.

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Popular science summary

Forests supply the raw materials for a variety of products that we use in our daily lives, such as paper, cardboard, furniture and even entire houses. Forests also supply renewable energy, providing heat and electricity for our homes, and are an essential resource in low-income countries where wood fuel is the most important wood product. In addition to these benefits, forests also play an important role in climate change mitigation. Trees absorb carbon dioxide (CO_2) from the atmosphere during photosynthesis, converting solar energy, CO_2 and water into carbohydrates while releasing oxygen. Therefore, a growing forest constitutes a carbon sink since the carbon absorbed from CO_2 is sequestered in the biomass. Woody biomass from sustainably managed forests can be used instead of energy-intensive materials such as concrete and non-renewable energy sources such as fossil fuels to reduce carbon emissions into the atmosphere. Therefore, forests can help achieve the sustainable development goals adopted by world leaders in the United Nations summit held in New York in September 2015, to promote prosperity and protect our planet.

However, forest supply chains usually require fossil fuels for the production, extraction, transport and conversion of biomass into bioenergy or other final products, as forestry machinery and trucks usually run on diesel fuel. The more fossil fuel a forest supply chain consumes, the less climate benefits it provides. Therefore, the biomass procurement and processing requirements will make some supply chains better than others from an environmental perspective.

Today in Sweden, the residual forest biomass (tops and branches) that is recovered after clearcutting is extracted from the forest and transported to the industry separately from stemwood. One alternative to the current conventional supply chains is the utilization of integrated supply chains in which the residual forest biomass is harvested and transported together with stemwood. Moreover, mobile production systems, such as small-scale mobile pellet plants, situated close to the raw material source could further enhance the efficiency of the residual forest biomass supply chains.

The aim of this thesis was to assess cost, energy consumption, greenhouse gas (GHG) emissions and other relevant environmental impacts of conventional and integrated forest supply chains in Northern Sweden. A case study in Western Canada and a mobile production system for pelletizing logging residues were also evaluated in the research underlying this thesis.

The results showed that integrated supply chains have the potential to reduce the supply cost for residual forest biomass. Moreover, the integrated supply chains were more energy efficient than conventional supply chains, and have the potential to reduce GHG emissions by approximately 13%. The Swedish supply chains also showed better environmental results than the studied Canadian supply chains. When all of the forest assortments were considered, the Swedish integrated supply chains exhibited between 30% to 38% lower average GHG emissions than the Canadian supply chains.

The analysis of a small-scale mobile pellet production system showed that the best option, from an environmental perspective, would be an electrified mobile system with high operational efficiency that is situated at the terminal (an intermediate site between the forest and industry where different forest assortments are temporarily stored and potentially pre-processed) close to the harvesting sites. This type of system could be an interesting option for the pelletization of Nordic logging residues, especially in regions that have long transportation distances to industry. The results presented in this thesis have provided knowledge that could be used to develop more efficient supply chains in the future.

Populärvetenskaplig sammanfattning

Skog och skogsbruk är en viktig leverantör av råvaror till produkter som vi använder i våra dagliga liv, som papper, kartong, möbler och hus. Skog levererar också förnybar energi som ger värme och el till våra hem. Dessutom spelar skogar också en viktig roll för att mildra klimatförändringen. Träd absorberar koldioxid (CO2) från atmosfären, omvandlar solenergi, CO2 och vatten till biomassa samtidigt som syre produceras och släpps ut. Därför utgör växande skog en kolsänka då kolet lagras i biomassan. Biomassa från hållbart brukade skogar kan användas istället för energiintensiva material som betong och fossila energikällor. Skog kan därför bidra till att uppnå de hållbara utvecklingsmål som världsledarna antog i september 2015 på FN-toppmötet i New York, för att främja välstånd och för att skydda vår planet.

Skogsförsörjningskedjor kräver emellertid fossila bränslen för skörd och transport eftersom skogsmaskiner och lastbilar oftast körs på dieselbränsle. Ju mer fossilt bränsle en skogsförsörjningskedja förbrukar desto lägre klimatfördelar ger den. Därför är vissa försörjningskedjor bättre än andra ur miljösynpunkt.

I Europa förväntas marknaden för skogsbioenergi och andra träbaserade produkter att fortsatt växa. Biprodukterna från den svenska skogsindustrin utnyttjas dock redan fullt ut. Därför måste en ökning ske genom att ta tillvara större mängder råvara direkt från skog än idag.

Tillgången av GROT (GRenar Och Toppar) beror på omfattningen av konventionella avverkningar, och främst då på föryngringsavverkningar. Nuvarande konventionella försörjningskedjor innebär att rundvirke och GROT tas tillvara i helt separata processer. Först avverkas och transporteras rundvirket till bilväg och en tid senare transporteras GROT ut med en annan skotare. Ett alternativ är att utnyttja integrerade försörjningskedjor där GROT skördas och transporteras tillsammans med rundvirket. Det är också ett alternativ att pelletera GROT på ett tidigt stadium i försörjningskedjan för att öka transporteffektiviteten fram till industri. För detta krävs nya metoder som har hög energieffektivitet, som inte förorsakar stora utsläpp av växthusgaser och som medför bättre ekonomi än konventionella försörjningskedjor.

Det övergripande syftet med denna avhandling var att utvärdera kostnad, energianvändning, växthusgasutsläpp och annan relevant miljöpåverkan för konventionella och integrerade försörjningskedjor av skoglig biomassa i norra Sverige.

Analyserna omfattade modellering av konventionella och integrerade försörjningskedjor och en fallstudie i västra Kanada för jämförelse. Analyserna innefattade också modellering av ett mobilt produktionssystem för pelletering av GROT från föryngringsavverkning. Analyserna har i huvudsak utförts med livscykelanalysmetodik (LCA).

Resultaten visade att integrerade försörjningskedjor har potential att minska kostnaden för GROT vid industri. Dessutom var de integrerade försörjningskedjorna mer energieffektiva än konventionella försörjningskedjor och har potential att minska utsläppen av växthusgaser med cirka 13%. Minskningen av ekosystemets försurning, övergödning av vatten, bildandet av fotokemiska oxidanter och minskad förbrukning av fossila bränslen i samband med övergång från en konventionell till en integrerad försörjningskedja var i spannet 13 till 24 %.

När alla sortiment beaktades uppvisade de svenska integrerade försörjningskedjorna 30 till 38 % lägre växthusgasutsläpp än de kanadensiska försörjningskedjorna.

Analysen av ett småskaligt mobilt pelletsproduktionssystem visade att ur miljösynpunkt borde det bästa alternativet vara ett eldrivet mobilt högproduktivt system som ligger vid terminal. Terminalen är då en temporär lagringsplats som ligger nära skogen, där en del material kan komma att förbehandlas. Denna typ av system kan vara ett intressant alternativ för pelletering av GROT, särskilt i regioner som har långa transportavstånd till industrin.

Resultaten som presenteras i denna avhandling har gett kunskaper som kan användas för att utveckla mer effektiva försörjningskedjor till befintliga och kommande industrier som baseras på skogligt biomaterial.

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