Improving supply chains for logging residues and small-diameter trees in Sweden

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Abstract

Forestry is expected to play a key enabling role in the transition towards a low-carbon, sustainable, and circular biomass-based economy in Europe. This will increase demand for forest biomass as a source of energy and traditional and new wood-based products. Consequently, it will be necessary to increase the mobilization of underutilized residual woody biomass such as logging residues (LR) and small-diameter trees (ST). While much residual biomass exists in forest land, significant quantities also exist in other lands such as overgrown agricultural land, power line corridors, and roadsides. However, high supply costs make it difficult to bring LR and ST to the market at a competitive price, which limits their utilization. Managing LR and ST supply chains is complex because it involves interconnected upstream and downstream operations performed by several contractors. This thesis aims to measure and analyse characteristics of LR and ST in Sweden, and the efficiency and costs of their supply systems, considering both current (heat and power plants, pulpmills) and future end-users (biorefineries). The main methods used for this purpose in this thesis are GIS analysis, time study, fuel-chip quality assessment, and discrete-event simulation. LR and ST were assessed along different supply chain operations in different operational environments, from the site to the end-user, and potential improvements leading to cost savings were identified.

Large quantities of underutilized ST were identified across Sweden. It was also shown that using machines to extract overgrown vegetation along power line corridors could be more cost-efficient than current motor-manual (brush saw) clearing practices: even if this did not provide a net income, it could partially or fully offset maintenance costs. Models for predicting the dry mass content of windrows could improve logistics, and a holistic, supply chain management approach, is crucial for cost-effective delivery of high-quality residual biomass. The use of terminals increases supply costs but helps to secure supply during peak demand and cope with operational problems in the supply fleet that would prevent demand from being met on time in a direct supply system. Further development of supply systems (working methods and technology) is needed to realize the sustainable potential of LR and ST. These results offer policymakers, researchers, and industrial developers and practitioners new knowledge that could improve supply chains and increase the cost-competitiveness and utilization of LR and ST.

Keywords: bioeconomy, bioenergy, biorefinery, forest fuels, wood chips, residual biomass, GIS, logistics, simulation, terminal.

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Effektivisering av försörjningskedjor för grot och klenträd i Sverige

Sammanfattning

Skogsbruk är en hörnsten för att möjliggöra övergången till en koldioxidsnål, hållbar och cirkulär biobaserad ekonomi i Europa. Efterfrågan på skoglig biomassa för energi samt traditionella och nya träbaserade produkter förväntas därför att öka. Det medför i sin tur att försörjningskedjor för underutnyttjade biomassaresurser som grot (grenar och toppar) och klenträd behöver effektiviseras. Betydande mängder av grot och klenträd kan även skördas från andra marker än skogsmark, som igenväxta jordbruksmarker, kraftledningsgator, vägkanter, osv. Höga kostnader för skörd och transport av dessa råvaror gör det dock svårt att etablera dem på marknaden till ett konkurrenskraftigt pris. Att styra försörjningskedjan av grot och klenträd är komplext då den består av sammankopplade operationer utförda av flera entreprenörer. Syftet med denna avhandling var därför att analysera effektivitet och kostnader på försörjningssystem för grot och klenträd till dagens och morgondagens industrier i Sverige. I detta forskningsarbete användes metoder som: GIS-analyser, tidsstudier, bränsleanalyser och händelsestyrd simulering.

Resultaten visar att det finns stora mängder outnyttjade resurser av klenträd i Sverige. Att använda skogsmaskiner för att ta tillvara klenträd från igenväxta kraftledningsgator kan vara ett mer kostnadseffektivt alternativ än nuvarande praxis (att röja med motormanuell röjsåg och lämna biomassan kvar i beståndet), även om det inte ger en nettoinkomst för markägaren då röjningen endast medför en kostnad. I avhandlingen presenteras modeller för prediktering av torrhalt i vältor av grot och klenträd, vilka kan användas i praktiken för att förbättra logistiken samt effektivisera leveranser av bränsleflis. Trots att användandet av terminaler i försörjningskedjan höjer försörjningskostnaderna till industrierna, så medför det att man kan säkerställa försörjning när efterfrågan är som högst och när det finns stor risk för störningar i flödet (till exempel under vårförfallet). Teknik, metoder och system för de olika delarna i försörjningskedjan behöver dock utvecklas ytterligare för att man skall kunna utnyttja den hållbara potentialen av grot och klenträd. Detta avhandlingsarbete utgör ett underlag för vidareutveckling av forskningsmetoder, effektivisering av försörjningskedjor, politiska beslut rörande bioekonomi, osv. I slutändan kan detta medföra ett ökat utnyttjande av hållbar biomassa från det svenska skogsbruket samt annan produktionsmark.

Nyckelord: bioekonomi, bioenergi, bioraffinaderi, skogsbränsle, flis, skogsrester, GIS, logistik, simulering, terminal.

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Mejora de la cadena de suministro de restos de corta y árboles de pequeñas dimensiones en Suecia

Resumen

Se espera que la silvicultura desempeñe un papel clave en la transición a una economía circular basada en la biomasa, baja en carbono y sostenible en Europa. Por ello, se prevé un incremento de la demanda de biomasa forestal para energía y productos madereros convencionales e innovadores. A su vez, será necesario incrementar el aprovechamiento de la biomasa forestal residual, como por ejemplo restos de corta (RC) y árboles de pequeñas dimensiones (AP). Además de los RC y AP en montes, existen cantidades significativas en terrenos agrícolas abandonados, pasillos de líneas eléctricas (franjas de servidumbre), cunetas, etc. No obstante, los elevados costes de suministro dificultan llevar RC y AP al mercado a un precio competitivo y limitan un mayor aprovechamiento. La gestión de la cadena de suministro de RC y AP es compleja, ya que se compone de múltiples actividades relacionadas entre sí y llevadas a cabo por diferentes maquinistas. El objetivo de esta tesis fue la medición y el análisis de características de RC y AP en Suecia, los rendimientos y costes de sus sistemas aprovechamiento, considerando las industrias actuales (plantas de cogeneración, plantas de celulosa) y futuras (biorefinerías) de esta biomasa residual. Los principales métodos fueron: análisis con SIG, estudios de tiempo, análisis de calidad de astillas y simulación por eventos discretos.

Los resultados revelaron la existencia de grandes cantidades infrautilizadas de AP en Suecia. Así mismo, el uso de maquinaria forestal para aprovechar AP en pasillos de líneas eléctricas podría ser una alternativa a la práctica actual (desbrozado manual con desbrozadoras y abandono de la biomasa en el terreno), capaz de compensar parcial- o totalmente los costes de mantenimiento. El uso de modelos predictivos del contenido de materia seca en pilas de RC y AP puede mejorar la logística de la producción de astillas. Un manejo holístico de la cadena de suministro es fundamental para proveer astilla de alta calidad. Aunque el uso de terminales logísticas incrementa el coste de suministro de biomasa a la industria, su uso contribuye a asegurar el suministro cuando la demanda es máxima y hay riesgo de problemas (baja traficabilidad de las pistas forestales debido a inclemencias meteorológicas, averías, etc.). Para aprovechar el potencial sostenible de RC y AP será necesario el desarrollo de la tecnología y la mejora de los métodos de trabajo. Los resultados de esta tesis constituyen una base para apoyar la toma de decisiones políticas sobre bioeconomía y la mejora de la competitividad de las cadenas de suministro de biomasa forestal residual para incrementar su uso sostenible.

Palabras clave: bioeconomía, bioenergía, biorefinería, combustible forestal, astillas de madera, biomasa residual, SIG, logística, simulación, terminales.

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Dedication

To Johanna and Selma.

If it's not in writing, it didn't happen.
Anonymous

Contents

List of publications

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

I Fernandez-Lacruz, R.*, Di Fulvio, F., Athanassiadis, D., Bergström, D. & Nordfjell, T. (2015). Distribution, characteristics and potential of biomass-dense thinning forests in Sweden. *Silva Fennica*, 49(5). https://doi.org/10.14214/sf.1377

II Fernandez-Lacruz, R.*, Di Fulvio, F. & Bergström, D. (2013). Productivity and profitability of harvesting power line corridors for bioenergy. *Silva Fennica*, 47(1). https://doi.org/10.14214/sf.904

III Fernandez-Lacruz, R.* & Bergström, D. (2017). Windrowing and fuel-chip quality of residual forest biomasses in northern Sweden. *International Journal of Forest Engineering*, 28(3), pp. 186-197. https://doi.org/10.1080/14942119.2017.1338391

IV Fernandez-Lacruz, R.*, Eriksson, A. & Bergström, D. Simulation-based cost analysis of industrial supply of residual woody biomass. *Submitted manuscript.*

* Corresponding author.

The contribution of Raul Fernandez Lacruz to the papers included in this thesis was as follows:

I Planned the study together with the co-authors. Prepared data and performed the analysis. Wrote the manuscript with input from the co-authors.

II Carried out the fieldwork together with Fulvio Di Fulvio. Performed the analysis and wrote the manuscript with input from the co-authors.

III Planned the study together with the co-author. Carried out the fieldwork and analysis. Wrote the manuscript with input from the co-author.

IV Planned the study together with the co-authors. Built the simulation model with input from the co-authors. Ran the simulation, interpreted and analysed the outputs. Wrote the manuscript with input from the co-authors.

Abbreviations

AC	Ash content (dry-basis)
AFH	Accumulating felling head
AHH	Accumulating harvester head
ANOVA	Analysis of variance
BDTF	Biomass-dense thinning forests
BR	Biorefinery
CHP	Combined heat and power plant
cm	Centimetre
CO_2	Carbon dioxide
DBH	Diameter at breast height (i.e. at 1.3 m above ground level)
DES	Discrete-event simulation
dm	Decimetre
dm^3	Cubic decimetre (1 dm^3=1 litre)
DML	Dry matter losses
DSH	Diameter at stump height
e.g.	For example
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
g	Gram
GIS	Geographical information system
GPS	Global positioning system
h	Hour
ha	Hectare
i.e.	In other words
kg	Kilogram
km	Kilometre
kW	Kilowatt
LR	Logging residues (slash, i.e. tops and branches)

M	Million
m	Metre
m^2	Squared metre
m^3	Cubic metre
MC	Moisture content (wet-basis)
min	Minute
mm	Millimetre
MWh	Megawatt hour
NFI	Swedish National Forest Inventory
p	*p*-value
PCT	Pre-commercial thinning
PL	Power line
PM	Productive machine (time), excluding all delays (i.e. productive work time, Björheden *et al.* (1995)
PMh	Productive machine hour
PMmin	Productive machine minute
PSD	Particle size distribution
R^2_{adj}	Adjusted R^2 (coefficient of determination)
SC	Supply chain
SCM	Supply chain management
SM	Scheduled machine (time), i.e. workplace time (Björheden *et al.*, 1995)
SMh	Scheduled machine hour
ST	Small-diameter trees
t	tonne (metric ton), i.e. 1 000 kg
TWh	Terawatt hour

Calculations used an exchange rate of 1 € (euro) = 9.6 SEK (Swedish crowns).

1 Introduction

1.1 Climate change and the forest-based bioeconomy

Since the beginning of the 19th century, the increasing exploitation of fossil-based resources (coal, oil and gas) (Ritchie & Roser, 2019) and other natural resources for energy generation and material production has enabled historically unprecedented demographic and economic growth (Winkel, 2017). However, the relentless increase in atmospheric levels of carbon dioxide (CO_2) (NASA, 2019) and other greenhouse gasses originating from fossil fuel combustion is causing global warming (EEA, 2019). The Paris Agreement (UN, 2017a) and the Intergovernmental Panel on Climate Change (IPPC, 2018) call for a reduction in the use of fossil-based resources to mitigate climate change. Ambitious targets for achieving this goal have been adopted in Europe (European Parlament, 2018). Globally, fossil fuels account for 81% of the total primary energy supply (IEA, 2018c), while bioenergy accounts for 10%. The expected increase in the world's population this century (UN, 2017b) will increase the global demand for food, fuel, and fibre (KSLA, 2012), necessitating a rapid transition to a low-carbon, sustainable, and circular biomass-based economy. Forestry is seen as a cornerstone of this transition in Europe (Verkerk *et al.*, 2019; Winkel, 2017; Mubareka *et al.*, 2016), but the transition must be made while maintaining forests' capacity to provide ecosystem services (de Rigo *et al.*, 2016; Verkerk *et al.*, 2014). If forest productivity and the efficiency of wood-based product manufacturing increases, the EU's CO_2 emissions could be reduced by as much as 20% by 2050 (Kauppi *et al.*, 2018).

The forest-based sector actively contributes to climate change mitigation by replacing large amounts of fossil-based energy and materials with renewable bioenergy and wood-based products (Leskinen *et al.*, 2018; Pelkonen *et al.*, 2014). Active and sustainable forest management is more beneficial to the climate than simply using forests as carbon sinks (Yousefpour *et al.*, 2018; Gustavsson *et al.*, 2017; Gustavsson *et al.*, 2015). Wood-based energy and products obtained by sustainable forest management (as implemented in Europe and elsewhere in the World) have a low-carbon footprint because their net CO_2 emissions are due to the processes involving in their manufacture rather than the raw materials themselves (wood is renewable, unlike fossil resources) (IEA Bioenergy, 2018; Berndes *et al.*, 2016; Beyer, 2012). Decarbonisation of supply chains (SCs) by adopting conventional technologies powered by biofuels (or new hybrid/electric machinery powered by renewable electricity) and increasing the efficiency of production processes will thus move forest biomass closer to carbon-neutrality. Life cycle assessment can quantify the CO_2 emissions due to production processes in SCs (De La Fuente Diez, 2017; Hammar, 2017), and have shown that the energy input into these processes can amount to ~2–6% of the energy content of the delivered wood (Joelsson *et al.*, 2016). Andersson *et al.* (2016) calculated that 28 units of energy are returned for each unit of energy input into an SC for fuel-chips derived from small-diameter trees (ST).

1.2 *"Yesterday's residual is today's raw material"* (Hakkila, 1989)

In Sweden, energy derived from renewable sources accounted for 55% of the total primary energy supply in 2017 (565 TWh), with bioenergy alone accounting for 25% (143 TWh) of this total (Swedish Energy Agency, 2019). The success of bioenergy in Sweden is due to the implementation of a CO_2 tax and an extensive forest industry (Andersson, 2015). Bioenergy is produced on an industrial scale and is largely sourced from residual streams from forest-related activities, notably black liquors from pulpmills (47 TWh) and unprocessed forest wood fuels (52 TWh) (Swedish Energy Agency, 2018). Of the unprocessed forest wood fuels, around half is extracted directly from the forest (i.e. primary forest fuels, including traditional firewood) and the remainder comprises by-products (secondary forest fuels, e.g. sawdust, bark, etc.) of roundwood processing at saw- and pulpmills. Total production of fuel-chips from primary forest fuels amounted to ~3.3 M dry tonnes (t) (16 TWh), with logging residues (LR; slash, i.e. tops and branches), sub-standard (defect) roundwood, ST (undelimbed) and stumps accounting for 54, 40, 5 and 1% of the total, respectively (Swedish Energy Agency, 2018). LR and stumps are produced during roundwood (sawn- and pulpwood) harvesting, while ST are harvested during thinnings of dense forests and clearings of other lands. A typical goal in Swedish forestry is to maximize the net present value of timber by focusing on the production of high quality industrial roundwood (rather than these residual forest biomasses) and the provision of other ecosystem services (Witzell *et al.*, 2019; Sängstuvall, 2010). The same is true in Finland (Petty, 2014), which is why primary forest fuels are often collectively referred to as residual forest biomass (Hakkila, 1989). Much of the forest industry's residuals are consumed by the forest industry itself (in direct combustion to generate heat and power). Surplus by-products are typically sold to pellet mills, and to the energy industry (together with primary forest fuels) for direct combustion in district heating plants and combined heat and power plants (CHPs). The use of by-products is currently near-maximal relative to their availability, as shown by Edlund *et al.* (2015). However, Routa *et al.* (2013) showed that only 50% of the technical potential of LR is currently realized; the corresponding figures for ST and stumps are 20% and 2%, respectively.

If the transition towards a forest-based bioeconomy continues, the demand for forest biomass is expected to increase (Börjesson *et al.*, 2017; Börjesson, 2016; Pöyry, 2016; Swedish Forest Agency, 2015a; Mantau *et al.*, 2010) because biomass will be needed for energy generation and for the manufacturing of traditional and new wood-based products such as textiles, bioplastics, liquid biofuels, and green chemicals in new biorefineries (BRs) (Attard *et al.*, 2018; Eriksson *et al.*, 2018; SP Processum, 2016; Bergström & Matisons, 2014). However, the roundwood harvest in Sweden is approaching its sustainable maximum (Nilsson *et al.*, 2018; Swedish Forest Agency, 2015b). Under certain future scenarios, the increase in demand for biomass is expected to spur competition between industries for raw materials (Mantau *et al.*, 2010). Consequently, it will be necessary to intensify forest production, improve the efficiency of SCs, and increase the mobilization of underutilized biomass resources such as stumps, LR, and ST. Although it is predominantly used for energy generation (by direct combustion), residual woody ("lignocellulosic") biomass can also be used as a feedstock in bio- and thermochemical biorefining processes (Sowlati, 2016) to produce high-value products. A BR is "*a facility that integrates conversion processes and equipment to produce fuels, power and chemicals from biomass*" (Yue & You, 2016). Commercial production of biofuels using black liquors from pulpmills as the feedstock has begun in Finland and Sweden (UPM, 2019; Sunpine, 2017). Additionally, there are ambitious plans in Sweden to use residual woody biomass in other biorefining processes (SCA, 2019; SEKAB, 2019; LTU, 2018; Bioendev AB, 2017; Preem, 2017; Wormslev *et al.*, 2016). In the United States, LR from Douglas fir have been used to produce jet biofuel, and there are plans to start commercial production (USDA, 2016). The interest in producing biofuels from residual woody biomass is strengthened by the fact that unlike other biomass sources (e.g. food crops such as sugarcane, starchy grains, and oil seeds), it can be produced without the risk of competing with food production or triggering potentially negative land use changes that could increase CO_2 emissions (Valin *et al.*, 2015; Harvey & Pilgrim, 2011). The establishment of new BRs will require efficient supply chain management (SCM) for woody biomass (to reduce its supply costs), further improvements in conversion processes, and the support of policymakers (Fethers, 2014; Sharma *et al.*, 2013).

Any end-user of woody biomass will require a reliable and cost-efficient feedstock supply throughout the year. Forest fuels are harvested year-round, but the demand curve of energy industries is highly seasonal: demand peaks in winter and bottoms out in summer. Consequently, forest fuels must be stored somewhere within the SC, and contractors supplying biomass directly from the forest must concentrate their operations during a few months of the year. A common practice in the forest fuel business is for the industry and suppliers to agree on a delivery plan specifying the quantity of chips to be supplied every month (Johansson, 2013). Conversely, the annual demand of Swedish BRs is expected to be relatively stable (non-seasonal) because they are likely to be integrated with existing pulpmills (Pettersson *et al.*, 2013), allowing contractors to maintain year-round operation. The supply costs of residual biomass could be significantly reduced if its supply was integrated with that of roundwood (Joelsson *et al.*, 2016). Roundwood contractors commonly reduce supply around July, ramp it up in August, and reach full capacity again in September, as shown by Erlandsson (2016). This means that contractors normally take holidays before production at the mills bottoms out and then resume supplying feedstock before the plants reach full production again. According to the Swedish Forest Agency (2019), current forest industries tend to reduce their stored biomass stocks during summertime and perform maintenance activities.

1.3 Alternative sources of residual woody biomass

Residual LR and ST are not only found in forest land; they also exist in significant quantities on other types of land and are produced by landscape care activities (Oldenburger, 2010). The supply of LR and ST from forest land can be integrated with that from other lands (Bergström *et al.*, 2015). In Sweden, brushwood (i.e., ST and shrubs) is cut during regular clearing or thinning of naturally overgrown vegetation, which may be conducted every 10-20 years in the course of landscape care operations to maintain essential infrastructure and keep the traditional landscape open (Ebenhard *et al.*, 2017). Lands maintained in this way include overgrown agricultural land (arable fields, meadows and pastures, including edge zones), power line (PL) corridors, roadsides, edges of railways, and green areas in urban environments. The overall techno-economical harvesting potential of brushwood from these lands is estimated to be ~1–2 M dry t year^{-1} (Andersson *et al.*, 2016). Biomass harvesting during landscape care operations could be beneficial in terms of both biodiversity and cultural heritage (de Jong *et al.*, 2017; Ebenhard *et al.*, 2017). Trees growing under the wires and around the pylons of PLs represent a threat to the power supply because they can cause power outages and fires, and thus pose a risk to people's safety (Svenska Kraftnät, 2017). The Swedish national grid consists of a network of 15 000 km of 220 and 400 kV lines. The overgrown vegetation in PL corridors is normally cleared using brush saws (and left on site to rot) by the same contractors who carry out pre-commercial thinning (PCT) in forestry.

The management of vegetation in these alternative lands has some similarities to coppice forestry in Europe (Dimitriou *et al.*, 2018; Johansson, 2014). Cut-away peatlands in Finland are another source of residual biomass, whose logging can be mechanized using forest machines (Jylhä & Bergström, 2016). In Spain, scrublands are a significant resource that can be harvested with balers (González-González *et al.*, 2017; Mediavilla *et al.*, 2017); this reduces the risk of wildfires and facilitates livestock grazing. The creation of firebreaks (by clearing vegetation along a linear strip) and thinnings for wildfire prevention (Lerma Arce, 2015) are additional potential sources of residual forest biomass in several European countries (Xanthopoulos *et al.*, 2006). Some landscape care operations are one-time harvests (for clearing or thinning overgrown ST) rather than periodic events. For instance, a one-off harvest can be performed to reinstate grazing in overgrown pastures (Waldén, 2018; Claesson & Bengtsson, 2014) or to establish a new forest stand on marginal land (Bergström *et al.*, 2015). Garrido Rodriguez (2017) showed that the abandonment of ecosystems such as wood pastures represents a challenge for their conservation. The term marginal land encompasses agricultural land abandoned due to its low yield or profitability (Shortall, 2013). Such land may be well suited for cultivating short rotation energy crops such as willow and poplar (Dimitriou & Mola-Yudego, 2017), energy grasses (Nilsson *et al.*, 2015), or oilseed species (Cañadas-López *et al.*, 2018), outside the scope of this thesis. Other residual woody biomass produced during activities such as agricultural pruning (Velázquez-Martí *et al.*, 2011) was also excluded from the analysis. The land use classification criteria that determine the boundaries between forests and other land types differ between countries. This thesis uses the FAO's definitions of forest land and other land uses (FAO, 2000), in accordance with the Swedish National Forest Inventory (NFI) (FAO, 2010). The term "residual woody biomass" is used throughout the thesis to refer to biomass from both forests and other land. The analyses presented here are restricted to the economic aspects (efficiency, cost, and quality) of sustainable SCs for LR and ST in Sweden.

1.4 Supply chain and operations management

An SC is *"the network of organisations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer"* (Christopher, 2011). In the framework of this thesis, the upstream of the SC is the wood procurement triad (Erlandsson, 2016), i.e. the supply: forest owners, forest owners association, and contractors. The downstream is the biomass processing industry, i.e. the demand or end-user. SCM is *"the task of integrating organizational units along an SC and coordinating materials, information and financial flows in order to fulfil (ultimate) customer demands with the aim of improving competitiveness of the SC as a whole"* (Stadtler, 2005). Logistics are part of SCM and consist of *"the planning and control of the flow of goods and materials through an organization or manufacturing process"* (Badiru & Bommer, 2017). The goal of logistics is to maximize the total benefit (Dahlin & Fjeld, 2004), so effective logistics are essential in forestry (Gunnarsson, 2007; Ranta, 2002). Forest biomass SCs are customer-oriented (Carlsson & Rönnqvist, 2005; Mikkonen, 2004) and must therefore achieve the *"seven rights"* of logistics by delivering *"the right product, in the right quantity and the right condition, to the right place at the right time for the right customer at the right price"* (Swamidass, 2000). Keeping track of stock inventory (at roadside storages, terminals, plant yards) and quality (by monitoring quality parameters) is fundamental in SCM (Lee & Billington, 1992).

Operations management is a core domain of SCM (Frankel *et al.*, 2008), defined as "*the design, execution, and control of operations that convert resources into desired goods and services, and implement a company's business strategy"* (Business Dictionary, 2019). Specifically, forest operations management consists of *"analysis, design, control, and continuous improvement of business processes, such as procurement, order fulfilment, distribution, monitoring and control within firms and business to business networks. It measures and analyses internal processes with emphasis on effectiveness, efficiency, and quality by using quantitative models to map and solve related problems of scheduling, inventory, shipment routing, or facility locations"* (Heinimann, 2007). In operations management, three planning levels can be defined based on the time scale of the decision(s) to be made: strategic (long-term, e.g. years or decades), tactical (medium-term, e.g. a year) and operational (short-term, e.g. days or months) (D'Amours *et al.*, 2008). The level of detail at which decisions are made increases as their timescale decreases.

Based on the definitions given above, operations management is management of the internal production processes within an SC that transform the raw material(s) used to manufacture end-product(s), while SCM is management of the entire SC, including the movement of materials from the source to the end-user. SCM in forestry is challenging because every link in a forest SC usually corresponds to an independent business that is interlinked with and influences the other links, which complicates their integration (D'Amours *et al.*, 2008). Heinimann (2007) noted that two key challenges in forest operations management are to achieve a transition from business management to SCM and to develop effective decision-support tools.

1.5 Methods for studying and improving forest operations

Since profit margins in primary forest fuel SCs are small (Eriksson, 2016), it is essential to improve their operations and SCM (i.e. to increase efficiency and cut costs by better management of work and energy inputs) to increase their cost-competitiveness. Karttunen (2015) found that improvements in biomass SCs should be applied across the entire network of an SC rather than exclusively within a company's internal operations; also, that research in process innovation is needed to reduce supply costs and increase the cost-competitiveness and added value of residual biomass. Business re-engineering has been implemented in chip SCs (Väätäinen, 2018; Windisch, 2015). However, before improvements can be implemented, the current systems must be understood.

1.5.1 Work studies

A method rooted in the discipline of Work Science, a work study is *"a systematic study of technical, psychological, physiological, social and organizational aspects of work"* (Björheden *et al.*, 1995). Work studies often involve work measurement based on time studies. The objective of work measurement is to describe the relationship between the inputs (e.g. time or energy) and outputs (e.g. mass or energy) of work, and the influence of process variables on that relationship (Magagnotti *et al.*, 2012). Efficiency is defined as the rate of input per produced unit for a given production system (e.g. time consumption per product output), while productivity is the inverse relationship (Björheden *et al.*, 1995). Productivity is the result of the interaction between human, technology, organization and environment (Häggström & Lindroos, 2016). The goals of time studies are to 1) improve work organization and planning, 2) monitor the control and follow-up of operations, 3) improve and compare working methods, tools and machinery, and 4) create data for performance and cost assessment (Björheden, 1991). A key goal of companies performing work studies is to develop productivity norms that can be expressed as equations (mathematical models) (Lindroos, 2018).

1.5.2 Simulation studies

A system (real or theoretical) can be defined as a group of parts or items that are joined together and interact over time to accomplish some purpose(s). A model is an abstract representation (simplification) of a system that is used to study some aspect of its behaviour and describes only those components and relationships relevant to the investigated problem (Banks *et al.*, 2010). A simulation involves experimentation using a model, with a specific purpose. This purpose could be, for example, to test operational options for increasing efficiency (i.e. to investigate "what if" questions) and advise decision-makers without requiring risky (and costly) real-world experiments. Simulation models are mathematical models, and can be static or dynamic, deterministic or stochastic, and discrete or continuous (Banks *et al.*, 2010). The results of time studies can serve as input data for simulation models (Eliasson *et al.*, 2017; Manner *et al.*, 2017; Eriksson, 2016). Discrete-event simulation (DES) is a dynamic simulation method commonly used with stochastic simulations (i.e. simulations with one or more random variables as inputs) that is characterized by the fact that the system's state variable changes only at a discrete set of points in time (when an event occurs). DES can be used to break down complex SCs and account for interactions between their components. It is therefore commonly used, along with optimization and risk assessment, to analyse SCs (Seay & You, 2016). In particular, it has been used extensively in biomass logistics (Aalto *et al.*, 2019; Kogler & Rauch, 2018) and the healthcare and manufacturing sectors (Jahangirian *et al.*, 2010; Jacobson *et al.*, 2006).

1.5.3 Geographical information systems (GIS) and other methods

GIS are used extensively as decision-support tools at all levels of forest operation planning (Grigolato *et al.*, 2017), sometimes in conjunction with optimization (Sosa *et al.*, 2015; Forsberg *et al.*, 2005). While simulations do not necessarily involve optimization, several decision-support tools use a combination of these techniques (Andersson *et al.*, 2018; SLU, 2016). Optimization has been extensively used for planning transportation (Acuna, 2017). Tools for improving forest operations and SCM in roundwood supply have been presented by Brown *et al.* (2011) in Australia and Skogskunskap (2019a) in Sweden. Statistics, simulation, and optimization are key methods in the discipline of Operations Research (OR), in which advanced analytical methods are used to improve decision-making (INFORMS, 2019).

1.6 Challenges in residual woody biomass supply chains

If the usage of residual woody biomass in the bioeconomy is to be increased, it must be brought to market with a competitive advantage – a cost advantage, a value advantage, or both (Christopher, 2011). Eriksson (2016) found that SC efficiency can be increased by maintaining high utilization of comminution machinery and taking quality parameters into account when planning SC operations. The configuration of a residual woody biomass SC is determined by aspects of the operational environment such as the terrain conditions and end-user type (Röser, 2012). The end-user (whether a CHP or a BR) determines the quantity and quality of feedstock that is required (Joelsson & Tuuttila, 2012; Ranta, 2002). SCs for primary forest fuels involve complex logistics due to the involvement of different contractors, the intrinsic characteristics of the feedstock, and their dependence on other SCs (e.g. roundwood) (Sowlati, 2016). Primary forest fuel procurement involves several, interconnected, upstream and downstream operations: harvest (cutting), forwarding (extraction), storage, comminution and transportation, all of which affect the production costs of chips (Aalto *et al.*, 2019; Karttunen, 2015).

The procurement of primary forest fuels has some challenges in common with that of roundwood supply. For instance, both resources are unevenly distributed in space and usually dispersed over large areas (Seay & You, 2016). Also, in both cases, as the biomass is supplied, supply nodes are dynamically replaced by new ones in different locations (Väätäinen, 2018). These factors force supply fleets to relocate between landings many times during the year. Demand nodes may be concentrated, for instance along shores (Svebio, 2018), meaning that many supply points are separated from end-users by relatively long trucking distances; the average trucking distance for primary forest fuels in Sweden is 63 km (Davidsson & Asmoarp, 2019). Efficient long-distance transport is thus needed to increase the use of residual forest biomass (Routa *et al.*, 2013). Trucks are the dominant means of transportation for distances < 100 km, while rail and boat dominate for longer distances (Karttunen, 2015; Wolfsmayr & Rauch, 2014; Dahlin & Fjeld, 2004). The accessibility of the resource can also vary over the year because the trafficability of forest roads may be limited during freeze-thaw melting periods or heavy rains (Rönnqvist, 2003). A major challenge of harvesting stumps, LR and ST is their high bulkiness when harvested, and their quality parameters such as ash content (AC) and moisture content (MC). These characteristics result in a low energy density, requiring some sort of densification (e.g. bundling, rough delimbing, comminution, etc.) and natural drying before long-distance transportation (Erber & Kuhmaier, 2017).

1.6.1 Harvest of logging residues

LR are produced during roundwood harvesting and recovered predominantly during final fellings of stands dominated by Norway spruce (*Picea abies*) (Routa *et al.*, 2013). LR harvesting is integrated with that of roundwood; the felling process is adapted by having the harvester pile LR in heaps at the side of the strip road (i.e. the road the harvester creates to perform operations from) to avoid driving on them. Before the LR are forwarded into windrows, it is recommended that the material is left at the cutting site for one summer to dry and induce the shedding of nutrient-rich fractions (i.e. needles and small twigs) (Pettersson & Nordfjell, 2007; Nurmi, 1999). However, for practical and economic reasons, LR are often forwarded directly after roundwood, using the same base machine (Björheden, 2010). To handle LR effectively, the forwarder should use a slash grapple (i.e. one with open forks) to minimize the risk of uprooting small undergrowth trees that may have mineral soil attached. Pre-clearing of the undergrowth vegetation is also recommended to reduce this risk (Eliasson & Johannesson, 2009). Since operations in the SC are interconnected, handling of the biomass at this early stage will affect downstream operations and variables such as chipping efficiency and fuel-chip quality.

1.6.2 Harvest of small-diameter trees

ST are harvested during thinnings of non-commercially thinned, overstocked, forest stands, referred to in this thesis as biomass-dense thinning forests (BDTF). Other authors have referred to these stands as “early thinnings” or “young dense forests” (Sängstuvall, 2018; Karlsson, 2013; Ulvcrona, 2011; Bergström, 2009). Their main feature is a high density of small, heterogeneously-sized trees, and they normally arise when tending practices (such as PCT) have been neglected or not performed properly since natural regeneration, seeding or planting. PCT entails cutting trees (motor-manually) and leaving them on the ground (Skogskunskap, 2019b) to reduce competition and obtain a homogeneous stand of future crop trees that will yield large quantities of high quality roundwood. Nilsson *et al.* (2018) showed that large forest areas are currently not subjected to PCT. In many of these stands, the right time to do PCT has passed, doing it now would be costly, and a conventional first commercial thinning for pulpwood would provide low returns (Di Fulvio & Bergström, 2013; Di Fulvio *et al.*, 2011b). Instead, ST can be harvested as whole, undelimbed trees, bucked into sections (“whole tree-parts”), and used for energy. If the harvest is integrated, the largest trees could be delimbed (or rough-delimbed) and bucked for use at pulpmills. The main assortments obtainable from BDTF are whole tree-parts and pulpwood, and the scope for their integration depends on tree size, the market, and distances to the end-user(s) (Bergström & Di Fulvio, 2014a; Petty, 2014; Jylhä, 2011; Vikinge, 1999). An alternative source of ST is clearings of other lands, performed using the same technologies as in BDTF (Andersson *et al.*, 2016; Bergström *et al.*, 2015; Di Fulvio *et al.*, 2011a; Iwarsson Wide, 2009). In contrast to thinning of ST in BDTF, the ST on these other lands can be clear-cut or thinned intensely, which can result in larger volumes per ha and more efficient logging operations (Fernandez-Lacruz & Bergström, 2015b). These stands are often easily accessible from existing road networks, but they can also be scattered in the landscape and they may be too small to be economically viable. Additionally, due to the great diversity of other land, large variations in logging operations efficiency should be expected.

Harvester productivity depends on the size of the removed trees (i.e. stem volume), tree density, and the intensity of removal (Eliasson, 1999). Consequently, the productivity of selective thinning of ST in BDTF is low, leading to high cutting costs. Cutting operations account for the dominant share of the costs in ST SCs, because ST require a separate dedicated cutting operation (Routa *et al.*, 2013; Laitila *et al.*, 2010) and this is a key barrier to cost-efficiency (Bergström & Di Fulvio, 2014a). These costs can make the use of ST unprofitable by causing the overall cost of their extraction to exceed the revenue obtained by selling the biomass. To increase cutting efficiency, heads with accumulating arms for handling multiple trees per crane cycle are often used. Accumulating felling heads (AFHs) are commonly used in energy thinnings or clearings, and accumulating harvester heads (AHHs) can also be used. AHHs are flexible because they can process trees (by rough-delimbing or delimbing and bucking into sections), allowing the integration of fuelwood (i.e. undelimbed ST) and pulpwood (i.e. delimbed ST). The density of the bunched ST can be increased by rough-delimbing or by using compressing stakes on the forwarder's load bunk, increasing productivity (Bergström & Di Fulvio, 2014b; Bergström *et al.*, 2010). Rough-delimbing allows nutrient-rich fractions to fall off during harvest, reducing the AC of the biomass and nutrient removal from the stand (Fernandez-Lacruz & Di Fulvio, 2014; Bergström *et al.*, 2010). Alternative, feller-bundlers designed to harvest ST (Manner *et al.*, 2017; Bergström *et al.*, 2016) can be used. Technologies and working methods (e.g. boom-corridor thinning, instead of conventional selective thinning) for efficient ST harvesting are undergoing rapid development (Sängstuvall, 2018; Bergström, 2009).

To better understand and improve the management of forest operations, time studies of systems working in operational environments (e.g. PL corridors) other than forest land will be needed. In parallel, the characteristics and potential of BDTF in Sweden should be analysed to support further technological developments and investments in new industries such as BRs.

1.6.3 Storage and management of quality parameters

Fuel-chip quality depends on the assortment used for chip production, the season in which it is cut, forwarded and chipped, its natural MC, the methods used during its harvest and storage, and its duration of storage (Filbakk *et al.*, 2011a; Filbakk *et al.*, 2011b; Kent *et al.*, 2011; Björheden, 2010; Nurmi, 1999; Lehtikangas, 1998; Lehtikangas & Jirjis, 1993; Jirjis *et al.*, 1989). Water accounts for ca. 50% of the weight of wood when harvested (Lehtikangas, 1998). MC is a key quality parameter for fuel-chips (Fridh, 2017) because payments for fuel-chips in Sweden are normally based on the amount of delivered energy, which is determined at the plant by scaling each truckload and MC sampling. Maximizing natural drying and minimizing re-moistening are essential elements of MC management (Routa *et al.*, 2015). To enable natural drying, after harvest (and subsequent on-site seasoning of LR), LR and ST are forwarded into windrows and normally covered with residue wrapping paper (Walki, 2019; Björheden *et al.*, 2013). To enhance natural drying, windrows should be exposed to ambient conditions (sun and wind), typically for one full drying season (i.e. a summer) (Skogskunskap, 2016). In addition to its role in drying, windrowing at landings provides a buffer that compensates for temporal imbalances in biomass supply and demand, and also reduces dry matter (mass) losses (DML) compared to storing comminuted material (Jirjis, 1995): windrowed LR exhibited DML below 1% per month (Jirjis & Lehtikangas, 1993), compared to 2-3% for chipped LR (Nilsson & Thörnqvist, 2013). It should be noted that MC is a less important measure of quality for some assortments: payments for uncomminuted LR or ST depend on measurement of their fresh weight, which rarely involves MC sampling, and the price of sub-standard roundwood is typically based on measurements of stack (truck frame) volume (Björklund & Fryk, 2014).

The gross calorific value of woody biomass depends on the natural ash and chemical composition of the assortment, but its net calorific value largely depends on its MC and contaminating ash (Thörnqvist, 1984). Incorrect handling can cause contamination with mineral soil, increasing AC and causing potential ash-handling problems in the furnace (Khan *et al.*, 2009). Unlike MC, AC is only determined a few times per year at most plants. Particle size distribution (PSD) can be influenced by chipper configuration, knife sharpness, temperature and MC (Eriksson *et al.*, 2013; Lehtikangas, 1998). High coarse and fine fraction contents can impair feeding and combustion in the boiler (Bäfver & Renström, 2013). Relatively small plants require high fuel-chip quality (i.e. low MC, AC, and homogeneous PSD), but larger plants are less sensitive and accept higher levels of variation in quality parameters (Röser, 2012).

1.6.4 Comminution and transport

In Europe, LR and ST are often comminuted at forest roadsides using mobile chippers (Ghaffariyan *et al.*, 2017; Díaz-Yañez *et al.*, 2013); forwarder-mounted chippers and chipper-trucks are the most common systems in Sweden (Eliasson & von Hofsten, 2017). Alternatively, uncomminuted LR or ST can be transported for chipping at terminals or at the end-user, using more efficient stationary or semi-stationary machines (Kuhmaier & Erber, 2018; Wolfsmayr & Rauch, 2014). However, the inefficiency of transporting uncomminuted biomass over long distances (Ranta & Rinne, 2006) other than defect roundwood, limits the cost-efficiency of this option. The choice of comminution strategy is determined by aspects of the operational environment (Röser, 2012) such as the placement of the windrows and transport distances to the end-user. According to Eriksson (2016), there is no perfect comminution system; each one has its own advantages and drawbacks.

For instance, a forwarder-mounted chipper is a flexible system that can work either by the roadside landing or off-road (i.e. at the cutting site, in cases where the windrow is unreachable from the road). One operational option for the forwarder-mounted chipper is to tip over the chip-bin by the roadside so that a self-loading chip-truck(s) can subsequently load and transport the chips to the terminal or end-user (Liss, 2006). This system configuration allows machines to work independently from each other (i.e. it is a "cold system"): there is no need for interaction because material can be stored on the ground temporarily between operations. However, the system's cost-efficiency may be reduced at small sites that necessitate many relocations of the chipper. Alternatively, the chipper could chip directly into containers by the roadside. This system configuration is "hot" and requires better planning (e.g. windrows placed by the roadside) and balance to minimize waiting times (the chipper cannot operate without a container). A chipper-truck (i.e. a truck with an integrated drum chipper, bin and container) is an independent ("cold") system for chipping and transport; it is less sensitive to object size because it relocates by itself. However, in practice, windrows must be within ca. 9 m of the roadside to be reached by the chipper's crane. Long trucking distances to the end-users could make it impossible to achieve high utilization of a chipper truck's chipping capacity, reducing the system's overall cost-efficiency (Skogskunskap, 2016).

The possibility to accurately predict the dry mass and chip volume in windrows containing LR or ST would make it possible to enable better planning of chipping operations.

1.6.5 Terminals in the supply chains of biomass

Terminals act as intermediate nodes between forests and industrial sites, and enable processes such as transloading (i.e. changing transportation modes), storage, and upgrading of biomass (comminution, sieving, drying, etc.) before final delivery. Terminals for fuel- and roundwood are common in Europe. They can be located close to the resource or the end-user ("feed-in terminal"), and are sometimes connected to a railway or adjacent to harbours (Kons *et al.*, 2014). Delivery via terminal inevitably introduces extra costs into the SC (compared to direct delivery) because of the investment necessary to build and maintain the terminal and increased material handling (Virkkunen *et al.*, 2015; Eriksson & Björheden, 1989). However, terminals can be essential because they increase the reliability of supply during peak demand (Ranta *et al.*, 2012). In addition, they make it easier to cope with operational problems in the supply fleet such as machine breakdowns or extreme weather events (e.g. freeze-thaw melting, wildfires, or windthrow) that may impede access to forest roadside storages. Terminals also provide buffering for industries with limited storage capacity. Plants near urban areas usually have small buffers that can only store a few days' worth of material, whereas plants outside urban areas can maintain much larger reserves (Olsson *et al.*, 2016). For plants located in urban areas, railway links to terminals can help avoid traffic congestion problems at the delivery point. Terminals can also help to maintain the year-round operation of supply fleets, serving as storage sites during periods of machine overcapacity (Raitila & Korpinen, 2016). In real-world operation, the chip flow through a terminal can range between 10-30% of the total annual supply (Asmoarp, 2013; Johansson, 2013; Hansson, 2010). The need for terminals is increasing as the capacity of industries expands, necessitating larger uptake areas and reliable high-efficiency procurement solutions (Virkkunen *et al.*, 2016; Tahvanainen & Anttila, 2011).

When managing an SC, one can adopt either a just-in-time (pull) or push strategy. In just-in-time systems, wherever possible, there should be no activity within the system until it is needed (Christopher, 2011). Thus, the end-user pulls products downstream and buffers are minimized. In a push system, products are manufactured according to forecasted demand, and stored in buffers along the SC. A just-in-time strategy for forest biomass SCs thus requires a reliable and agile supply fleet that can quickly ramp up production. It also increases risks and makes the SC sensitive to disruptions. Push strategies have higher costs because they require buffers (terminals), giving rise to DML, although the latter can be minimized by using optimal storage methods, as shown by Anerud *et al.* (2018).

The design of efficient SCs for LR and ST could be facilitated by developing a simulation model able to quantify the cost of incorporating a terminal (which will depend on the type of end-user to be served and the forecasted demand).

2 Aim and objectives

The overall aim of this thesis was to measure and analyse characteristics of LR and ST in forest and other land in Sweden, and to evaluate the efficiency and costs of their supply systems. The ultimate goal was to generate useful knowledge for policymakers, researchers, and industrial developers and practitioners that could help improve supply chains if used correctly, increasing the cost-competitiveness and utilization of this residual woody biomass.

The studies on which this thesis is based and the relationships between them are summarized in Figure 1. The specific objectives of the thesis were to:

- Describe the areal distribution, characteristics and harvesting potential of biomass-dense thinning forests in Sweden (Paper I).
- Describe the characteristics of the overgrown vegetation in a power line corridor in central Sweden (Paper II).
- Model the efficiency of a forest machine system in harvesting and extracting whole trees for bioenergy during power line corridor cleaning, calculate its costs, and compare it to motor-manual clearing (Paper II).
- Describe the storage conditions of windrows containing LR and ST from forest and other land, and assess the quality of the resulting fuel-chips (Paper III).
- Develop a predictive model for estimating the dry mass content of windrows containing LR and ST from forest and other land (Paper III).
- Develop a simulation model to analyse the supply cost of chipped LR and ST, from chipping to delivery to the end-user. Two end-user demand curves were considered, one for a theoretical combined heat and power plant and one for a biorefinery. In addition, two different demand levels (low and high), and two possible modes of supply chain operation were considered: exclusive direct supply from the sites to the end-user and combined supply via a feed-in terminal (Paper IV).

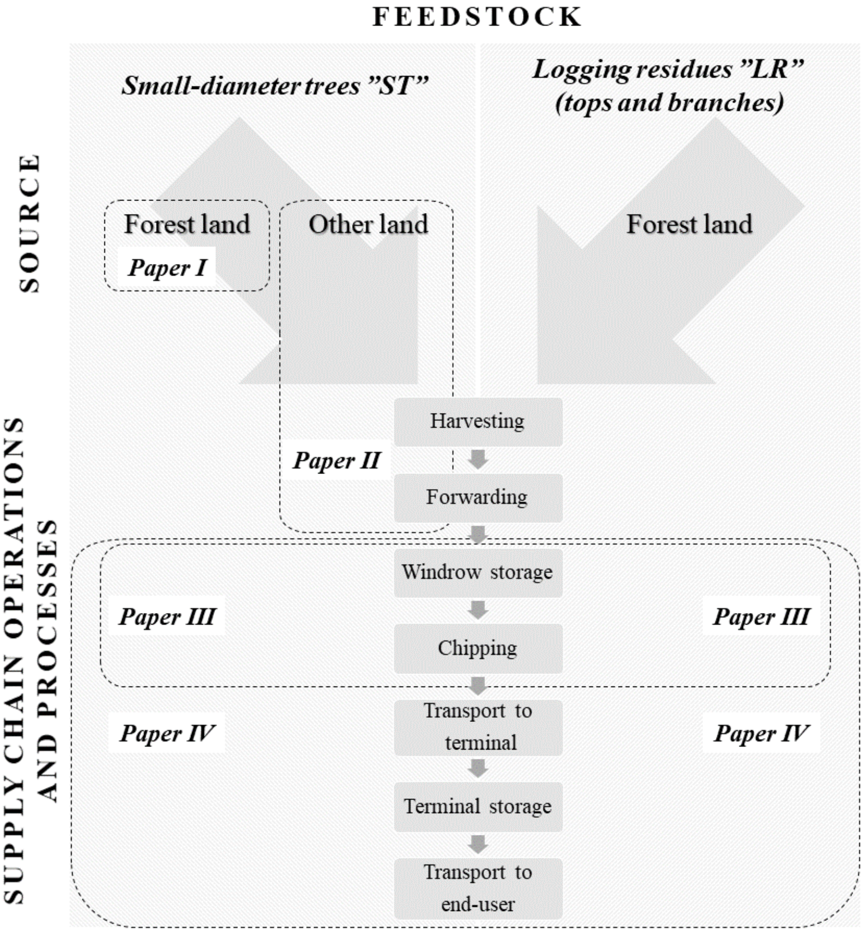

Figure 1. Conceptual framework of the thesis and underlying studies (papers). The dashed lines enclose the topics addressed by each paper. Every paper deals either with the characterization of the feedstock (and its sources), supply chain operations, or both. Three end-users were considered: a combined heat and power plant (all papers), a pulpmill (Paper I), and a biorefinery (Paper IV).

3 Materials and Methods

The choice of materials and methods in this thesis was determined by the objectives and the type of information to be processed in each study (Table 1). The goal of representing the characteristics and distribution of BDTF and analysing a large NFI dataset prompted the use of GIS-based analysis in Paper I. Paper II describes an inventory and experimental time study on the operations of a harvester and forwarder. The machines' operational environment and work were studied and analysed in conjunction with literature data. Paper III presents an observational field study conducted to characterize an operational environment, its windrows, and the fuel-chips produced at the sites. Finally, Paper IV describes a simulation-based cost analysis using DES and input data from Paper III. Simulations were used because of the need to study the real-world operation of chipping systems and its evolution over time.

Table 1. *Sources of input data and research methods used in the papers included in this thesis*.

Paper	Sources of input data	Research methods
I	NFI	GIS
II	Fieldwork, literature	Forest inventory, time study, statistics
III	Fieldwork, CHP	Survey, fuel-chip sampling and quality assessment, statistics
IV	Paper III, literature	DES, statistics

3.1 Paper I

3.1.1 Forest dataset and analysis with GIS

The NFI provided a dataset containing details of all forest inventory plots of productive forest land in Sweden (29 105 plots, clustered, with a radius of 7 or 10 m, covering 22.5 M ha in total) for the period 2006-2010 (Axelsson *et al.*, 2010). The variables listed in Table 2 (based on measurements of all trees in the plot that had reached breast height, i.e. 1.3 m) were used in subsequent analyses. The dataset was imported into a GIS using ArcGIS®. Plots containing four categories of BDTF in the dataset were then identified by successively applying the following selection criteria:

A. non-commercially-thinned plots, with an average tree height ≥ 3 m and average diameter at breast height (DBH) < 20 cm;
B. plots of category A with an above-ground biomass density ≥ 30 dry t ha^{-1};
C. plots of category B with an average tree height < 12 m;
D. plots of category C with an average stem volume (denoted *v*) of 10–120 dm^3, divided into five subclasses:
    1. $10 \leq v < 20$ dm^3: typical PCT forest, normally cleared with a brush saw;
    2. $20 \leq v < 30$ dm^3: energy thinning forest, normally harvested as fuelwood with AFHs;
    3. $30 \leq v < 40$ dm^3: thinning forest, harvested either as fuelwood only (AFHs), or integrated with pulpwood (AHHs);
    4. $40 \leq v < 60$ dm^3: thinning forest, harvested either as pulpwood only (AHHs) or integrated fuelwood;
    5. $60 \leq v < 120$ dm^3: pulpwood thinning forest harvested with AHHs.

Table 2. *Variables in each NFI plot used in analyses.*

Variable	Explanation
Diameter at breast height (DBH)	Average of all trees, basal area-weighted.
Height	If height ≥ 7 m, the average height of all trees weighted by basal area; if height < 7 m, the arithmetic average of the dominant trees.
Tree density	Number of trees ha^{-1}.
Above-ground biomass (i.e. growing stock) density	dry t ha^{-1} of stemwood with bark and living branches including needles and fine fractions (calculated according to Marklund (1988).
Standing volume per ha	Stem volume over bark and above the stump, including the tops.
Maturity class	Cutting class according to Nilsson *et al.* (2018).
Stand age	Years.
Composition of tree species	Proportions (%) of Scots pine, lodgepole pine, Norway spruce and broadleaves.
Ground moisture, soil parent material	Classes using the Swedish terrain classification method of Berg (1992).
Pre-commercially thinned	No / Yes
Commercially thinned	No / Yes
Previous land use other than forest	No / Yes (e.g. pasture, arable land, gravel pit, etc.)

Category A included all plots (11 823) containing trees that had passed the regeneration stage, because 2–4 m is the usual height for applying PCT in Sweden (Skogskunskap, 2019b). However, it excluded plots containing very thick trees (DBH ≥ 20 cm) because such trees can be used to produce high-value sawlogs, as shown by Varmola and Salminen (2004). Category B included 8 262 of these plots, excluding plots having a standing biomass < 30 dry t ha^{-1} because it is reasonable to let such stands continue to grow to increase their biomass concentration (Nordfjell *et al.*, 2008). Category C included 3 437 plots, excluding plots with an average tree height ≥ 12 m because the most economical strategy for such plots is to perform a conventional first thinning and use the trees to produce pulpwood rather than fuelwood (Heikkilä *et al.*, 2009; Nordfjell *et al.*, 2008). Category D included 2 446 plots, excluding plots containing trees with an average stem volume ≥ 120 dm^3, because they can be harvested exclusively as pulpwood rather than fuelwood using conventional techniques. Category D also excluded plots containing trees with extremely small stem volumes (< 10 dm^3), because these cannot be harvested effectively with current technology; even anticipated technological developments are unlikely to make their mobilization economical, as shown by Sängstuvall *et al.* (2012).

Most analyses were performed at a regional level, based on Sweden's historical divisions: Norrland (the northernmost region), subdivided into northern Norrland and southern Norrland; Svealand (the central region); and Götaland (the southernmost region) (Nilsson *et al.*, 2018). Detailed calculations of variables such as the area occupied by BDTF in relation to the total forest area and the average age of the BDTF were performed at the county level. The area and growing stock of BDTF on difficult terrain was also determined. Difficult terrain was defined as terrain falling into class 4 or class 5 according to the classification system of Berg (1992) in which class "1" indicates very firm, stable ground and "5" indicates very soft ground with a low bearing capacity.

3.1.2 Harvesting potential of biomass-dense thinning forests

The techno-economical harvesting potential of BDTF was calculated after filtering the dataset by applying selection criteria A–D (which implicitly account techno-economic constraints), explicit technological constraints (it was assumed that only 70% of the BDTF area had a bearing capacity high enough to support machines) and ecological constraints (harvesting was considered to be sustainable, corresponding to removal of 100% of the annual increment in stemwood volume). The NFI data provided the mean annual increment in stem volume for each plot (m^3 ha^{-1} $year^{-1}$). Stem volume was defined as the volume over bark above the stump up to the top, excluding branches and needles. Solid m^3 was converted to dry t, using WeCalc (Nylinder & Kockum, 2016), based on the observed proportions of tree species within the BDTF and an assumed basic stemwood density of 402 dry kg m^{-3}. The potential of whole-tree harvesting was also calculated. Stemwood accounted for 70% of the dry weight of standing biomass within the studied BDTF, while branches and needles accounted for 30%. The potential of whole-tree harvesting was based on these proportions and an assumed basic density of 479 dry kg m^{-3} for the branch fraction.

3.2 Paper II

3.2.1 Study site

Fieldwork was conducted during May 2012 in Knivsta (east-central Sweden). The PL to be cleared carried a voltage of 400 kV, with a corridor width of 50 m (equivalent to the outer wires' projection). The average distance from the wires to the ground ranged from 16 to 26 m. When working in PL corridors, the crane's tip (including grasped trees) must be at least 5.5 m from the nearest wire in the vertical direction and at least 6.5 m in the horizontal direction for safety reasons (Svenska Kraftnät, 2015). A total of 13 study units were marked out, with lengths of 20 m in the direction of the PL and widths of 40–50 m (corresponding to the corridor width). Before harvesting, a systematic stand inventory was conducted in each unit by defining 6 circular plots of radius 2 m in each one. The terrain conditions were assessed according to Berg (1992), by considering bearing capacity (G), roughness (Y) and slope (L). The average GYL in the study area was 1.2.1., corresponding to a good bearing capacity with a shallow slope and a few boulders.

3.2.2 Time study

A time study was conducted on a harvester and a forwarder working in the inventoried units. The harvester was a Skogsjan 495 (162 kW engine power, 15 t mass, 4 wheels fitted with chains, and an 11 m crane). It was equipped with a Bracke C16.b AFH that was specifically designed for thinning and clearing of ST, with a cutting chain mounted on a saw disc, four-jawed cutting arms, and four-jawed accumulating arms. The harvester used the pre-existing strip road to move from the landing to each unit (Figure 2). Separate time studies were conducted in each unit, beginning when the harvester started cutting trees at point "A_1", on one side of the unit. The time study was continued as the harvester moved along an obround path within the unit, felling a 10 m wide swath as it went, and concluded when it reached the end point, designated "B_1". The harvester then moved from point "B_1" to the starting point of the next unit, "A_2".

After harvesting, the biomass was forwarded to the landing using a Valmet 890.1 forwarder (154 kW engine power, 18 t mass, 18 t load capacity, 8 wheels and 8.5 m crane) equipped with a CE360 slash grapple with two forks each having two legs for effective handling of ST/LR. The time study began when the forwarder began its unloaded journey from the landing to the unit. The forwarder followed the same path as the harvester inside each unit. Once all the biomass from the unit was loaded, the forwarder drove back to the landing, where the biomass was weighed and then unloaded in two windrows, ending the time study. The process of weighing the biomass was excluded from the time studies.

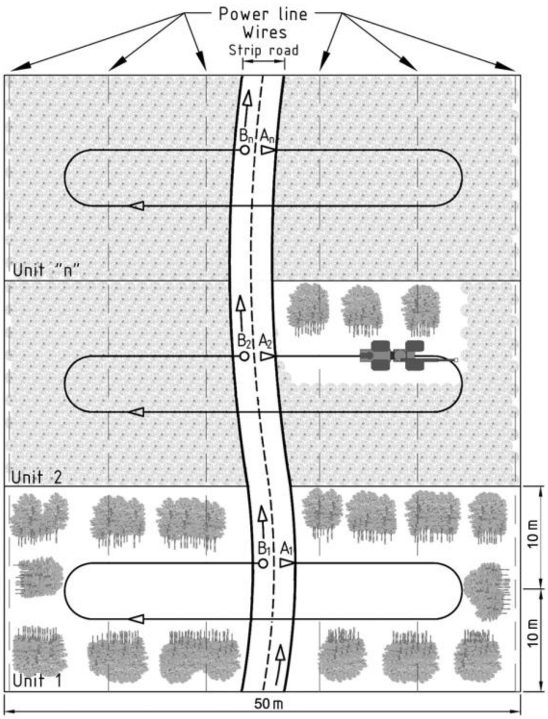

Figure 2. Working method of the harvester in the PL corridor. It started to work at "A_1", followed the path shown and finished when it reached the point "B_1" (unit 1). It moved from "B_1" to "A_2", in the next unit (unit 2). The forwarder followed the same path as the harvester inside each unit.

In this study, the scheduled machine (SM) time comprised all machine working time including delays shorter than 15 min but excluding driving time between units and relocations. Productive machine (PM) time was defined as SM time excluding all delays. The SM time of the harvester was recorded by conducting a frequency study (Harstela, 1991) using an Allegro Field PC® equipped with SDI software (developed by Haglöf Sweden AB) because the harvester work cycle involves brief repeated elements. The work element being performed by the harvester was recorded once every 7 seconds. These elements included *Boom out*, *Felling*, *Boom in*, *Moving*, *Miscellaneous*, and *Delays* (Paper II). The running time per unit was recorded with a chronometer to correct for possible missing observations from the frequency measurement. The forwarder time study was performed as a continuous time study (Harstela, 1991) because its work elements last long enough to be recorded individually with adequate precision. These elements included *Loading*, *Moving while loading*, *Driving loaded*, *Unloading*, *Driving empty*, *Miscellaneous*, and *Delays*. The forwarder's loading distances and forwarding distances (driving loaded and empty) were also recorded.

3.2.3 Economic analysis

The fieldwork data (i.e. the inventory and time study results) were used to model the biomass removal and efficiency (time consumption per biomass output) achieved by the forest machines as a function of tree height. Models were built by regression analysis using Minitab™15, using a significance threshold of $p < 0.05$. Based on the derived models, the net income (profit) of PL corridor clearing using the mechanized harvesting system was calculated as the difference between the revenue from selling the undelimbed ST and the cost of harvesting and forwarding, including a relocation cost. The calculated profit was compared to the cost of motor-manual cleaning reported in the literature. The economic analysis was conducted for a theoretical unit with a rectangular size of 1 ha (50 m × 200 m), assuming a one-way forwarding distance of 100 m, and it was presented as a function of average tree height.

The estimated revenues were based on the then-prevailing market price for uncomminuted, undelimbed ST at the roadside, which amounted to 22 € solid m^{-3} (average in Sweden in 2012), equivalent to 44 € dry t^{-1}, using a basic density of 497 dry kg solid m^{-3} (Nylinder & Kockum, 2016). Logging costs were calculated by multiplying the hourly operating cost of the machines by the SMh required to harvest and forward the biomass from the modelled unit (depending on the specified tree height). Hourly operating costs were calculated according to Nordfjell (2010), including fixed and variable costs (Paper II), and amounted to 90 and 80 € SMh^{-1} for the harvester and the forwarder, respectively. The modelled efficiencies of the harvester and forwarder were used to calculate the required PMh in the modelled unit. PMh was converted into SMh by adding a 10% delay time (the maximum percentage of delays during fieldwork). A relocation cost to the site of 208 € (for a truck with a low-bed trailer) was included for each machine.

The cost of motor-manual clearing was calculated by multiplying the hourly operating cost by the SMh required to clear the vegetation in the modelled unit. The cost of the operator was set at 31 € SMh^{-1} based on the reference price in

Sweden in 2012. The PM time for motor-manual clearing was calculated using Eq. 1 (SLA-Norr, 1991), a formula used for PCT in conventional forestry. Here, T denotes PMmin ha^{-1}, RA the tree density in the unit ($\times 10^3$ trees ha^{-1}) and h the average tree height (m). An extra time consumption of 5% was added to account for the presence of obstacles on the ground, as observed during the fieldwork. The average tree density, RA, was calculated as a function of the average height, decreasing from 18 000 to 12 000 trees ha^{-1} as the average tree height increased from 3.4 to 6.3 m. PMh were converted into SMh by including 25% delays, assuming 6 PMh out of 8 SMh per day, discounting planning, refuelling, etc.

$$\mathrm{T} = 0.765 \times \left((15.08 \times RA) + (9.5 \times RA \times h) - (0.15 \times RA^2 \times h) + 91\right) \quad (1.)$$

3.3 Paper III

3.3.1 Study sites

From February to April 2014, 44 windrows containing LR and 32 windrows containing ST were surveyed at 34 sites in the vicinity of Umeå (northern Sweden) owned by private forest owners belonging to *Norra Skogsägarna*. LR were harvested predominantly during final-fellings of spruce (*Picea abies*), along with minor fractions of stemwood and other species. ST were either harvested at full length (“whole unprocessed trees”) or bucked into sections (“unprocessed whole tree-parts”), ca. 6–9 m long. Assessments of species in ST windrows revealed a dominance of grey alder (*Alnus incana*), birch (*Betula spp.*) and willow (*Salix spp.*), with an overall average butt-end diameter (basal-area weighted) of ~11.2 cm (range: 9.7–13.7 cm). Harvesting was conducted by conventional operations (final-fellings and thinnings) in forest land at 65% of the sites, by clearing other lands (overgrown edges of arable land, roadsides, and industrial land) at 26% of the sites, and by a mixture of forest and other land operations in the remaining 9% of sites. The average cut area was 5.3 ha (range: 0.1–25 ha). All windrows had been built within 1 month of harvest, and most of them were covered with 4 m-wide residue wrapping paper. The average windrowing time was 10 months (range: 1–31 months). The height of the front sides of the windrows was measured with a stick. The length of each windrow’s base (and top if trapezoidal; see Figure 3) was measured along the front side, and the width was measured along the left and right sides.

The inventoried windrows were comminuted using a Bruks 805 CT chipper with a self-dumping chip-bin (volume: 21 m^3), mounted on a Komatsu 860.4 forwarder. The fresh mass (fresh t) of every chip load was registered using an integrated scale in the bin. Each loaded bin was tipped at the roadside or a large landing, and loaded within 2 days into a self-loading chip-truck with a container and trailer (total volume: 122 m^3). The trucks delivered the fuel-chips to *Dåva 2* CHP in Umeå and each truck was scaled on a static weighbridge. Since truckloads could be tipped directly into the dump pocket at the CHP, the truck driver filled a 3-litre paper bag with fuel-chip samples immediately before loading at the forest roadside, as stipulated by Umeå Energi AB (2014). The CHP determined the MC of the delivered biomass according to EN 14774-2:2009 (CEN, 2009a) (48 h) and provided a dataset specifying (*inter alia*) the site of origin, assortment, mass and MC of each truckload.

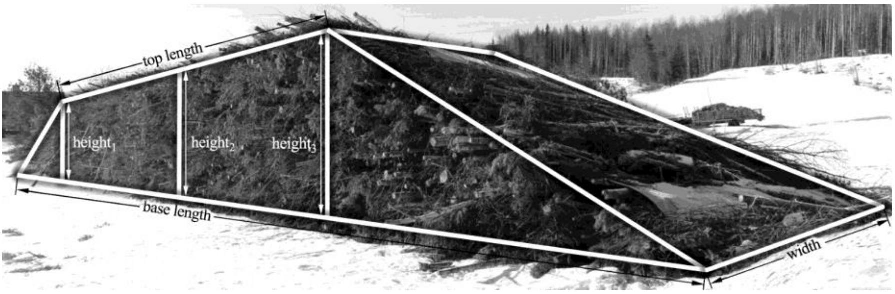

Figure 3. Dimension measurements on a windrow approximated as a trapezoidal prism.

3.3.2 Fuel-chip sampling during fieldwork and analyses

Fuel-chips were sampled from 25 paper-covered windrows (10 LR and 15 ST), at 16 sites within a few hours of the chipper tipping them onto the ground. The number of samples per windrow (range: 1–3) and windrows sampled per site (range: 1–4) depended on the size and total number of windrows, and the time available before the trucks started loading the chips. During sampling, a 5-litre bucket was filled with 5–8 subsamples shovelled from different points and heights of the chip pile.

The MC, PSD and AC of each collected sample (46 in total) were determined. MC was determined following EN 14774-2:2009 (CEN, 2009a) (24 h). To calculate PSD, the same (dry) samples were then subjected to a 15-min pre-defined program in an electromagnetic sieve shaker BA 400N with oscillating circular sieves (opening mesh sizes: 63, 45, 31.5, 16, 8 and 3.15 mm). The 7 fractions were weighed to determine the percentages of dry mass associated with each particle size class. To determine AC, the seven fractions were then pooled and milled down to 1 mm. Each milled sample was subdivided with a riffle box to obtain a 0.5-litre subsample from which two ~2 g subsamples were taken for AC determination following EN 14775:2009 (CEN, 2009b). Statistical analyses were performed using Minitab™16 and R 0.99 (R Core Team, 2015), deeming results to be significant if $p < 0.05$. Measurements of quality parameters (MC, PSD, AC) of fuel-chips were compared by one-way ANOVA with Tukey's post-hoc tests, aiming to identify possible assortment-based differences (LR vs. ST) and sampling-method (fieldwork vs. plant)-based differences (only for MC).

The fresh and dry bulk density of each LR and ST windrow were calculated in terms of fresh mass and dry mass (dry t) per bulk m^3. For this purpose, the windrows' bulk volumes were calculated using the measured dimensions, approximating the geometrical shape of each windrow as a trapezoidal, triangular or rectangular prism as appropriate. The fresh and dry mass of each windrow were calculated by two approaches. In the first (referred to as the "chipper" approach), registered fresh masses from the chipper and calculated dry masses were used, with MC values obtained from fieldwork sampling (when available). For windrows not subjected to MC sampling in the field (i.e. by the researcher during fieldwork), a weighted average MC based on the CHP measurements was assumed for all windrows within the same site.

The second approach (the "plant" approach) used only data from the CHP. Because mass measurements at the CHP were conducted for truckloads rather than individual windrows, the fresh mass of each windrow was estimated as follows: the bulk volumes of all windrows in each site were summed, then the percentage contributions of each windrow were calculated and multiplied by the total fresh mass (i.e. all truckloads) delivered from the site to obtain a theoretical windrow fresh mass. The dry mass was then calculated using the weighted average MC of all truckloads from the site.

Differences in dry bulk density between assortments (LR vs. ST) based on results from the same data source (chipper or plant) were tested by one-way ANOVA, as were differences between data sources (chipper vs. plant) based on results for the same assortments. Linear regression was used to investigate the dependence of windrows' dry mass (dry t, dependent variable) on their bulk volume (bulk m^3, independent variable).

3.4 Paper IV

3.4.1 Description of the simulation model

A simulation model was constructed using DES in ExtendSim®9.2. An operational environment was designed (resembling that studied in Paper III) and the work of a theoretical chip supplier over one year was modelled. The objective was to provide the defined end-users with chips from a mixture of LR and undelimbed ST seasoned in windrows at forest and other land storage sites. The simulated windrows were generated at the sites (i.e. the entities whose attributes are shown in Table 6), and chipped by two machine systems, which delivered chips to the end-user's buffer (plant yard) (Figure 4). To mimic real-world operations, the model included stochasticity based on probability distributions for biomass characteristics, process times for machine activities, delays, and forecasted demand (a deviation of ±20% relative to forecasted demand values was incorporated). The supply of chips was modelled separately for two theoretical end-users with distinct demand profiles: a CHP and a BR (Figure 5).

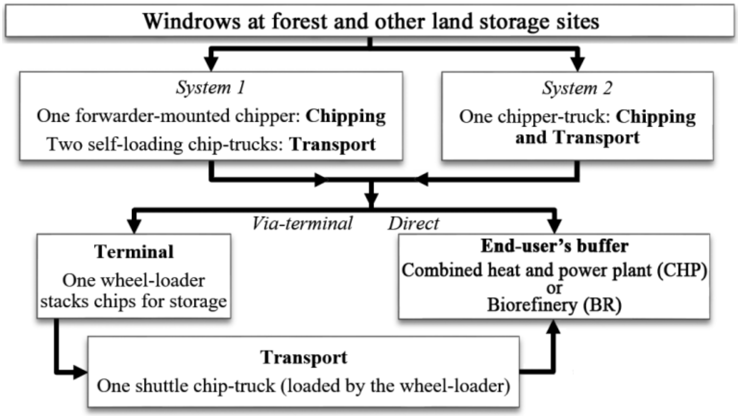

Figure 4. Outline of the combined supply chains (direct and via-terminal deliveries).

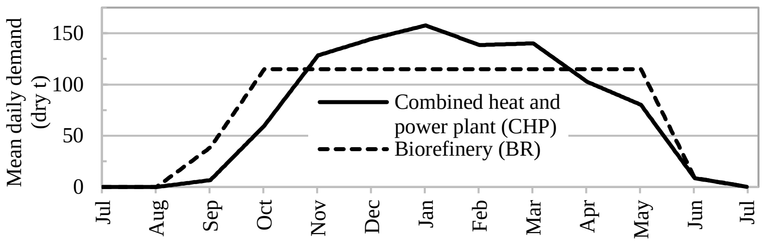

Figure 5. Simulated mean daily chip demand for each end-user (high-demand scenarios).

Both end-users were assumed to be located at the same place and consume the same feedstock. Processing of the incoming chips at the plant was outside the model boundaries. The CHP's demand curve was derived from data on mean production at *Dåva 2* in Umeå provided by *Umeå Energi AB,* while the BR's demand was assumed to be non-seasonal. Two demand scenarios were defined: low, corresponding to a demand of 21 000 dry t per annum, and high (29 000 dry t per annum). A daily delivery plan for the chip supplier was calculated for each demand level and end-user, matched against the daily shares of forecasted demand. The simulated demand volumes (low: 21 000 dry t, high: 29 000 dry t) represented ca. 40 and 55%, respectively, of the mean supply of primary forest fuels for heat and power in Umeå (0.256 TWh per year during 2012-2016) (Energy Companies Sweden, 2017). Two possible modes of SC operation were modelled: exclusive direct supply from the sites to the end-user, and combined supply via a feed-in terminal (using a combination of direct and via-terminal deliveries).

The modelled terminal area was set to 2 ha, of which 90% was devoted to storage (Paper IV). The terminal's storage capacity when supplying the CHP was assumed to be identical to that when supplying the BR, corresponding to a buffer time of 1 month at the CHP (based on demand in January). A DML of 2% per 30 days of storage was assumed, and the DML was calculated for each dry t leaving the terminal based on its storage time at departure. A shuttle chip-truck was available, driving 10 km (one-way) between the terminal and the end-user. A wheel-loader operated at the terminal, equipped with a scale to measure outbound deliveries and avoid overloading the shuttle chip-truck. Facilities and machinery were shared with other suppliers, but machinery was available to the modelled chip supplier with no waiting time. The terminal lacked equipment such as a weighbridge and drying oven. Therefore, drivers of incoming trucks were expected to measure the chip volume in the cargo and the chips' MC using handheld equipment.

The model included a buffer at each end-user's yard (i.e. the delivery point). Plant buffers were equal in capacity for the CHP and BR and corresponded to 4 days of mean demand in January at the CHP. Alarms based on storage levels at the end-user's buffer pulled chips downstream, thereby controlling upstream SC operations in the model: if storage levels exceeded 95% of total capacity, chips were redirected to the terminal, and the generation of new sites by the model was paused; for levels between 60–95%, only direct deliveries from the sites were allowed; and when storage levels at the buffer fell below 60%, the terminal was opened for outbound deliveries, thus combining direct and via-terminal deliveries. The same alarm levels were set for both the CHP and the BR, aiming to achieve a chip flow through the terminal of 10–30% of total supply.

3.4.2 Machine systems working for the modelled chip supplier

The modelled fleet consisted of two supply systems, with one unit of each system. The simulated systems were identical for all scenarios save for the terminal machinery (exclusively used in combined SCs). System 1 comprised a forwarder-mounted chipper and two self-loading chip-trucks. These trucks transported the chips to the terminal or end-user, depending on the current alarm levels at the plant buffer. Relocation of the forwarder-mounted chipper between sites was performed by driving on the road by itself (over distances shorter than 10 km) or by a truck with a low-bed trailer. System 2 consisted of a chipper-truck used for roadside comminution and transport to the terminal or end-user.

The logic of the work and efficiency of the modelled machines (Paper IV) was based on literature measurements conducted in Swedish or similar operational environments (average for LR and ST). The model dynamically computed the size of every chip truckload, which depended on the current MC. The limiting factor for relatively dry chips was the cargo volume, but weight was limiting for relatively wet chips, as in Eriksson *et al.* (2014b). Trucks were only allowed to drive to the terminal or end-user if they were fully loaded, so they had to relocate between sites until fully loaded. A queueing time at the delivery point (Väätäinen, 2018) was also incorporated.

Machines were scheduled to work 200 days annually, using the same shift configuration for both end-users. Machines were set off-shift from the middle of June to the end of August (i.e. annual holidays were concentrated this period). The SMh comprised PM time including delays due to operator or mechanical breakdowns and machine relocation. From September to the end of February, System 1 and System 2 were scheduled to perform double shifts (16 SMh) per day. From March until the middle of June, these machines performed single shifts (8 SMh), halving the chip flow from the roadsides. This was done to simulate an extreme weather event, as observed during fieldwork in Paper III. It was assumed that the roads would sometimes be untrafficable during March-May due to freeze-thaw and snow melting (allowing the machines to operate for only one shift per day on average), and because of the need to avoid soil damage. Single shift operation was assumed from May to June because of the decline in demand and to avoid accumulating large stocks of chips at the terminal during summer. The summed SMh for the forwarder-mounted chipper, self-loading chip-trucks, and chipper-truck amounted to 2 648 SMh each. The wheel-loader and shuttle chip-truck were scheduled to work double shifts from September to the end of April, and single shifts from May to the middle of June, amounting to 2 992 SMh each.

3.4.3 Cost calculation and experimental design

The hourly cost of machines and the terminal's operational cost were computed (Paper IV), using the "FLIS" machine-cost calculator (von Hofsten *et al.*, 2006). Contractors were assumed to work for other suppliers during off-shift time (and during eventual idle time due to lack of material) until they reached 3 200 SMh (corresponding to year-round double shifts). The total supply cost calculation included costs for chipping, transport, relocations, and terminal activities (wheel-loader operation, shuttle chip-truck operation, including terminal operational costs). The calculated total supply cost included the production cost of biomass lost due to DML during terminal storage. Mean supply cost (€ dry t^{-1}) was calculated as the total supply cost divided by the actual delivered biomass to the end-user. Costs due to machine idling, stumpage, tied up capital at storages, snow shovelling (to access the sites and clean the terminal), and upstream SC operations (i.e. harvesting and forwarding) were excluded.

Model verification was performed using subjective methods, namely visualization (assisted by the software's graphical interface) and walkthroughs (Balci, 1994). Model validation was performed by discussing its output with experts familiar with the modelled systems to confirm that its behaviour reproduced that of real systems, and by checking that some of its key outputs (e.g. efficiency, work time elements' distribution, and costs) were consistent with previous studies. All these tests indicated the model to be reasonable.

Simulations were performed for eight defined scenarios (Table 3). Inputs and system configurations were kept constant between runs. Five replicate simulations were performed for each scenario. Results were compared by one-way ANOVA with Tukey's post-hoc tests, using a significance threshold of $p < 0.05$. A sensitivity analysis was performed to evaluate the cost impact of integrating supplies of chips from forest and other land, assuming that an integrated biomass supply from multiple sources would increase biomass concentrations and reduce relocation distances. To this end, analyses were performed, assuming a "high" level of integration with 50% shorter relocation distances, and a "low" level involving 50% longer relocation distances.

Table 3. *Simulated scenarios.*

End-user	Demand level	Supply alternative	Scenario
Combined heat and power plant (CHP)	Low (21 000 dry t)	Direct (only)	1
		Combined (direct and via-terminal)	2
	High (29 000 dry t)	Direct (only)	3
		Combined (direct and via-terminal)	4
Biorefinery (BR)	Low (21 000 dry t)	Direct (only)	5
		Combined (direct and via-terminal)	6
	High (29 000 dry t)	Direct (only)	7
		Combined (direct and via-terminal)	8

4 Results

4.1 Paper I

All results presented relate to BDTF of category D (i.e. sites selected from the overall NFI dataset by applying all four of the selection criteria A–D). The area occupied by BDTF amounted to 2.1 M ha, corresponding to 9% of Sweden’s total productive forest land (Table 4). Both the absolute and relative areas of BDTF increased on moving northwards (Figure 6). Most of the BDTF area was found in Norrland (65%, representing 6% of Sweden’s productive forest land), followed by Svealand (20%) and Götaland (15%). In general, across the counties of Norrland, productive forest land contained the greatest proportion of BDTF and coastal counties had high proportions of productive forest land.

Table 4. *Regional distribution of BDTF area (ha), average above-ground biomass density (dry t ha^{-1}) and total growing stock (M dry t), by average stem volume subclass.*

Region	Subclass (average stem volume “v”, dm^3)								
	$10 \le v < 20$			$20 \le v < 30$			$30 \le v < 40$		
	ha	dry t ha^{-1}	M dry t	ha	dry t ha^{-1}	M dry t	ha	dry t ha^{-1}	M dry t
N. Norrland	262 292	50.1	13.14	147 003	54.6	8.03	108 859	55.3	6.02
S. Norrland	195 624	58.8	11.51	128 204	61.0	7.83	79 770	57.3	4.57
Svealand	146 521	53.6	7.85	83 711	55.3	4.63	57 296	57.3	3.28
Götaland	93 846	54.4	5.10	53 124	59.7	3.17	49 465	63.6	3.15
Total	*698 282*	*53.8*	*37.60*	*412 042*	*57.4*	*23.65*	*295 390*	*57.6*	*17.02*
	$40 \le v < 60$			$60 \le v < 120$			Total		
	ha	dry t ha^{-1}	M dry t	ha	dry t ha^{-1}	M dry t	ha	dry t ha^{-1}	M dry t
N. Norrland	137 044	49.3	6.76	142 258	54.8	7.80	*797 455*	*52.3*	*41.74*
S. Norrland	76 397	61.1	4.67	97 930	60.3	5.90	*577 924*	*59.7*	*34.48*
Svealand	75 715	60.5	4.58	66 881	59.3	3.96	*430 125*	*56.5*	*24.30*
Götaland	64 683	67.1	4.34	44 556	66.7	2.97	*305 673*	*61.3*	*18.73*
Total	353 839	57.5	20.34	351 624	58.7	20.64	2 111 177	56.5	119.26

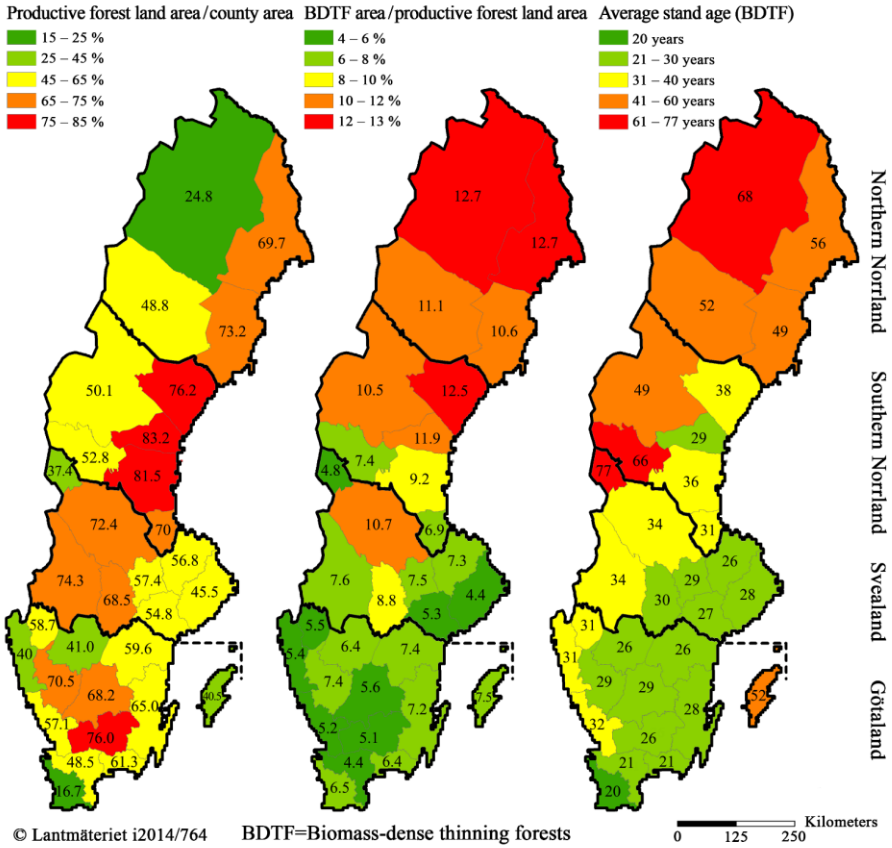

Figure 6. The areal proportion (%) of productive forest land by county (left), the areal proportion (%) of BDTF within the productive forest land by county (middle) and the average stand age of BDTF by county (right).

Most of the BDTF were Scots pine-dominated (52% of the BDTF area), followed by Norway spruce- (27%), broadleaf- (11%) and lodgepole pine- (7%) dominated stands. BDTF on former (abandoned) agricultural land accounted for 41 517 ha (2%) of the BDTF area, of which 38% was found in Götaland, 39% in Svealand and 23% in Norrland. These stands were dominated by spruce (66%) and broadleaves (25%). About 451 000 ha (21%) of the BDTF area was on difficult terrain, of which peatlands accounted for 26%. The analyses showed that 251 247 ha (12%) of the BDTF area had been subjected to PCT.

The total growing stock of BDTF amounted to 119 M dry t (7% of the total stock on Swedish productive forest land) (Table 4). Most of the biomass was found in Norrland (64%), followed by Svealand (20%) and Götaland (16%). About 65% of the BDTF area fell within the 0–40 years average stand age class (with 7% and 58% in the 0–20 and 21–40 years classes, respectively). Stands

41–60 years and > 60 years old accounted for 19% and the remaining 16% of the BDTF area, respectively. The average stand age (Figure 6) increased from South to North and East to West, being 28, 33, 42 and 57 years in Götaland, Svealand, southern Norrland and northern Norrland, respectively. Average BDTF characteristics are reported as cumulative percentages in Figure 7.

The analyses revealed a techno-economical harvesting potential of 4.3 M dry t year^{-1} of undelimbed whole trees (10.2 M m^3 year^{-1}) and 3.0 M dry t year^{-1} of delimbed stemwood including tops (7.5 M m^3 year^{-1}) (Paper I).

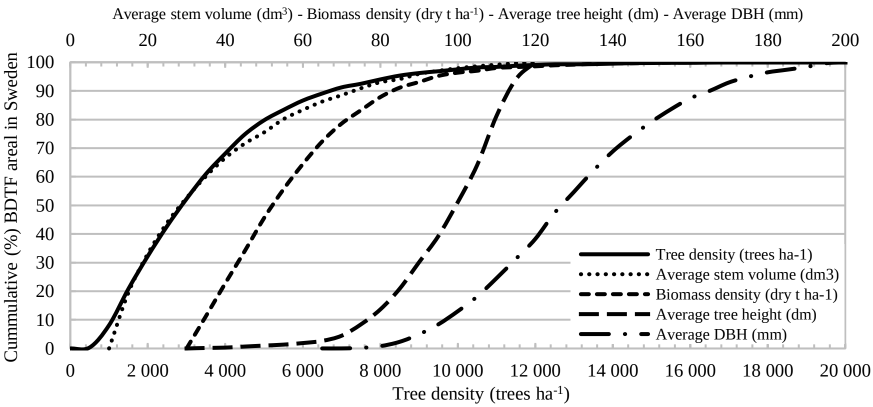

Figure 7. Characteristics of the BDTF across the whole of Sweden. The y-axis shows the cumulative percentage of the area occupied by the stands characterized by the parameters represented on the upper and lower x-axes. The absolute BDTF areas are shown in Table 4.

4.2 Paper II

4.2.1 Characteristics of power line corridors

The inventory of the harvesting units (Table 5) revealed a dominance of broadleaves, high tree densities (range: 10 080–30 239 trees ha^{-1}) and above-ground biomass density (i.e. biomass removal) of 19–37 dry t ha^{-1}. The measured biomass removal (dry t ha^{-1}) was modelled as a function of the average tree height, denoted h (m), yielding Eq. 2 (R^2_{adj}=0.573; p=0.0017).

$$Biomass\ removal = 0.6712 + 5.8736 \times h \qquad (2.)$$

Table 5. *Main parameters of the harvesting units.*

Unit	Species[1] (% b/s/p)	DBH[2] (cm)	DSH[2] (cm)	Height[2] (m)	Density (trees ha^{-1})	Harvested area[3] (m^2)	Harvested biomass[4] (dry t)	Biomass removal (dry t ha^{-1})
1	86/12/2	2.7	4.0	3.7	15 717	908	2.52	27.8
2	93/7/0	2.3	3.4	3.5	30 239	795	1.64	20.6
3	73/24/2	2.3	3.5	3.4	20 640	812	1.85	22.8
4	86/11/4	3.1	4.4	4.0	14 854	819	1.90	23.2
5	86/14/0	4.7	6.5	4.9	15 385	592	2.16	36.5
6	93/7/1	4.7	6.2	4.7	15 099	677	2.17	32.1
7	85/15/0	3.1	4.5	4.0	13 396	659	1.51	22.9
8	94/6/0	2.5	3.7	3.8	15 648	921	1.76	19.1
9	92/8/0	2.4	3.6	3.7	15 252	1 120	2.14	19.1
10	95/5/0	3.7	5.2	4.5	10 080	600	1.61	26.8
11	99/1/0	3.5	4.9	4.5	12 202	668	1.45	21.7
12	95/5/0	3.0	4.3	4.1	12 732	609	1.52	25.0
13	98/2/0	3.9	5.1	6.3	17 507	620	2.19	35.3
Mean	90/9/1	3.2	4.6	4.2	16 058	754	1.88	25.6

1. b, broadleaves (birch, *Betula spp.*, and willow, *Salix spp.*); s, spruce (*Picea abies*); p, pine (*Pinus sylvestris*).
2. Mean values, weighted by basal area. In every sample plot (6 plots per unit), the DBH of all trees with DBH ≥ 1 cm was measured. The diameter at stump height (DSH, measured at 10 cm above the ground, i.e. the estimated cutting height) and the tree height were measured for a sample of 3 trees per plot.
3. The effective harvested area was measured after forwarding using a GPS on a personal data assistant.
4. The harvested biomass was forwarded to the roadside landing and weighted, one unit at a time, with an axle load scale system. MC was determined according to EN 14774-2:2009 (CEN, 2009a), cutting 3 wood discs from 10 sample harvested trees, and it averaged 45% (range: 43.7–46.2%).

4.2.2 Mechanization of power line corridor cleaning

The harvester was studied during 14.62 SMh (1.9% delay time) and its efficiency (PMmin dry t^{-1}) was modelled based on the field observations, as a function of the average tree height, denoted *h* (m), yielding Eq. 3 (R^2_{adj}=0.617; p=0.0009).

$$\text{Harvester's efficiency} = e^{5.4935} \times h^{-1.379} \quad (3.)$$

The forwarder was studied during 4.73 SMh (1.3% delay time). One load was sufficient to complete the extraction of the biomass in each unit (a full load corresponded to 2.52 dry t). The efficiency (PMmin dry t^{-1}) of the work element *Loading* was modelled as a function of the removal of biomass per unit, denoted *b* (dry t ha^{-1}, Eq. 2), yielding Eq. 4 (R^2_{adj}=0.468; p=0.0059). The time consumption of *Driving empty* and *Driving loaded* was modelled as a function of forwarding distance (one-way), denoted *d* (m), using the average measured empty and loaded driving speeds of 83.1 and 67.3 m min^{-1}, respectively. Average efficiency values of 2.11, 1.08, and 0.51 PMmin dry t^{-1} were used for *Driving while loading*, *Unloading*, and *Miscellaneous*, respectively. The forwarder's efficiency (PMmin dry t^{-1}) was then modelled based on the summed field observations of these work elements, yielding Eq. 5.

$$\text{Loading efficiency} = e^{3.6365} \times b^{-0.7616} \quad (4.)$$

$$\text{Forwarder's efficiency} = e^{3.6365} \times b^{-0.7616} + \frac{\left(\frac{d}{83.1} + \frac{d}{67.3}\right)}{2.52} + 2.11 + 1.08 + 0.51 \quad (5.)$$

For the modelled unit size of 1 ha, and considering the lowest (3.4 m) and highest (6.3 m) average tree heights observed in the field, the net income for the mechanized harvesting system was negative (Figure 8). The net income of the mechanized harvesting system and the cost of motor-manual clearing reached the same (negative) value for an average tree height of 5.9 m. Therefore, for trees above this height, the mechanized harvesting system would be a more cost-efficient alternative. For an average tree height of 7.6 m, the mechanized system would give a net income of zero.

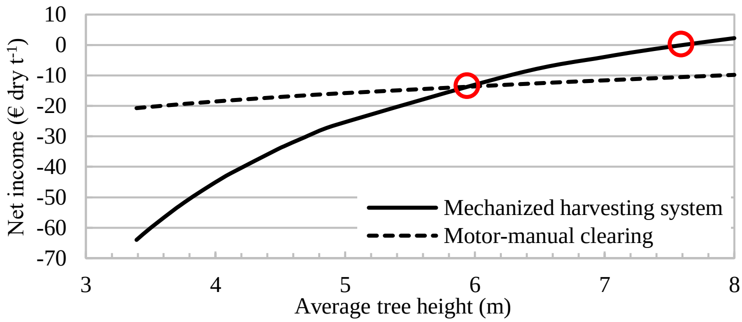

Figure 8. Net income of the mechanized harvesting system (i.e. harvester and forwarder) and costs of motor-manual clearing as functions of the average tree height. The red circles indicate the tree heights at which the net income of the mechanized system equals the cost of motor-manual clearing (left) and the mechanized system gives a net income of zero (right).

4.3 Paper III

4.3.1 Characteristics of windrow storage sites and fuel-chip quality

A total windrow stacked volume of 42 298 bulk m^3 was measured in the field, and a total fuel-chip mass of 2 651 dry t (12 940 MWh) was scaled at the CHP. To facilitate subsequent analyses in Paper IV, the surveyed characteristics (attributes) of the windrows and storage sites were analysed using Stat::Fit®, to find probability distributions fitting the fieldwork data (Table 6). To ease the interpretation of the distributions, the range of variation (around the median) of

95% of the measurements was determined. The survey found that most LR windrows were located in the cutting site and were outside the reach of the chipper's crane if operated from the roadside (Table 7). Conversely, most ST windrows were placed on a roadside or a large landing, within reach. 42% of the total sampled windrows were not reachable from the roadside.

Table 6. *Main attributes of the surveyed sites in forest and other land.*

Attributes	Unit	Distribution	95% of values between
Site size[1]	dry t	Gamma (12,1.53,44.6)[2]	42-88
Individual windrow size	dry t	Gamma (12,3.43,10.9)[3]	30-55
Moisture content (MC)	%	Triangular (26,45,61)[4]	44-48
Trucking distance from sites to the terminal or end-user[5]:			
May-November	km	Triangular (40,49,99)[4]	45-54
December-April	km	Triangular (4,27,35)[4]	20-29
Relocation distance between sites[6]	km	Beta (0.10,68,0.56,4.83)[7]	5-15

1. Surveyed sites consisted of 1–10 windrows.
2. Gamma (minimum, shape parameter, scale parameter), with an upper boundary of 350 dry t.
3. Gamma (minimum, shape parameter, scale parameter), with an upper boundary of 111 dry t.
4. Triangular (minimum, mode, maximum).
5. Observed trucking distances to the CHP during fieldwork. To be used in Paper IV, distances were clustered into two groups: one for sites that were far from end-users (during the low heating season) and the other for sites close to end-users (during the high heating season). The distribution of trucking distances between the sites and terminal was assumed to be identical to that for distances between sites and end-users.
6. Distances were calculated based on the chipper's routes observed during the fieldwork.
7. Beta (minimum, maximum, lower shape parameter, upper shape parameter).

Table 7. *Windrow placement and underlay for tipping over the chip-bin.*

Assortment	Placement (%)			Underlay[1] (%)		
	Roadside	Big landing	Out of reach	Snow	Clean bare ground	Forest ground
LR	32	2	66	41	7	52
ST	63	28	9	91	3	6

1. Snow was often compacted and flattened by the forwarder's front-mounted shovel and crane, with the help of a log. Clean bare ground consisted of grass or gravel. Forest ground (in the cutting site) was an irregular underlay with stumps, undergrowth, moss, mineral soil, etc.

The overall mean plant-determined MC was 45% and varied significantly both between and within sites, with inter- and mean intra-site standard deviations of 7.1% and 3.4%, respectively. Comparisons revealed that the MC associated with assortments (LR vs. ST) or sampling methods (fieldwork vs. plant) did not differ significantly. LR yielded significantly (ca. two-fold) higher proportions of fines (particle size class < 3.15 mm) and oversized (> 63 mm) fractions than ST (12.2 vs. 5.8% and 2.2 vs. 1.1%, respectively), and significantly higher AC (mean

2.43%, range: 1.67–3.44%, standard deviation 0.49%) than ST (mean 1.54%, range: 0.56–2.93%, standard deviation 0.56%) (Paper III).

4.3.2 Predictive models of dry mass content in windrows

Dry bulk densities of windrows averaged 68–66 and 58–59 dry kg bulk m^{-3} for LR and ST, respectively, depending on whether chipper or plant data were used. Dry bulk densities differed significantly between assortments but not between methods of calculation (i.e. the results obtained using chipper data did not differ from those based on plant data). Regression analyses showed that the dry mass of the windrows depended strongly on the windrow bulk volumes measured in the field and generated four predictive models (Figure 9): one for each permutation of dry mass of LR or ST based on chipper or plant data (i.e. one for each method of calculation).

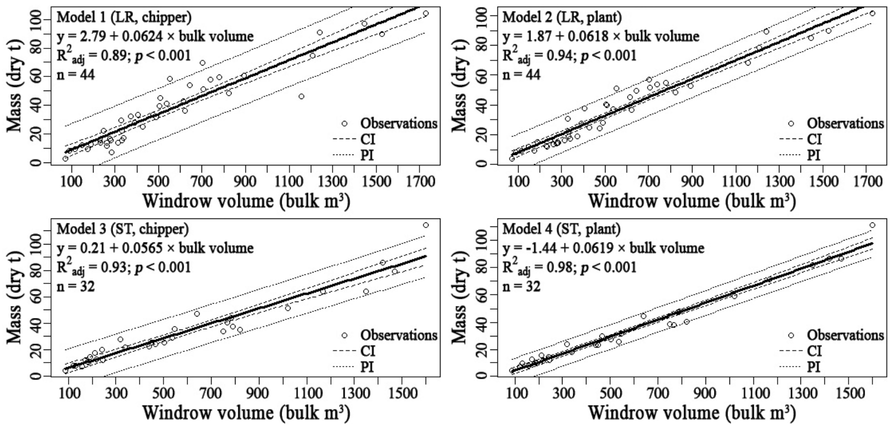

Figure 9. Predictive models for dry mass of LR and ST windrows. Confidence intervals (CI) and prediction intervals (PI) are represented by dashed lines and dotted lines (95% confidence level).

4.4 Paper IV

4.4.1 Simulated supply cost of chips

The simulations revealed that the mean supply cost of chips was 9% higher on average (47.0 vs. 43.2 € dry t^{-1}, range: 5–11%) in the combined SC scenarios than the direct SC scenarios. The cost of direct and combined supply to the CHP averaged 42.7 € dry t^{-1} and 47.0 € dry t^{-1} across scenarios, respectively, while those of direct and combined supply to the BR averaged 43.8 € dry t^{-1} and 47.0 € dry t^{-1}, respectively. No significant differences in unitary biomass costs or annual (total) supply costs were found between end-users in the combined SC scenarios, but direct supply to the BR yielded a 3% higher mean cost than to the CHP. System 1 accounted for 59–72% of the annual supply costs, including relocations, while System 2 was responsible for 28–35%. Because 42% of the sampled windrows were unreachable from the roadside (see Paper III), System 1 was assigned a higher priority, leading to a comparatively high use of the forwarder-mounted chipper. This explains its large share of the total supply cost. System 1 also had an 8% higher operational cost than System 2 (44.2 vs. 40.8 € dry t^{-1}). Terminal activities accounted for 5–6% of the annual supply cost in the combined SCs.

Sensitivity analyses revealed that reducing the integration of chip supply from forests and other lands (increasing relocation distances from ca. 13 to 20 km) increased supply costs by ca. 2% (average for both end-users). Conversely, increasing the integration (by reducing relocation distances from ca. 13 to 7 km) when supplying the CHP reduced mean supply costs by ca. 2%. A similar decrease was observed when supplying the BR directly, but the decrease was not significant (p=0.065) when compared to combined supply.

The distribution of workload (represented by monthly production) over the year (Figure 10) when supplying the BR directly was more even than when directly supplying the CHP, which had a seasonal demand. Regardless of the end-user, combined supply via terminal evened out the contractors' annual workload.

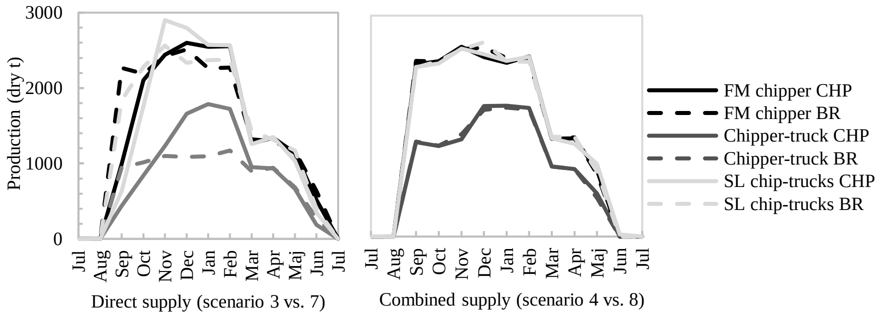

Figure 10. Mean monthly production (dry t) of the supply fleet for direct (left) and combined chains (right) when supplying the combined heat and power plant (CHP) and biorefinery (BR) at the high-demand level. FM=forwarder-mounted, SL=self-loading.

4.4.2 Simulated chip flow

In the low-demand scenarios, the chip supplier provided all agreed chip amounts on time. In the high-demand scenarios, supply was only delivered on time in the combined SC scenarios (scenario 4 and 8); in direct SC scenarios (scenario 3 and 7), a volume corresponding to ~8% (average 2 386 dry t) of the annual demand was not provided on time. In scenario 3, the CHP's demand was not met on time for several days in January and February (peak demand), and also for several days in March, April, and early May (due to operational problems in the SC, i.e. untrafficability of forest roads). In scenario 7, the BR's demand was not met on time for several days from the middle of March to the middle of May. For combined SC scenarios, at the high-demand level, the amount of biomass passing through the terminal ranged from 15 to 17% of the total supply (4 486–4 927 dry t, in scenario 4 and 8, respectively). When supplying the CHP (Figure 11), the storage of chips at the terminal increased from September and peaked in November. The majority of outbound deliveries occurred between the end of February and the beginning of May. Conversely, when supplying the BR, terminal storage accumulated more uniformly, peaking at the beginning of March. The majority of outbound deliveries occurred from March onwards.

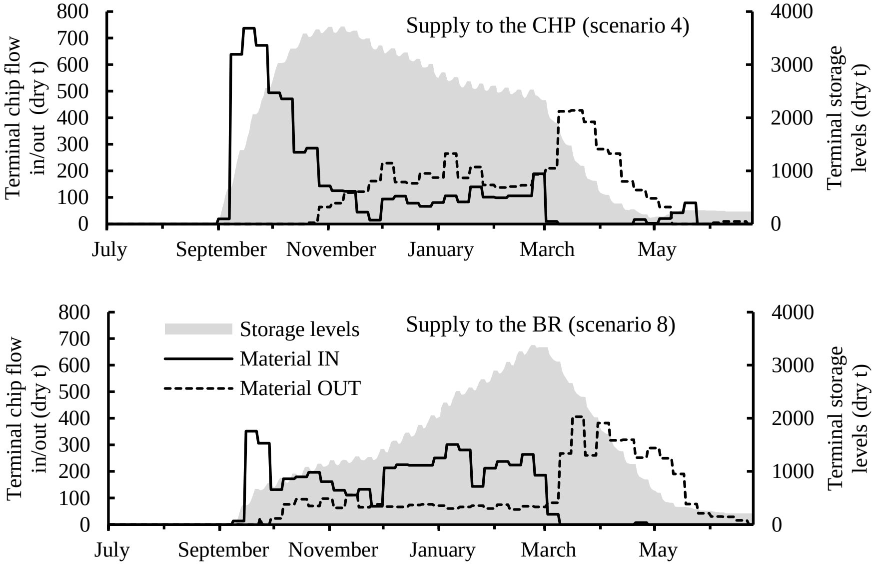

Figure 11. Mean chip flow in/out of the terminal (weekly) and storage levels (daily).

Mean storage time at the terminal was 4–22% greater when supplying the CHP (28–15 weeks in the low and high-demand scenarios) than the BR (27–12 weeks). The longer storage times, together with the higher mean storage levels, resulted in 12–43% greater DML when supplying the CHP (547–400 dry t, in the low- and high-demand scenarios) than the BR (488–279 dry t). DML when supplying the CHP corresponded to 2.5–1.4% of annual supply and 2.3–0.9% when supplying the BR, in the low- and high-demand scenarios, respectively.

5 Discussion

5.1 Usefulness of results and filled knowledge gaps

This thesis provides a foundation for further studies on forest operations. Furthermore, the results presented herein can be used for teaching and learning purposes to help students understand the state-of-the-art in residual biomass utilization, including issues such as biomass sourcing, SC engineering, chip quality assessment, and SCM. Target groups (stakeholders) likely to be interested in the outcomes reported here include policymakers, researchers, and industrial developers and practitioners in the SC. In a broader context, the global climate system (and thus society as a whole) could indirectly benefit from the implementation of this thesis' concluding recommendations.

5.1.1 To policymakers

The quantification of the areal distribution, potential and characteristics of BDTF (Paper I), provides strategic information that could be used to develop new silvicultural regimes in forest management. For instance, early thinnings could be performed instead of PCT if there was a higher willingness to use ST in energy or biorefining processes (Sängstuvall, 2018; Karlsson, 2013). Paper I revealed the considerable sustainable potential of ST across Sweden (particularly in the northern part of the country), which could influence strategic decisions regarding investments in new infrastructure (e.g. railways or terminals) and new industries. The model presented in Paper IV could support such investments by guiding the design of environmentally sound and efficient forest biomaterial SCs. However, long-term stable policy frameworks are needed to enable the commercial-scale deployment of biorefining processes and investments in BRs (Mustapha *et al.*, 2017a; Mustapha *et al.*, 2017b).

There is an on-going electrification of passenger cars and light commercial vehicles worldwide (IEA, 2018b). Nevertheless, demand for fossil fuels is expected to increase in the coming decades (IEA, 2018a) because aircraft, ships, and heavy-duty vehicles such as trucks, forest machines, and construction machinery will continue to be powered by combustion engines for the foreseeable future. However, some of this demand could be met by biofuels. Of the feedstocks that could be used for biofuel production, residual forest biomass has one of the lowest carbon footprints (Ganguly *et al.*, 2018; Valin *et al.*, 2015). To avoid misleading interpretations and decisions, policymakers must take into account the time scales considered and assumptions made in analyses of the sustainability of feedstocks for biofuel production (Berndes *et al.*, 2016). Additional policy instruments are needed to displace fossil fuels and make wood-based biofuels competitive. Residual woody biomass from forest and other lands is a local resource whose use contributes to the fulfilment of EU renewable energy targets (European Parlament, 2018), in line with the Paris Agreement, and help mitigate climate change. A higher mobilization of this biomass could further reduce the EU's dependence on imported fossil fuels and imported pellets, enhancing energy security, maintaining and creating new jobs in rural areas, and increasing the resilience of forests towards disturbances such as wildfires and insect pests.

5.1.2 To researchers

Paper I refined earlier assessments of the potential of ST in Sweden (Athanassiadis & Nordfjell, 2017; Routa *et al.*, 2013; Nordfjell *et al.*, 2008). Sängstuvall (2018) found that previous potential assessments had yielded very different results depending on the model used, temporal scope, and assumed restrictions, which complicates direct comparisons. The calculated techno-economical potential reported here should be considered optimistic because the inclusion of ecological constraints to account for impacts on nutrient balance in the remaining stands in the recommended manner (Agestam, 2015; Swedish Forest Agency, 2008), would reduce the calculated potential. Additional explicit economic restrictions (e.g. the imposition of minimum stand sizes or maximum forwarding distances) would further reduce this potential. Nevertheless, the results presented here could be used to further analyse logistics from BDTF to potential end-users, as shown by Sánchez-García *et al.* (2017). Such analyses could use optimization to find optimal locations for new BRs and terminals.

The models of machine efficiency presented in Paper II could provide input data for other studies (e.g. simulation studies like that reported in Paper IV) and could also be applied to alternative lands with similar tree sizes and species, such as cut-away peatlands (Jylhä *et al.*, 2015). Other systems, such as biomass harvesters used in short rotation coppices (Vanbeveren *et al.*, 2017), could also be suitable for use in PL corridors or linear clearings in firebreaks or roadsides. The models for predicting the dry mass content of windrows (Paper III) could be further developed for use as a decision-support tool in combination with drying models to forecast MC (Routa *et al.*, 2015; Acuna *et al.*, 2012). The potential of such approaches was demonstrated by Windisch *et al.* (2015), who combined DES and GIS to improve the allocation of a chip supply fleet in Finland. Similarly, Eriksson *et al.* (2017) developed and implemented another SCM system to prioritize chip deliveries based on storage time, fuel-chip quality and trucking distances. Predictive models (Figure 9) and drying models can provide input to such SCM systems, improving the precision of deliveries.

5.1.3 To industrial developers and practitioners

The calculated amounts of ST and the characteristics of their stands across Sweden (Paper I) clearly demonstrate that substantial quantities of material are available to contractors and could potentially supply BRs. The creation of new end-users and the considerable potential of ST could motivate investment by machine manufacturers and spur the development of ST harvesting technologies.

The data on the characteristics of PL corridors (Paper II) could help the managers of PLs make strategic decisions about maintenance operations and better adjust the frequency of clearings with regards to safety regulations. For instance, a mechanized harvest of PL corridors could be integrated with forest operations in nearby forest land (using the same machines) to achieve cost savings. The analysis presented in Figure 8 could be used to guide the selection of a cost-efficient system based on the size of trees to be cleared. Even if it does not provide a direct economic profit per se, the results presented here show that residual biomass utilization could offset maintenance costs in PL corridors because the clearing has to be performed anyway. The efficiency models of machines developed in this work could be used to improve the planning of operations at the tactical and operational levels by helping to size the machine fleet, forecast the time required to complete operations, and determine whether machines are working properly. The base machines studied in Paper II (a harvester and forwarder) represent the most common machine system in forestry in Sweden. However, the usability of medium- or large-sized forest machines in operational environments other than forest land may be limited due to the low bearing capacity of the ground. For example, arable land has soft soil; this difficulty could be avoided by harvesting in winter when the ground is frozen or in summer when it is dry. Alternatively, smaller forest machines or alternative systems (e.g. biomass harvesters or farm tractors) could be used.

Paper III describes important characteristics of the operational environment and fuel-chip quality of LR and ST in northern Sweden. The survey revealed a wide range of variation in quality parameters (MC, AC and PSD), which poses challenges to end-users (e.g. the chips' MC ranged from 26 to 61%). In this case, the end-user was a large CHP (*Dåva 2* in Umeå), with flue gas condensation that can handle wide variation in chip quality (unlike small heating plants). The comparatively higher quality of ST than LR in terms of AC and PSD (less ash, fines, and oversized fractions) is consistent with previous reports (Kons *et al.*, 2015; Pettersson & Nordfjell, 2007). The results and findings presented in Paper III can be useful to contractors, chip supplier companies, and heating plants, helping them to improve their SCM.

Since upstream and downstream SC operations are closely interconnected, a holistic, SCM approach, from the harvesting site to the end-user, is crucial for cost-effective delivery of high-quality residual biomass. Field observations (Paper III) revealed that some windrows contained small uprooted trees (with mineral soil and stones attached), perhaps resulting from the use of a roundwood rather than a slash grapple. Despite the cautious work of the operator, some impurity-containing biomass may have been fed into the chipper, leading to high AC in the sampled chips. Therefore, good communication between contractors along the SC is needed, since low-quality work in the initial stages results in low chipping productivity (as the operator will have to sort the material and change blades often) and low fuel-chip quality. The MC, AC and PSD of the delivered fuel-chips can thus be enhanced by maintaining proper handling practices along the whole SC. Attempts were also made to avoid overturning the chip-bin on bare forest ground (which increases the risk of contamination and material losses during fuel-chip loading onto trucks), but this was not always possible due to the narrow roadsides. From an SC manager perspective, it is preferable that contractors leave some material on the site (i.e. not forward it) than not load chips (or overspill) onto trucks, because each unit of produced chips accumulates a cost along the SC (Eriksson, 2016).

The use of bottom sieves during chipping, and screening (Spinelli *et al.*, 2011), produce more homogeneous chips and improve the use of different particle sizes: e.g. fines could be used in BRs or potting-soil industries, medium-sized fractions for combustion or torrefaction, and coarse fractions for further chipping. Fractionation can be combined with wind shifting to reduce amounts of impurities (e.g. stones). The resulting improvements in feedstock quality and system efficiency, together with the reduced risk of failure or damage to the end-user's feeding systems, may compensate for the extra costs of such systems.

The predictive models developed in this work (Figure 9) can forecast the dry mass content in windrows based on simple field measurements of windrows' height, length and width. Their output can be used to estimate the chip volumes produced during chipping operations. This information can improve the planning of logistics on the tactical and operational levels by guiding the sizing of machine capacity (e.g. helping identify the optimal type of chipper and required number of trucks), system configuration, and vehicle routing. Alternatives to manual volume measurements, such as photogrammetric techniques (i.e. structure from motion) and drones can be viable options for stockpile inventory, especially at terminals and the end-user (Forsman, 2016).

The simulation model presented in Paper IV was designed to quantify the extra cost of using a terminal in an SC for chipped LR and ST, and to study the logistical implications of supplying different end-users (CHP or BR) at different expected levels of demand. The main outcome was that the use of terminals increases supply costs compared to direct supply but helps to secure supply during peak demand and to cope with operational problems in the supply fleet (in cases where direct SCs would be unable to meet demand on time). The cost of not meeting demand on time can be difficult to quantify in real-world operation, so it can be convenient to use a terminal to reduce risks despite the increase in the cost of supply. The simulations also revealed that DML at terminals may amount to 0.9–2.5% of annual supply. Therefore, when managing terminals, DML should be minimized by using optimal storage methods (Anerud *et al.*, 2018) and finding a balance between maintaining low storage levels and being able to rapidly meet demand as needed.

Results (Figure 10–11) also revealed that direct supply of chips to a BR, and combined supply via-terminal to a CHP or BR evened out the contractors' annual workload and enabled more steady annual operation. The model can be tailored to different cases to answer other questions and assist in decision-making relating to strategic (e.g. terminal design), tactical (annual procurement plans, supply fleet sizing, DML, etc.), and operational (machine utilization, vehicle routing, bottlenecks, etc.) issues.

The key findings of this thesis and their practical relevance to selected stakeholders are summarized in Table 8.

Table 8. *Key findings from this thesis and recommendations for specific stakeholders (target groups).*

Policymakers	Researchers	Industrial developers and practitioners
There are large amounts of underutilized residual LR and ST across Sweden, in forest and other lands, that we can sustainably harvest to boost the growth of the bioeconomy. New management regimes can be developed for increasing the harvest of ST. Despite the considerable potential LR and ST, high supply costs limit their utilization, making it difficult to compete with cheaper feedstocks. Thus, innovative solutions must be developed. The results presented here could support strategic investments in new infrastructure (e.g. railway, terminals) and industries (e.g. biorefineries using residual woody biomass). Long-term policy frameworks to support the development of new infrastructure and industries are needed. Additional policy instruments are needed to accelerate the transition towards the bioeconomy. To avoid misleading interpretations and decisions, consider the time perspective and assumptions of analysis assessing the sustainability of feedstocks for biofuel production.	Previous potential assessments were refined, and additional environmental and economic constraints will reduce potential amounts of ST. Biomass potential estimates can support new analyses for various potential end-users. The models of machine efficiency and the simulation model can provide input to other studies, and a foundation for future supply chain analyses. There is room for large cost savings in LR and ST supply chains, but further developments of supply systems are needed. Innovative and alternative systems to conventional forest machines should be evaluated when harvesting in other land. Predictive models of dry mass can be used as a decision-support tool (combined with drying models) and provide input to fleet management systems for improving supply chain management. Simulations can support the design of efficient and environmentally sound biomaterial supply chains for industrial end-users. Research methods could be further developed: automatic data gathering in work studies, higher integration of GIS with optimization and simulation, etc. Further developments and translation of applied research results into decision-support tools are needed.	There are large amounts of residual feedstocks to supply new biorefineries across Sweden. New developments from machine manufacturers are needed to harvest ST with high cost-efficiency. When planning power line corridor cleaning, consider to integrate a mechanized harvest with forest operations in nearby forest land (using the same machines) to achieve cost savings. Handle material correctly in early stages of the supply chain (harvest and forwarding) and minimize material losses during handling. This will result in high chipping productivity, high transport efficiency and high-quality chips (lowering supply costs and increasing revenue, and thus profit margins). Good communication between contractors along the supply chain is fundamental. Wide variation in fuel-chip quality parameters (ash content, moisture content, particle size distribution) should be expected in chips from LR and ST. Bottom sieves, screening and wind shifting can produce homogeneous chips and lower ash content. Predictive models of dry mass in windrows can be used to size machine capacity (forecast chip volume, chipping time, and truckloads), vehicle routing, etc. Use simulations for supply chain engineering: terminal design, cost-efficient supply chain configurations, forecasts of material flows, bottlenecks, etc.

5.2 Strengths and pitfalls of chosen research methods

The approach used in Paper I, involving static GIS-analysis of NFI data, made it possible to achieve the study's goals and generate cartographic models with results on a regional or county level. To support future investment decisions, it would be necessary to account for the current and future demand nodes of this biomass, as highlighted by Sängstuvall (2018) and shown by Sánchez-García *et al.* (2015) in northern Spain. GIS permits advanced analyses (Grigolato *et al.*, 2017), but the quality of the outputs and reliability of results depends on the amount and quality of input data. Paper I used a high-detail dataset from the NFI, but comparable datasets may not be available in other countries, limiting the extent of the analyses that can be conducted; in such cases, it will be necessary to modify the study design used here accordingly. When working with large datasets, it is essential to understand how the data is structured. If a spatial representation was not needed, the analyses could be done in a spreadsheet.

Paper II presented an experimental study, modelling the harvester and forwarder's efficiency by measuring time inputs and mass outputs under controlled conditions in 13 different study units. The resulting models can predict the time consumption of similar machines in similar environments, but the studied units do not represent the whole spectrum of conditions existing in PL corridors. The study examined only one operator per machine, and while they were very skilled, operators affect system performance (Purfurst & Lindroos, 2011). Therefore, the uncertainty of the models' output would be increased if they would be applied to alternative conditions with different tree sizes, levels of terrain roughness or different machines. Time studies are commonly performed to measure work, and were performed by personnel using handheld equipment (manual timing) in Paper II. However, automatic data collection procedures could also be used (Manner, 2015; Nuutinen, 2013). Such approaches enable monitoring of machinery over longer periods, but the risk of losing detail and not fully understanding the studied working methods increases. In forestry studies, it is common to use tree volume or DBH to model harvester efficiency. However, tree height was chosen in this case because of its significantly greater effect on efficiency and because PL maintenance operations are based on tree height. PL corridors are a unique operational environment, with distinct safety regulations. Although the estimated costs of motor-manual clearing were based on productivity norms for PCT in conventional forestry, consultations with practitioners indicated that they were reasonable. Nevertheless, the economic analysis (e.g. Figure 8) should be adapted when applying the methods used here to other cases.

Paper III was an observational study, following the campaign of a chipping contractor in northern Sweden over two months. The predictive models (Figure 9) developed in this study were based on a survey of 76 windrows at 34 sites and can be considered consistent. Photogrammetry and drone-based imaging could be used instead of manual measurements in such volume measurements (Forsman, 2016). The CHP provided a dataset recording the fresh, dry mass and MC of every truckload it received during the trial. However, a systematic sampling was lacking when fuel-chips were sampled in the field by the researcher. In practice, the number of samples taken depended on the time available before the chip-trucks started loading the chips. Therefore, the use of a standard method such as EN 14778:2011 (CEN, 2011) would have been impractical. Statistical analysis was thus restricted to linear regression analysis and ANOVA. With a more thorough experimental design, multivariate statistics could have been used to study the effect of storage conditions on fuel-chip quality. When determining MC for trade purposes, sampling must be performed correctly to correctly estimate MC. Therefore, the intensity of sampling should be adapted to the size of the chip delivery (Björklund & Fryk, 2014).

Paper IV presented a simulation-based cost analysis. Simulations can help to evaluate real or future systems and their operational alternatives, at comparatively lower costs and with lesser risks than real-world experiments. Several assumptions and trade-offs were made when designing the simulation model, simplifying the real systems. However, increasing the level of detail wouldn't necessarily improve the results. A balance must therefore be found, keeping in mind the simulation's purpose. Given the interconnectivity and complexity of SC operations, DES was identified as a powerful method for modelling machine interactions and stochastic events. Its use was motivated by the results of Asikainen (1998), who found that costs can be underestimated by ca. 20% if delays caused by interactions and random elements (e.g. breakdowns) are neglected, and by the assessment of the differences between static approaches and DES presented by She *et al.* (2018). Although the modelled systems (Paper IV) were meant to be "cold", it would have been impossible to perform the analyses using static, analytical approaches due to the large number of random variables that had to be accounted for. In addition to the capabilities of DES, the use of software such as ExtendSim®, which has a user-friendly graphical interface, made it possible to monitor material flows in real-time (Fernandez-Lacruz, 2018). It should be noted that several caveats emerged during the conduct of the simulation study. First, it was clear that learning-by-doing and discussion with experts are needed for successful simulation. Second, transportation was not optimized, which could have reduced total supply costs. However, it is important to recall that real-world transportation may be nonoptimal, as observed during the fieldwork (Paper III): the chipper often deviated from planned routes to find alternative sites because some forest roads became untrafficable due to freeze-thaw and snow melting during March-April. Third, hourly operating costs of machinery can be difficult to estimate, especially in isolated analyses such as those presented in Papers IV and II. A machine's expected annual working time strongly affects its calculated hourly costs, so the economic results must be treated as an approximation of reality.

Analysis of the four studies' limitations thus yielded several learning outcomes, which are summarized in Table 9.

5.3 Harvesting small-diameter trees

The area of BDTF exhibiting a given stand characteristic depended on the parameter under consideration (Figure 7). For instance, about 13% of the BDTF area (~274 000 ha) contained stands with a mean DBH < 10 cm. Figure 7 also shows that over 67–47% of the stands had a density exceeding 2 000–3 000 trees ha^{-1}, which is the target density for future crop trees after PCT (Skogskunskap, 2019b; Varmola & Salminen, 2004). Analyses showed that only 12% of the BDTF area had been subjected to PCT. Parameters such as average stem volume (dm^3) are arithmetic averages, and can therefore be misleading for plots with many small stems and a few big trees. The mean DBH is arguably a more robust indicator because it was weighted by basal area (i.e. thicker trees were better represented). To improve operations planning, detailed inventory data would be needed to assess the distribution across DBH classes, rather than average values. In the year 2010, the break-even tree size (for harvested trees) needed to make a profit in energy thinnings in Sweden was around a DBH of 8 cm (stem volume of ~35 dm^3) (Di Fulvio *et al.*, 2011a). In Finland, a DBH of 9–10 cm is seen as the break-even size for harvesting ST as pulpwood instead of fuelwood (Petty & Kärhä, 2014). This break-even size will depend on factors such as current market prices, species, and trucking distances to the end-user. Regional differences in mean annual stem volume increment explain the spread in stand age across BDTF (Figure 6), and for this reason the term "young" was avoided when referring to the BDTF; instead, the discussion and analysis focus on stand characteristics from a harvesting perspective.

The harvester's efficiency (Paper II) was consistent with that observed during harvesting of short rotation coppice willow (Di Fulvio *et al.*, 2012), with the same AFH. The small trees of PL corridors, whose overall mean DBH and height were 3.2 cm and 4.2 m, respectively (Table 5), have stem volumes of ~3–5 dm^3, similar to those in PCT stands. Forest stands with such undersized trees were excluded from analysis in Paper I because their use is unlikely to be economical

Table 9. *Learning outcomes (strengths, pitfalls and other advice) from the practical execution of the studies in this thesis.*

Paper	Learning outcomes
I	GIS-analysis can produce results that are easily interpreted by wider audiences (e.g. map-based visualizations).
	Plan the analysis based on the study's goals and available data. The level of detail and quality of results will depend on the quality of input data.
	When working with datasets, it's crucial to understand how the data is organized and the representativeness of attributes. Consider data pre-processing.
	GIS can be combined with other powerful techniques such as simulation and optimization.
II	Plan the experimental design based on the study goals (in good time before starting the fieldwork) and compromise with your available time (budget).
	Detailed guidelines on experimental design for biomass production studies have been presented by Magagnotti *et al.* (2012).
	Consider the required level of detail: personnel in the field performing a time study (manual timing) or automatic data collection by the forest machines (and eventual filming of the operations). Fieldwork helps one understand better how a system works, eventual bottlenecks, and the reasons for delays.
	Good communication with contractors during fieldwork and their willingness to collaborate in the research are essential.
	Consider using an integrated crane scale in the forwarder, rather than portable wheel-weighing scales, which are time-consuming to set on rough terrain.
	The use of efficiency models in operational environments differing from those in which the models were derived could produce uncertain estimates.
III	Common learning outcomes from Paper II. Protocols may be updated during fieldwork, as new issues often emerge in practice.
	Plan chip sampling thoroughly and consider the number of sites to sample (it can be time-consuming). Representative sampling is essential to obtain correct estimates of quality parameters: it is said that 80% of errors are associated with sampling rather than laboratory analysis.
	In addition to fieldwork sampling, use data from the measuring station at the receiving plant if possible (they may use measurements for trade purposes).
IV	First, define the study purpose and which questions should be answered. Second, make a process map with pen and paper.
	Think of the components of the real system that are relevant to the study's goals. It's essential to understand how the real system works and how its components interact with each other (and other systems). Set clear boundaries to prevent the model from becoming unnecessarily large.
	Discrete-event simulation is a powerful simulation technique for supply chain engineering and cost analysis. Make notes while building up the model. Graphical interfaces make it possible to e.g. keep track of material flows at any time, and easily present the model to people unfamiliar with simulations.
	The model must be built correctly, and it must be the right model for the study's purpose. To determine whether the right model has been built (validation), it's important to discuss it with experts with the real systems, and to evaluate key preliminary model outputs (e.g. comparing efficiency and costs to previous studies, an expert's experience or your own). Simulation software with graphical interfaces will decrease the time spent debugging (verification, making sure the model was built right), allowing you to invest more time into building the right model.
	Decide the level of detail: more detail doesn't necessarily mean better results. A compromise must be found that reflects the study's purpose, the potential users of the results and the time available to perform the study. It can take time to build a model and gather input data (from practitioners, literature, new time studies, etc.). Even if the right model has been correctly built, the quality of outputs will depend on the quality of input data.

in the near future. Motor-manual clearing will continue to be a cost-efficient option in many operations related to landscape care activities, unless the tree size exceeds some threshold or the cost of contractors performing motor-manual clearing increases notably. In some cases, however, as found in Paper II, the recovery of biomass could partly offset maintenance costs even if it is not profitable. Other constraints, e.g. long forwarding distances, soft ground, or the need to strike agreements with different landowners (to drive forest machines across their estates) may limit the scope for mechanized harvesting in other lands. Conditions in other lands are very heterogeneous (Andersson *et al.*, 2016; Fernandez-Lacruz & Bergström, 2015b; Iwarsson Wide, 2009), and they may contain large trees, as found in Paper III (where the mean butt-end diameter was 11 cm). During PL corridor cleaning, the utilization of the forwarder's loading capacity (18 t) never exceeded 25% (corresponding to a full load of 4.5 fresh t). To make the utilization of ST profitable (whether harvested in forest or other land), further development of cutting technology and working methods is needed (Jundén *et al.*, 2013; Sängstuvall *et al.*, 2012; Bergström, 2009).

5.4 Current supply costs

Di Fulvio *et al.* (2016) assessed the amount of LR that could be mobilized at a given supply cost in Europe. The costs of forwarding, chipping and transport are fairly similar for LR and ST (Ghaffariyan *et al.*, 2017; Brunberg, 2013), so they were treated simultaneously in the simulations (Paper IV). Production of LR is integrated with that of roundwood, so its harvest adds no extra cost unless pre-clearing is performed. The main difference in overall supply cost between LR and ST is the extra cost of felling ST, which requires a dedicated operation. The simulations showed that the costs of direct and combined supply via-terminal of chipped LR and ST to a CHP averaged 42.7 € dry t^{-1} (range: 42.2–44.0 € dry t^{-1}) and 47.0 € dry t^{-1} (range: 45.8–48.3 € dry t^{-1}) across scenarios, respectively, (accounting for the cost of chipping, relocations, transportation and eventual terminal cost). These values are within the cost range based on earlier studies (Väätäinen *et al.*, 2017; Belbo & Talbot, 2014; Eriksson *et al.*, 2014b; Brunberg, 2013; Routa *et al.*, 2013). Direct cost comparisons between studies can be difficult and misleading because specific results are only valid for a given set of input data and relationships between model components, which are often unique to the case study. For a tree height of 6 m, the cost of harvest and forwarding of ST during PL corridor clearing (including machine relocations) was 56.6 € dry t^{-1}. In combination with the mean cost of direct supply to the CHP, the overall supply cost (excluding additional costs such as stumpage and administration) would amount to 99.3 € dry^{-1} (for delivery at the industry gate).

The simulation's results (Paper IV) revealed that the mean supply cost of chips was 9% higher on average in the combined SC scenarios than the direct (i.e. just-in-time) SC scenarios. Direct supply was feasible in the low-demand scenarios, in which case using a terminal could be seen as an unnecessary cost. Conversely, at higher levels of demand, the agreed volumes could only be delivered on time when using the terminal (otherwise 8% of the annual demand could not be delivered on time). The terminal helped to secure supply during peak demand and to cope with operational problems in the supply fleet (i.e. untrafficability of forest roads and breakdowns) in cases where direct SCs were unable to meet demand on time. The model applied a mix of push-pull strategies: the inventory levels at the end-user's buffer sent feedback upstream that controlled material flows and could cause the generation of new sites to be paused. The growth of the bioeconomy may spur an increase in the use of terminals as new industries flourish and existing industries increase in capacity, necessitating the construction of safe and efficient SCs.

The simulations (Paper IV) assumed that trucks would relocate between sites until they were fully loaded (thus mixing chips from different sites). However, when forest owners' associations supply chips, material from different sites must be kept distinct to compensate each landowner based on the amount of energy delivered. The results indicated that this alternative approach (in which trucks need not arrive at the CHP fully loaded) increased supply costs by 12%. This illustrates the large cost saving potential in transportation. The integration of scales into the trucks (von Hofsten, 2018) and the use of handheld equipment for MC determination (Fridh *et al.*, 2018) could allow chips from different landowners to be mixed in the future.

The simulations (Paper IV) indicated that integrating chip supply from forests and other land would reduce mean supply costs by 2% and allowed the forwarder-mounted chipper to perform more relocations by itself instead of using a truck with a low-bed trailer. The concept of integration should not be limited to comminution and transport; it is also applicable to upstream operations such as harvesting, forwarding, and managerial work (which generates overhead costs). The cost savings of integration would be greater if flexible harvesting systems were used for diverse operations, i.e. harvesting and forwarding (Joelsson *et al.*, 2016; Bergström & Di Fulvio, 2014b; Di Fulvio & Bergström, 2013; Di Fulvio *et al.*, 2011a). Integration of fuel- and pulpwood harvest could be performed in large areas of BDTF based on their characteristics (Figure 7); in Finland, integration was found to be most cost-efficient for trees of DBH < 15 cm (Petty & Kärhä, 2014). Alternatively, a single assortment could be produced, e.g. bundled whole tree-parts, and the fuel- and pulpwood fractions could be separated at the end-user (Bergström *et al.*, 2016; Jylhä, 2011). Integration could be relevant to private forest owners' associations because contractors work in relatively small sites and must relocate several times per year. Integrating biomass supply from forest, agricultural, and other land could thus reduce supply costs to future BRs (Sultana & Kumar, 2011).

5.5 Potential cost savings by improving supply chains

The practical implementation of the methods and results presented in this thesis and earlier publications could improve operations in the SC and SCM as a whole. Even if an improvement only yields a small percentage decrease in supply cost (per unit of finished product), this can give large savings (increases in profit margins) because of the large volumes of chips traded by chip supplying companies over a year. Improvements leading to cost savings are relevant to industries that rely on continuous material flows (sawmills, pulpmills, future BRs) and those with seasonal demand (CHP and heating plants). In addition to cost savings, adding value (quality improvement) to the supplied feedstock is also important. Considering an ST-derived chip SC (from the standing tree to the end-user), a potential conservative estimation of cost savings along different operations in the SC (relative to a business-as-usual baseline) would be:

- Harvest and forwarding (using boom-corridor thinnings, optimized bundle-harvesters and load-compression devices in the forwarder): 12% (Bergström & Di Fulvio, 2014a).
- Enhanced windrow storage (decreasing MC to 35%): 10% (Eriksson *et al.*, 2014a).
- Enhanced material handling at roadside (minimizing material losses): 4% (Eriksson *et al.*, 2014a).
- More efficient chipping at roadside. Many measures could increase efficiency (Eliasson, 2016); a good example is replacing chipper knives before they become too blunt: ~5% (Eliasson *et al.*, 2011).
- Higher supply integration between forest and other land (only for comminution and transport): 2% (Paper IV).
- Higher efficiency of truck transportation (ensuring full truckloads): 12% (Paper IV).
- Optimising transportation and time of delivery, aggregating different assortments, and collaboration: 22% (Flisberg *et al.*, 2015).

The above estimates show that there is the potential for large cost savings along the whole SC. Further cost savings of 10% could be also achieved, e.g. by using

74-ton chip-trucks (Enström, 2016). Such savings would reduce the required inputs of work time and fuel as well as the carbon footprint of SC operations. However, further improvements of harvest and comminution operations (technology, working methods) and logistics are needed to realize this cost saving potential, as also highlighted by Röser (2012) and Ranta (2002). Windisch *et al.* (2010) estimated that cost savings of 40% over the SC could be achieved by implementing an SCM tool for forest fuel procurement. Systems for SCM using optimization, information and communication technologies (GIS, GPS, wireless) already exist for roundwood procurement (Svenson, 2017; Dahlin & Fjeld, 2004; Mikkonen, 2004), but they are less well established in the forest fuel business. Systems for on-line measurement of chip quality parameters (Fridh, 2017; Fernandez-Lacruz & Bergström, 2015a) could also improve SCM.

An SCM perspective is needed to avoid sub-optimizing systems (Dahlin & Fjeld, 2004). The truth of this comment was especially apparent in Paper III, which showed that SC activities upstream (harvest and forwarding) were closely interrelated with activities downstream (chipping and transport), and that both affected the quality and production cost of the fuel-chips. Placing windrows closer to the roadside (when forwarding the LR and ST into windrows) would have reduced terrain driving time for the chipper (which always discharged its chip-bin by the roadside) and increased chipper utilization rates, reducing overall supply costs. The placement of windrows far from the roadside appears to have been driven by a lack of space, low-hanging PL conductors, terrain conditions, and deliberate choices probably made to dry the biomass more effectively.

5.6 Current demand, future opportunities and challenges

Despite the large potential of ST in forest (Paper I) and other land (Andersson *et al.*, 2016), and the potential of LR in forest land (Di Fulvio *et al.*, 2016; Routa *et al.*, 2013), only a small part is currently used. High supply costs prevent higher utilization of these biomass resources. In parallel, the availability of cheaper energy feedstocks (bark, sawdust, sub-standard roundwood, demolition waste wood, household waste, etc.) makes it difficult to bring ST and LR to the market cost-competitively. The prices paid for biomass at the gates of industry affect all upstream operations in the SC, determining how far the biomass can be delivered profitably and whether it is profitable to extract biomass at all (Joelsson *et al.*, 2016; Fernandez-Lacruz & Bergström, 2015b). Average prices paid for fuel-chips at the gates of CHP and heating plants decreased by 16%, from 22.3 €/MWh (~108 € dry t^{-1}) in 2011 to 18.8 €/MWh (~91 € dry t^{-1}) in 2017 (Swedish Energy Agency, 2019). End-users' willingness to pay for expensive assortments such as LR, ST and stumps is thus low. Low prices could even cause the disappearance of SCs that took several years to establish, along with "know-how", investments in machinery and jobs in rural areas (Segerstedt, 2016). However, recent signs point to a change in this trend (Melin, 2018).

To reduce the dependence on the ups and downs of the energy market, the use of LR and ST could be increased by creating new sources of demand such as BRs that convert these biomasses into high-value products (Bergström & Matisons, 2014; Karlsson, 2013). It seems the use of LR and ST will be favoured in the near future versus stumps (Väätäinen, 2018), partly because of the comparatively high supply costs of stumps (Brunberg, 2013). However, LR and ST will require new developments to realize their sustainable potential in a cost-competitive way, and to compete with petrol-based feedstocks in refineries.

The willingness of forest owners to mobilize LR and ST will also increase if a sufficiently lucrative market exists. Current forest management practices treat the harvest of ST as a corrective action to create value in a stand (Mellanskog, 2019) rather than an alternative to PCT (Sängstuvall, 2018). However, management regimes could change if the demand for ST increases. Concerns about soil damage, nutrient depletion, and impacts on biodiversity must also be addressed, e.g. by adopting novel methods (Marra *et al.*, 2018). The regular clearing of vegetation during landscape activities is considered beneficial for biodiversity, as many species are dependent on open landscapes, but this depends on how, where and when the clearing takes place (Andersson *et al.*, 2016). The extent of nutrient removal caused by extracting LR and ST will depend on the properties of the stand, making it difficult to draw general conclusions; ash recycling can therefore be recommended (Emilsson, 2006).

European forests have been intensively shaped by humans over the last 5 000–6 000 years following the settlement of the first agricultural societies (Kaplan *et al.*, 2009). During the twentieth century, Europe's forest land area and growing stock has increased markedly (Nabuurs, 2016), due to the practice of sustainable forest management, afforestation, reforestation, and socioeconomic changes that are leading to the abandonment of agricultural land and natural overgrown (McGrath *et al.*, 2015; Terres *et al.*, 2013). Some studies have quantified the conversion of agricultural land into forest land, in Sweden (Kempe & Fridman, 2011), Spain (Delgado Artés, 2015) and the whole of Europe (Fuchs *et al.*, 2015; Fuchs, 2013). In contrast to the situation in Europe, deforestation continues in Latin America, Africa and subtropical Asia, with commercial agriculture being its main driver (Kissinger *et al.*, 2012). Melin (2014) showed that from 1980 to 2010, the total growing forest stock in Europe increased by ~60% (~10 billion m^3). It is therefore reasonable to expect an increase in the volumes and areas covered by dense stands for the foreseeable future, posing new challenges and opportunities for their management.

6 Conclusions

The overall conclusions of this thesis are that:

- There are large amounts of underutilized, residual ST in Sweden, in forest and other lands, that could boost the growth of the bioeconomy.
- It is possible to utilize part of the sustainable potential of ST and LR in a cost-efficient way, but further developments of supply systems (working methods and technology) and forest management (e.g. new silvicultural regimes in which early thinnings are performed instead of PCT), are needed to reduce supply costs and fully utilize their sustainable potential.
- There is room for large cost savings in the SCs of ST and LR if further developments of supply systems are implemented.
- Simulation is a powerful tool for SC engineering, allowing different scenarios to be tested at minimal cost and risk in order to advise decision-makers.

More specific conclusions include:

- Biomass-dense thinning forests (containing ST) constitute a large biomass resource in Sweden (especially in the northernmost part), covering at least 9% (2.1 M ha) of the productive forest land area.
- Large proportions of biomass-dense thinning forests could be thinned with existing technologies and working methods, but further technological developments are needed to increase their cost-competitiveness.
- The use of machines for harvest and extraction of the overgrown vegetation in power line corridors can be a more cost-efficient alternative than motor-manual clearing (if trees are at least 6 m high). Cost-competitive utilization

of residual woody biomass from landscape care operations is therefore possible in stands that have reached a certain tree size.

- Even if it does not provide a direct economic profit per se, the maintenance costs of essential infrastructure (e.g. power lines, roads, railways, etc.) could be partially or fully offset by biomass recovery. For safety reasons, this overgrown biomass must be cleared in any event.
- Fuel-chips from undelimbed ST were of higher quality than those from LR (less ash, fines and oversized fractions) for the end-user considered (direct combustion for heat and power). However, in the growing bioeconomy, quality requirements will differ between end-users.
- The predictive models developed to estimate dry mass contents in windrows containing LR or ST can be used as decision-support tools in logistics planning to size supply fleets and estimate costs. They could also be combined with drying models to provide input to SCM systems.
- Fieldwork and analyses revealed that since upstream and downstream SC operations are closely interconnected, a holistic, SCM approach that considers flows from the harvesting site to the end-user is needed for cost-effective delivery of high-quality residual woody biomass.
- The simulation model indicated that the use of terminals can increase supply costs by 5–11% (when compared to direct supply), but terminals help secure supply during peak demand and cope with operational problems in the supply fleet in cases where direct SCs would be unable to meet demand on time.
- Direct supply of chips to a biorefinery, and combined supply via-terminal to a combined heat and power plant or a biorefinery, can even out contractors' annual workload, enabling more steady annual operation.
- Integrating the supply of residual biomass from forest and other land could reduce supply costs by at least 2%, and mixing chips from different sites until trucks were fully loaded could reduce supply costs by 12%.

This thesis covers the whole SC from the forest and other land to the end-user (Figure 1): Papers I and II describe supply sources, Paper II addresses cutting and extraction, Paper III examines storage, and Paper IV deals with chipping and final transport to the end-user, either directly or via a terminal. Despite the Swedish scope of this work, its conclusions could be valid in other countries or regions facing similar problems, challenges and opportunities. However, to produce meaningful results in other contexts, the methods presented here will have to be tailored to the case at hand, using representative input data for the operational environment. Suitable data sources include:

- Forest inventory data (with an appropriate level of detail and geographical extent).
- Supply systems data (e.g. the available machinery in the case study area, the structure of the wood supply business: current practices, the organization of the SC, and its efficiencies and operational costs).
- Structure of the demand: (e.g. type of consumer of the biomass, required quality and volumes, current market price for the biomass).
- Sustainability and legal constraints (e.g. limitations of the ground's bearing capacity, steepness of terrain, biodiversity considerations, nutrient balances in the stand, and laws regulating forest operations).

7 Future research

Future studies could assess the impact of integrating residual woody biomass supply from forest, agricultural, and other lands on factors such as cost-efficiency, biodiversity, soil damage, nutrient balances, and employment and welfare in rural areas. A potentially interesting issue to study is integrated harvesting using multipurpose machines (e.g. feller-bundlers, harwarders, biomass harvesters) and integrated logistics.

Additional GIS-based analyses could consider demand nodes (e.g. pulpmills, CHP and heating plants, future biorefineries) to estimate transport distances and supply costs of residual biomass on a detailed level. Optimization techniques could be used to determine optimal locations of terminals and conversion facilities, and to identify the optimal area of supply needed to meet a specific, integrated, demand.

Another area in need of further development is the design of decision-support tools based on information systems, simulations, and existing results from research. This could be done by extending systems for SCM of primary forest fuels (as used with roundwood) using input data from, e.g. predictive models of dry mass and moisture content. This could help improve the allocation of supply fleets and improve overall SC efficiency. In general, more development work is needed to translate the results of applied research into practice.

Further research in neighbouring areas could focus on the integration of residual woody biomasses (e.g. LR, ST and stumps) into biorefinery processes.

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Popular science summary

Forestry is regarded as a cornerstone that will enable the transition towards a low-carbon, sustainable and circular biomass-based economy in Europe while safeguarding biodiversity and other ecosystem services. If the bioeconomy develops, there will be an increase in demand for forest biomass for energy and for traditional and new wood-based products (textiles, bioplastics, liquid biofuels, etc.). Consequently, there will be a need to increase the mobilization of underutilized residual woody biomass resources such as logging residues (LR) and small-diameter trees (ST). In addition to the residual biomass in forest land, significant amounts can be found in other land such as overgrown agricultural land, power line corridors, and roadsides. At present, most LR and ST are used to generate renewable heat and electricity, and delimbed ST are used for pulping. Biorefineries could become major consumers of this residual biomass in the near future. However, high supply costs make it difficult for LR and ST to compete with cheaper feedstocks in the market, limiting their utilization. This thesis aimed to measure and analyse characteristics of LR and ST in forest and other land in Sweden, and the efficiency and costs of their supply systems. The results obtained offer useful knowledge for policymakers, researchers, and industrial developers and practitioners that could improve LR and ST supply chains, increasing their ability to compete with cheaper feedstocks and their utilization. The main findings of this thesis were:

1 *There are large amounts of underutilized residual ST in Sweden which can boost the growth of the bioeconomy. Dense thinning forests cover 2.1 million ha (much of which is in northern Sweden), or around 9% of Sweden's productive forest land area. However, further developments of supply systems (technologies and working methods) are needed to realize their sustainable potential at a competitive cost.*

2 *Depending on the tree size and market conditions (the price paid for the biomass and distance to the plant), it could be economically viable to use forest machines to harvest and extract overgrown vegetation in power line corridors and use it later for generating heat and power (instead of current clearing practices with a brush saw and leaving the trees to rot in situ). Even if it doesn't provide a direct economic profit per se, the extraction and sale of this biomass could partial- or totally offset maintenance costs of power lines and other infrastructure (roads, railways, etc.). For safety reasons, these trees must be cleared no matter how they are subsequently used.*

3 *ST-derived fuel-chips were of higher quality than those from LR, having less ash, fines and oversized fractions for renewable heat and power generation. However, holistic management of the supply chain, from the site to the end-user, is crucial for cost-effective delivery of high-quality chips.*

4 *We can predict the dry weight of windrows containing LR and ST by taking simple measurements (height, length and width) in the forest and using predictive models. These models could be used to improve the management of operations and logistics.*

5 *Using terminals increases supply costs (when compared to direct supply), but terminals help secure supply during peak demand and cope with problems in the supply fleet (machine breakdowns and extreme weather), that would prevent direct supply chains from meeting demand on time. The cost of not meeting demand on time can be difficult to assess in the real-world, so terminals reduce risk.*

6 *There is room for large cost savings along the whole supply chain of ST and LR, when compared to current practices. These monetary savings could also reduce CO_2 emissions associated with production processes in the chain. However, cost savings will only be realized if technology, working methods, supply systems and management of the supply chain are notably improved.*

7 *Simulation is a tool for supply chain engineering that enables testing in different scenarios, allowing decision makers to obtain good advice at minimal cost and risk (compared to real-world experiments).*

Residual woody biomass such as ST and LR is an indigenous resource that can reduce our dependence on fossil fuels and enhance energy security, providing a benefit in the fight against climate change. The sustainable use of ST and LR from the forest and other lands represents an opportunity to maintain and create new jobs in rural areas, at the same time, increasing the resilience of forests against disturbances such as wildfires and insect pests.

Populärvetenskaplig sammanfattning

Skogsbruk är en hörnsten för att möjliggöra övergången till en koldioxidsnål, hållbar och cirkulär biobaserad ekonomi i Europa. Detta samtidigt som man säkerställer bevarandet av den biologiska mångfalden och andra ekosystemstjänster. Om bioekonomin fortsätter att växa, förväntas efterfrågan på skoglig biomassa för energi samt traditionella och nya träbaserade produkter att öka (textilier, bioplaster, flytande biodrivmedel, osv.). Det medför i sin tur att försörjningskedjor för underutnyttjade biomassaresurser som grot (grenar och toppar) och klenträd, utvecklas och effektiviseras. Betydande mängder av grot och klenträd kan även skördas från andra marker än skogsmark som igenväxta jordbruksmarker, kraftledningsgator, vägkanter, osv. Höga kostnader för skörd och transport av dessa råvaror gör det dock svårt att etablera dem på marknaden till ett konkurrenskraftigt pris (jämfört med andra billiga och/eller icke förnybara råvaror), vilket begränsar dess utnyttjande. Att styra försörjningskedjan av grot och klenträd är komplext då den består av sammankopplade operationer (skörd, terrängtransport, flisning, vägtransport) utförda av flera entreprenörer. Syftet med denna avhandling var därför att analysera effektivitet och kostnader på försörjningssystem för grot och klenträd till dagens och morgondagens industrier i Sverige. De viktigaste resultaten av denna avhandling är följande:

1 *Det finns stora mängder av outnyttjade resurser av klenträd i Sverige, som kan utgöra en råvara till nya bioraffinaderier. Täta (och ofta unga) gallringsskogar täcker 2.1 million hektar (65% av dessa är belägna i Norrland), vilket motsvarar ungefär 9% av den total produktiva skogsmarken i Sverige.*

2 *Beroende på trädstorleken och marknadspris som betalas för biomassan, kan det löna sig att använda skogsmaskiner för att ta tillvara klenträd från igenväxta kraftledningsgator och producera förnybar bioenergi (värme och el). Nuvarande praxis är att man röjer motormanuellt med en röjsåg och*

lämnar klenträd kvar i beståndet. Tillvaratagandet av dessa klenträd kan således minska underhållningskostnaden för viktig infrastruktur (kraftledningar, vägar, järnvägar, osv.). Även om en skörd inte ger en nettoinkomst för markägaren, kan kostnaden understiga en röjningskostnad. På grund av säkerhetsskäl måste dessa klenträd oavsett röjas bort!

3 *Bränsleflis från klenträd har högre kvalité än bränsleflis från grot (mindre mängd aska och mer homogen flisstorlek) för generering av förnybar bioenergi. Resultaten visar att kommunikation mellan de olika entreprenörerna i varje led av försörjningskedjan är avgörande för att kunna leverera bränsleflis av hög kvalité för ett lågt pris.*

4 *Vi kan förutse torrvikt på vältor som innehåller oflisad grot och klenträd genom att med enkla mätningar (höjd, längd och bredd), mäta vältors volym i fält och sedan prediktera torrvikten med framtagna modeller. Dessa modeller kan användas i praktiken för att förbättra logistiken (till exempel styra flishuggar och transporter) som i sin tur medför en effektivisering av leveranser.*

5 *Trots att användandet av terminaler i försörjningskedjan höjer försörjningskostnaderna till industrierna så medför det att man kan säkerställa försörjning när efterfrågan är som högst och när det finns stor risk för störningar i flödet (till exempel under vårförfallet) eller vid maskinavbrott.*

6 *Det finns utrymme för kostnadsbesparingar längs hela försörjningskedjan av grot och klenträd. Teknik, arbetsmetoder och system för de olika delarna i försörjningskedjan behöver dock utvecklas ytterligare för att kunna möjliggöra betydande besparingar och utnyttja den hållbara potentialen av grot och klenträd.*

7 *Simulering av försörjningskedjor möjliggör att man kan svara på olika frågor och rådgöra beslutsfattare till en mindre kostnad och risk än att genomföra verkliga tester.*

Detta avhandlingsarbete utgör ett underlag för vidareutveckling av forskningsmetoder, effektivisering av försörjningskedjor, politiska beslut rörande bioekonomi, osv. I slutändan kan detta medföra ett ökat utnyttjande av hållbar biomassa från det svenska skogsbruket samt annan produktionsmark. Grot och klenträd representerar en inhemsk resurs som kan minska vårt beroende av fossila bränslen och öka energisäkerheten, vilket är positivt i kampen mot klimatförändringen. Den hållbara användningen av grot och klenträd är också ett sätt att behålla och skapa nya arbetstillfällen på landsbygden och öka skogarnas motståndskraft mot till exempel skogsbränder och skadegörare.

Resumen de divulgación científica

La silvicultura se considera una piedra angular para hacer posible la transición a una economía circular basada en la biomasa, baja en carbono y sostenible en Europa (al mismo tiempo, salvaguardando la biodiversidad y otros servicios ambientales). Si el desarrollo de la bioeconomía continúa, se prevé un incremento de la demanda de biomasa forestal para energía y productos de madera convencionales e innovadores (textiles, bioplásticos, biocombustibles líquidos, etc.). A su vez, será necesario incrementar el aprovechamiento de la biomasa forestal residual, como por ejemplo restos de corta (RC) y árboles de pequeñas dimensiones (AP). Además de los RC y AP en montes, existen cantidades significativas en terrenos agrícolas abandonados, pasillos de líneas eléctricas (franjas de servidumbre), cunetas, etc. No obstante, los elevados costes de suministro hacen difícil llevar RC y AP al mercado a un precio competitivo (comparado con otros recursos más baratos y/o no renovables) y limitan un mayor aprovechamiento. La gestión de la cadena de suministro de RC y AP es compleja, ya que se compone de múltiples actividades relacionadas entre sí (corta, desembosque y apilado, astillado, transporte a planta, etc.) y llevadas a cabo por diferentes maquinistas. El objetivo de esta tesis fue la medición y el análisis de características de RC y AP en Suecia, los rendimientos y costes de sus sistemas aprovechamiento, considerando las industrias actuales (plantas de cogeneración, plantas de celulosa) y futuras (biorefinerías) de esta biomasa residual. Los principales resultados fueron los siguientes:

1 *Existen grandes cantidades infrautilizadas de AP en Suecia que podrían ser la materia prima para futuras biorefinerías. Montes densos (y a menudo jóvenes) con necesidad de claras cubren 2.1 millones de hectáreas, lo que equivale aproximadamente al 9% de la superficie total de monte productivo.*

2 *Dependiendo del tamaño del árbol y del precio que el mercado paga por la biomasa, puede ser rentable el uso de maquinaria forestal para la limpieza de AP en pasillos de líneas eléctricas y su aprovechamiento para generar*

bioenergía (calor y electricidad). En la actualidad, la práctica más común consiste en el desbrozado motorizado con desbrozadoras y su abandono en el terreno. Su aprovechamiento podría reducir los costes de mantenimiento de infraestructura esencial (líneas eléctricas, vías de tren, carreteras, etc.). Por motivos de seguridad, esta biomasa debe de ser cortada igualmente.

3 *Las astillas de AP tienen una calidad superior a las astillas de RC, presentando un menor contenido en cenizas y tamaño más homogéneo para generar bioenergía. Buena comunicación y colaboración entre los diferentes maquinistas a lo largo de toda la cadena de suministro es fundamental para poder abastecer el mercado con astillas de alta calidad a un precio bajo.*

4 *Podemos predecir el peso seco en pilas de RC y AP (no astilladas) mediante la toma de medidas (altura, longitud y anchura) en campo y posteriormente, usando los modelos predictivos presentados en la tesis. El uso de estos modelos en la práctica puede mejorar la logística (planificación de la ruta de las astilladoras, transportes) e incrementar la eficiencia del suministro.*

5 *El uso de terminales logísticas incrementa el coste de suministro de biomasa a la industria, pero su uso contribuye a asegurar el suministro a tiempo cuando la demanda es máxima y hay riesgo de problemas (dificultad para transitar pistas forestales debido a inclemencias meteorológicas o averías).*

6 *Existen oportunidades para reducir costos a lo largo de la cadena de suministro de RC y AP. No obstante, para hacer posible estos ahorros y aprovechar su potencial sostenible, será necesario el desarrollo de la tecnología, los sistemas de suministro y la mejora de los métodos de trabajo.*

7 *El uso de modelos de simulación para cadenas de suministro de biomasa puede dar respuesta a multitud de preguntas y aconsejar la toma de decisiones, a un menor coste y riesgo que llevar a cabo experimentos reales.*

Esta tesis constituye una base para apoyar la toma de decisiones políticas sobre bioeconomía y mejorar la eficiencia de las cadenas de suministro de RC y AP, en último término, contribuyendo a incrementar su uso sostenible. La biomasa forestal residual representa un recurso local, cuyo uso disminuye nuestra dependencia de los combustibles fósiles e incrementa nuestra seguridad energética, lo cual es positivo en la lucha contra el cambio climático (la madera es un recurso renovable). La gestión forestal sostenible, activa, mediante la silvicultura (como se realiza en Europa y otras regiones del mundo), proporciona un mayor beneficio al clima que usar los bosques únicamente como sumideros de carbono. Además, su aprovechamiento sostenible contribuye al mantenimiento y creación de puestos de trabajo en zonas rurales e incrementa la resistencia de los montes ante perturbaciones como incendios forestales y plagas.

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