Improved harvesting technology for thinning of small diameter stands

Impact on forest management and national supply of forest biomass

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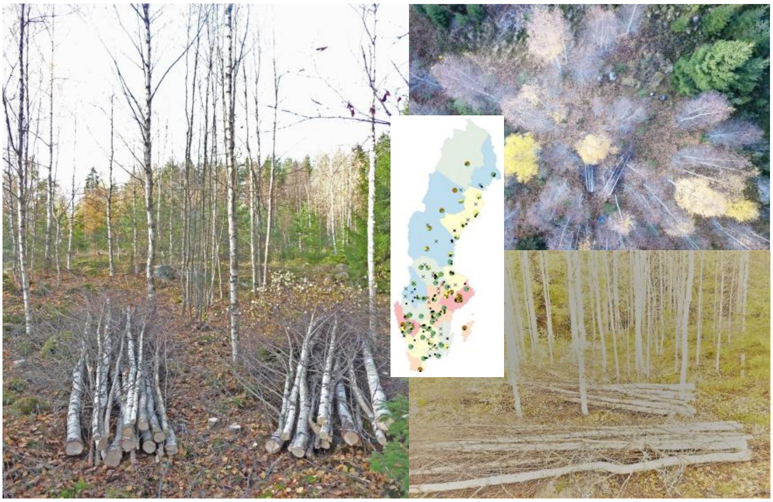

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Cover: Two 2×10 m^2 harvest corridors in a V-shaped pattern.
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Abstract

Forest biomass is used as feedstock for forest products as well as for bioenergy. The current Swedish roundwood utilization is near the sustainable maximum. This implies that increased forest biomass consumption in Sweden must utilize additional parts of the trees already harvested, and/or that small trees not utilized today must be harvested, with current or novel methods, techniques and practices. This thesis explores thinning of small diameter forest stands with the removal of thinned trees including stems, tops, branches and needles – biomass thinning (BT) in Sweden. Major advances in BT were witnessed in the Nordic countries between the years 2005-2010. Harvesting in a geometrical pattern (boom-corridors), with a conventional harvester head or a specialized area-based felling device, was defined and conceptually evaluated. These evaluations showed potential BT harvester productivity gains, but the lack of generic productivity models for BT machines prevented further analyses. The overall objective of this thesis is to analyse the impact of such new BT harvesting technology with regards to recovery costs, forest management and national forest biomass supply.

Many of the scenarios analysed in this thesis include non-existing phenomena, a fact being one of the challenges for providing reliable BT assessments. A harvester simulation model was used to quantify BT harvester productivity benefits from geometrical harvest patterns and area-based felling devices. Deductive modelling boosted the conclusions that could be drawn from a limited and heterogeneous set of empirical observations on BT haulage with medium-sized forwarders. Derived generic BT harvester and forwarder productivity functions were implemented in the Heureka decision support system and thus available in the subsequent SweFor partial equilibrium model, which was examined for influences of assumptions regarding land owner behaviour and saw log supply models. Finally, SweFor was employed to quantify the forest impact, and national potential supply, of forest biomass from BT. Given the current energy market conditions, BT was the preferred management regime on about 15% of the managed Swedish forest area, and provided 15% of the total supply to heat plants. Market limitations aside, BT could increase with more than 300%, which could be seen as a potential for increased forest biomass utilization for other products.

In conclusion, this thesis demonstrates methods to address forest operations and management research questions including non-existing phenomena, and confirms BT as a viable major future option in Swedish forestry.

Keywords: Thinning, biomass, harvester, forwarder, simulation, deductive framework, forest planning, forest impact, sector model, partial equilibrium model.

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Sammanfattning

Biomassa från skogen används som råvara för såväl skogsprodukter (papper, massa, sågade trävaror) som bioenergi. Den svenska avverkningen av rundvirke ligger nära den högsta hållbara nivån. Detta innebär att ökat utnyttjande av biomassa från den svenska skogen till del måste baseras på andra delar av de träd som redan avverkas, och/eller småträd som inte tillvaratas idag, med hjälp av befintlig eller ny drivningsteknik. Denna avhandling undersöker gallring av klen skog med tillvaratagande av stamved, toppar, grenar samt barr och blad – biomassagallring – under svenska förhållanden. Stora utvecklingssteg togs inom biomassagallring i de nordiska länderna under åren 2005-2010. Gallring i ett geometriskt mönster (krankorridorer) som ett alternativ till selektiv gallring, med ett konventionellt skördaraggregat eller en specialbyggd arealbaserad fällningsutrustning, definierades och utvärderades konceptuellt. Utvärderingen visade på potentiella produktivitetsökningar i biomassagallring, men var för begränsad för att tjäna som underlag för mer generella slutsatser. Det övergripande syftet med denna avhandling är att analysera effekterna av nya tekniker och metoder för biomassagallring, med avseende på drivningskostnad, skogsskötsel och nationell biomassaförsörjning från den svenska skogen.

Flera av de analyserade scenarierna i denna avhandling innehåller icke-existerande fenomen (t.ex. den arealbaserade fällningsutrustningen), vilket utgör en extra utmaning i utvärderingen av biomassagallring. Skördarproduktivitet i biomassagallring med bl.a. geometrisk skörd och arealbaserad fällningsutrustning utvärderades med en simuleringsmodell. Skotarproduktivitet i biomassagallring kunde skattas med högre noggrannhet ur ett begränsat datamaterial tack vare deduktiv modellering. Funktioner för skattning av produktivitet i biomassagallring implementerades sedan i beslutsstödssystemet Heureka, för vidare användning i SweFor, en sektorsmodell över det svenska skogsbruket och den svenska skogsindustrin. SweFor kontrollerades med avseende på markägarbeteende vid föryngringsavverkning samt modellering av sågtimmerförsörjning. Därefter beräknades de skogliga och energiförsörjningsmässiga konsekvenserna av biomassagallring med nya tekniker och metoder. Med dagens marknadsförutsättningar blev biomassagallring optimal skötselregim på 15% av den brukade skogsmarksarealen och stod för 15% av skoglig biomassaförsörjning till värmeverken. Med obegränsad efterfrågan på skoglig biomassa, givet dagens prisnivåer, ökade den nyttjande volymen från biomassagallring med 300%. Denna ökning kan ses som en potential för ökad användning av skoglig biomassa till nya industrier eller produkter.

Sammanfattningsvis visar denna avhandling exempel på metoder för att analysera skogliga frågeställningar som inkluderar icke-existerande fenomen, och indikerar att biomassagallring kan få ett stort genomslag i svenskt skogsbruk.

Nyckelord: Gallring, biomassa, skördare, skotare, simulering, deduktivt ramverk, skoglig planering, skogliga konsekvensanalyser, sektorsmodell, partiell jämviktsmodell.

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Dedication

To my family.

A work task will occupy the amount of time allotted to it.
- Freely after C. Northcote Parkinson

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 Sängstuvall, L.*, Bergström, D., Lämås, T. & Nordfjell, T. (2012). Simulation of harvester productivity in selective and boom-corridor thinning of young forests. *Scandinavian Journal of Forest Research,* 27(1), pp. 56-73.

II Sängstuvall, L.*, Lämås, T. & Nordfjell, T. (2014). Application of a primarily deductive framework describing time consumption for hauling of logs to road-side. *Annals of Operations Research* 219(1), pp. 477-489.

III Eriksson, L.O.* & Sängstuvall, L. Sensitivity of a Swedish forest sector model to assumptions regarding forest owner behaviour and saw log supply. Submitted manuscript.

IV Sängstuvall, L.*, Lämås, T., & Eriksson, L.O. Analyzing bioenergy from young dense stands using a forest sector partial equilibrium model – optimal forest management and Swedish wood market consequences. Manuscript.

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The contribution of Lars Sängstuvall to the papers included in this thesis was as follows:

I Planned the study together with the co-authors. Responsible for major parts of the model development, simulations and analyses and significantly contributed to the writing of the manuscript.

II Elaborated the initial idea and planned the study. Responsible for the modelling, calculations and analyses, as well as writing major parts of the manuscript.

III Planned the study together with the co-author. Responsible for major parts of indata preparation, essential parts of the model structure, and minor parts of the model implementation. Contributed to the analysis as well as writing of the manuscript.

IV Planned the study in conjunction with the co-authors. Responsible for major parts of indata preparation, and parts of the model implementation. Conducted major parts of the analysis and significantly contributed to the writing of the manuscript.

Abbreviations

The following abbreviations are used throughout this thesis:

BT - *biomass thinning*
ContC$_2$ - *area-based, continuous felling, multi-tree handling felling mode, working in two meter wide boom corridors*
DF - *deductive framework*
DSS - *decision support system*
NFI - *national forest inventory*
NoBT - *ordinary forest management with no BT*
NPS - *net present surplus*
PCT - *pre-commercial thinning*
PEM - *partial equilibrium model*
TC - *time consumption*
TMC$_2$ - *tree-based multi-tree handling felling mode, working in two meter wide boom corridors*

1 Introduction

Sweden is a country rich in forests, which constitute a renewable resource that has been important in the provision of goods and services to society and individuals during the past, present and presumably future. Whereas the demand for forest goods and services in the past often stemmed from its superior usability and/or economic advantages, the present and future demand also includes values like sustainability and climate mitigation. Forest biomass used for e.g. energy can be seen as a contributor to climate change mitigation because of its potential to replace fossil fuels and application in an expanding range of products, with varying climate benefits for different products and supply chains, as well as different perspectives applied in the assessment (Berndes et al., 2016). Intensive forest management combined with subsequent utilization of forest products as a substitute to other materials in construction, packaging and as an energy feedstock has been proposed to be a more efficient strategy for climate change mitigation than forest conservation and storing CO_2 in the growing forest (Gustavsson et al., 2017). Furthermore, the applications of forest biomass in new kinds of products continuously expands (Demirbas, 2009; BillerudKorsnäs, 2018; Domsjö Fabriker, 2018). The current Swedish utilization of forest biomass in the form of roundwood – saw logs and pulpwood – is near the sustainable maximum (Swedish Forest Agency, 2015), and so increases in forest biomass utilization must come from other parts of the tree. There are many methods for extracting forest biomass, including among others the thinning of forest stands with the removal of thinned trees including stems, tops, branches and needles or leaves, and utilizing trees of smaller diameter than what is commonly used for pulpwood. This thesis explores some possibilities for such forest biomass thinning (BT) in Sweden.

1.1 Forest biomass utilization in Sweden – the current situation

The Swedish forest area amounts to 28.0 million hectares (ha), or about 69 % of the land area, of which 23.2 million ha is productive forest land with the potential to produce more than 1 m^3ob ha^{-1} yr^{-1}. The annual net increment is estimated at 103 million m^3ob (stem volume over bark from stump to tip), which includes an estimated climate change effect of 4 million m^3ob. Protected land in formal reserves, areas that have been voluntary set aside and retained trees and zones within managed areas make up 3.9 million ha of productive forest land, leaving 19.3 million ha productive forest land available for forestry. The annual net increment of this forest land has been estimated at 91 million m^3ob (Swedish Forest Agency, 2015). The annual felling amounts to around 90 million m^3ob, or more than 70 million m^3ub (stem volume under bark, not including the top), out of which 37 million m^3ub is used as saw logs, 28 million m^3ub is used as pulpwood and 7 million m^3ub is used as fuelwood (firewood and roundwood not fulfilling the quality for pulpwood).

The current Swedish primary use of forest biomass for uses other than sawnwood, pulp for paper, or energy amounts to less than 2 million m^3ub yr^{-1} (Swedish Forest Agency, 2014; Domsjö Fabriker, 2018) with a large proportion of this biomass transformed into other solid materials, such as viscose fabric or boards, as end-products. A majority of the wood is processed domestically, with the Swedish forest industry producing about 18 million m^3 sawnwood and 12 million tonnes of pulp, out of which about 70% and 80% are exported, respectively (Swedish Forest Agency, 2014; Swedish Forest Industries Federation, 2017). Sweden has less than 1% of the world's forests, but about 5% of the global annual forest industry production (sawnwood and pulp), and is among the world's four largest exporters of forest products (Swedish Forest Agency, 2014; Swedish Forest Industries Federation, 2017).

The total Swedish energy supply amounted to 555 TWh in 2014. Renewable energy sources accounted for 292 TWh (53%), with the combustion of biofuels contributing 130 TWh (23%) (Swedish Energy Agency, 2018). In 2014, 19% (106 TWh) of Sweden's energy supply could be traced to biomass from the forest. Forest biomass for energy supply may be in the form of primary or secondary fuels; primary wood fuels are harvested from the forest with the sole purpose to serve as an energy feedstock, whereas secondary fuels are by-products from sawmill or pulp industries. When we look at energy supply from forest biomass in 2014, approximately 54 TWh (10% of the total supply) were supplied from processed wood fuels or by-products from the forest industry (e.g. black liquor; the pulp and paper industry alone uses 50 of those TWh), while the remaining 52 TWh (9.4% of the total supply) were produced from unprocessed wood fuels. When the latter supply is studied in more detail, 25 TWh comes from unprocessed by-products such as bark and saw dust, and 27 TWh (4.9% of the total supply) – corresponding to 13.5% of all utilized forest stem biomass – were produced from primary wood fuels, with branches and tops contributing 10.5 TWh (1.9% of the total supply), tree sections (from small-diameter trees as well as long tops) 1.5 TWh (0.28%) and stumps 0.26 TWh (0.05%) (Swedish Energy Agency, 2015; Swedish Energy Agency, 2018). The 106 TWh that was produced from forest biomass roughly corresponds to 40-50 million m^3ub of stemwood, or 60-70% of the entire Swedish forest stemwood biomass utilization. This comparison does not consider, e.g., the import of roundwood and/or wood fuels, but merely aims to show how much forest biomass already contributes to the energy supply today. The price at heat plant for wood chips from forest biomass has ranged from 100-140 SEK × MWh^{-1} over the years 2000 to 2006, then risen to 200-220 SEK × MWh^{-1} over the years 2010-2013, and is at present established at around 180-200 SEK × MWh^{-1} (Swedish Energy Agency, 2017).

1.2 Forest biomass harvesting alternatives

Ghaffariyan et al. (2017) performed a comprehensive international review of primary forest biomass supply systems, which revealed major variations in forest biomass supply costs across assortments, technologies and countries. The main source of primary forest biomass fuel in Sweden is logging residues from final fellings (Swedish Energy Agency, 2015), and this source has been fairly well utilized during past years. There is, of course, some regional and periodical variation due to changes in total demand (Swedish Forest Agency, 2017), as well as competition from other, non-forest energy sources (Swedish Energy Agency, 2015). Therefore, other sources must be better utilized if the supply of primary forest biomass fuel is to increase (Routa et al., 2013). Harvesting stumps in final fellings could contribute a significant amount of primary forest biomass fuel in Sweden (Swedish Forest Agency, 2015b). However, this approach is impeded by higher costs (Berg, 2014; Lundmark, et al., 2015; Athanassiadis & Nordfjell, 2017), higher levels of contaminants than other sources of forest biomass (Anerud, 2012) and a disputed ecological impact (Swedish Forest Agency, 2009; Melin, 2014). Hence, the current stump harvesting activity is in practice non-existing in Sweden.

Harvesting of small-diameter trees is another potential source of primary woody biomass fuel. Productivity for harvesting stemwood from larger trees with the cut-to-length method is well explored under Nordic conditions (e.g. (Brunberg, 1997; Nurminen et al., 2006)), and described in generic productivity functions. Stemwood of sufficient dimensions and tree species is usually used in the pulp or sawmill industries, but with increasing interest from the energy sector, stemwood may be more profitable to sell as fuelwood than pulpwood (Swedish Energy Agency, 2017; Swedish Forest Agency, 2016). When harvesting a tree for energy production purposes, an integrated harvesting operation also makes it possible to utilize the tops, branches and needles of the tree. This significantly increases the utilized volume from the harvested trees, and most so in young dense stands in which trees are small of diameter and a relatively large proportion of the stemwood biomass falls short of the minimum diameter for pulpwood (di Fulvio et al., 2011). For example, utilizing all aboveground biomass in 10.4 and 13.9 cm DBH stands increased the biomass output with factors 3 and 1.5, respectively, compared to the output of pulpwood from the same stands in a study by di Fulvio et al. (2011).

Major advances in BT systems and techniques and, notably, an expansion of the scope where BT is economically viable in the short term, were witnessed in the Nordic countries between the years 2005-2010 (Bergström et al., 2007; Jylhä & Laitila, 2007; Laitila et al., 2007; Iwarsson Wide & Belbo, 2009; Bergström et al., 2010a,b; Oikari et al., 2010; di Fulvio et al., 2011). Among others, harvesting in a geometrical pattern – as exemplified in Figure 1 – with either a conventional multiple-tree handling harvester head or an idea-based BT harvester head with an area-based felling device was defined and conceptually evaluated by Bergström et al. (2007). This initial evaluation showed potential BT harvester productivity gains, which eventually led to the development of a prototype harvester head with continuous accumulation of small-diameter stems (Forsberg & Wennberg, 2011). This course of events illustrates the early stages of a business innovation process quite well; Ideation, Concept design, and Prototyping (Geissdoerfer et al., 2016). The drivers behind such business innovation processes in forest operations may however differ: Lindroos et al. (2017) described the (re-)emergence of the interest for forest biomass as energy feedstock as an example of how *new products* can act as a driver of advances in mechanized timber harvesting. They also mention the opposite; when the cost for an established system increases and *new technology* is needed to maintain competitiveness (also confer Samset's Law of discontinuous evolution (1966)). BT has elements of both those perspectives.

Returning to the business innovation perspective, the subsequent steps are *detailed design, implementation* and *adjustments & diversification* (Geissdoerfer et al., 2016), with iterations and backtracking across the stages a natural part of the business innovation process. It is important to remember that this is a resource intensive process, as the diverse tasks of each stage require time and money. Thus, the product development process will be more efficient if the duration of a step can be accelerated. In the case of the area-based felling device, further prototyping was planned but has yet to be carried out. This is partly due to a decrease in primary forest fuel demand, i.e. a market change – which essentially is addressed in the implementation stage. The Swedish energy market change has decreased the in utilization of primary forest biomass from e.g. logging residues (Swedish Forest Agency, 2017), and a materially reduced BT activity in Sweden. A parallel decrease in the further research and development of forest biomass harvesting alternatives as energy feedstock took place before BT – even with a common tree-based felling device – had matured into an established forest management action. Thus, no generic BT productivity estimates were elaborated following the aforementioned early exploring studies. One of the closest calls were however Laitila et al.'s (2007) study of forwarding of whole-trees, which covered a great variation in stand and operations characteristics, but was limited in terms of machine size – and also brand.

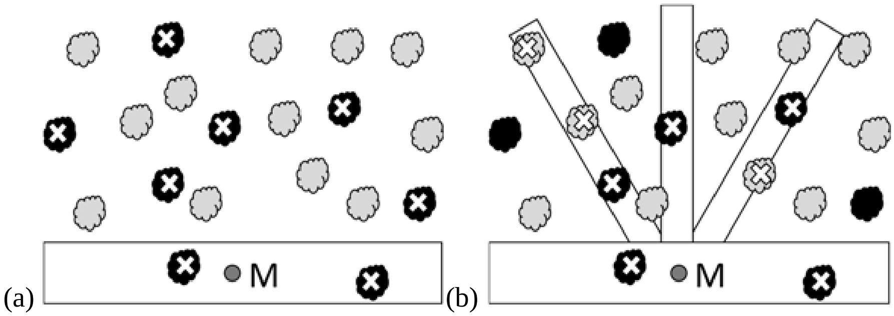


Figure 1. Examples of (a) selective harvest and (b) geometrical harvest patterns in boom corridors (cf. Bergström et al. 2007), in identical stands. The machine-center position is indicated by M, Xs indicate trees that will be actually cut, and black shading indicates trees selected for cutting under the selective system. The horizontal boxes indicate the strip road whereas the lines radiating from the strip road represent imaginary boom-corridors.

Recent long-term field evaluations have indicated that geometrical/corridor pre-commercial thinning (PCT, i.e. no commercial volumes are extracted during the treatment, also known as cleaning) or thinning do not produce any noticeable differences in volume growth or standing volume compared to selective PCT or thinning (Karlsson et al., 2013). In contrast, a review by Egnell (2017) found a short- and medium-term volume growth reduction related to the removal of branches, tops and needles in addition to stemwood removal during thinning. The decrease is of the magnitude of 5%, but varies across tree species, site quality and latitude. These dynamics imply that long-term evaluations should provide the most reliable final conclusions also with regards to this nutrient aspect. Egnell’s review, along with others covering biodiversity, soil and water quality, and heavy metal availability, served as the basis for a workshop series focusing on sustainable biomass harvest levels in Sweden (de Jong et al., 2017).

PCT redistributes the growth potential of a forest stand to fewer stems (Pettersson, 1993). This allows the forest manager to influence the remaining stand by selecting which trees to thin and which trees to leave. As a result, the individual retained trees will have a higher diameter increment (Varmola & Salminen, 2004), leading to higher wood prices and lower cutting costs per volume unit (Nurminen et al., 2006). Even so, PCT is often neglected in Swedish forestry (Swedish Forest Agency, 2018). This is probably because PCT is costly from the short-term perspective, and because many forest owners have other goals and strategies than the maximization of economic returns, as shown by Eggers et al. (2014). Hence the Swedish forests hold large areas of young forests where no PCT has been performed in due time according to current forest management guidelines, and a reduction of number of stems would favor e.g. the net present economic value (NPV) of the forestry (Hyytiäinen et al., 2005; Fernandez-Lacruz et al., 2015): these forests currently encompass 2.1 – 9.8 million ha of productive forest land (Fernandez-Lacruz et al., 2015), depending on the criteria applied in the definition, and the application of BT to these areas could provide a significant source of primary forest biomass.

1.3 Potential for utilization of forest biomass in Sweden

The current Swedish national estimate of forest biomass potential (including logging residues in final felling, stumps and biomass from thinning stands) is part of the national forest impact analyses, named SKA 15 (verbatim Skogliga KonsekvensAnalyser – Forest Consequence Analyses), and last performed in 2015 (Swedish Forest Agency, 2015b). However, SKA 15 only considered the biologically feasible harvesting of roundwood (with bioenergy assortments obtained as a by-product wherever ecologically suited), and not the economically valid deposition of the harvested wood, or the existence of competing sources or consumers of wood. Roundwood has been addressed in SKA 15 by indirectly assuming that future demand will equal future supply, along with an appended consequence analysis that bases future supply on the current demand structure (Swedish Forest Agency, 2015a). However, this approach would be inappropriate for fractions that currently have a low market share, such as BT volumes.

In addition to SKA 15, several other Swedish regional and national level studies on forest biomass potential have been conducted, most of which have been reviewed by Wetterlund et al. (2013). A number of these studies include biomass from thinnings in the form of harvesting residues that are separated from harvested roundwood (Lundmark et al., 2015; Swedish Forest Agency, 2015). Only a handful of forest biomass potential studies include BT as an integrated operation (Nordfjell et al., 2008; Fernandez-Lacruz et al., 2015) and a majority apply a simple statistical analysis approach (cf. (Dees & Rettenmaier, 2009)). A selection of such studies is presented and categorized in Table 1. For the Swedish studies, the short-term potential ranges from about 2 TWh × yr^{-1}, when considering market aspects, to a span of about 10 to 25 (mean 17) TWh × yr^{-1}, market aspects aside.

Allocating the entire sustainable growth of stemwood, branches, tops and stumps in Sweden to energy generation would correspond to about 300 TWh (Swedish Forest Agency, 2015b), or more than 50% of Sweden's annual energy supply. However, a number of issues limit such a radical utilization. **Techno-economical limitations** such as production rates and transportation costs are typically addressed using rules-of-thumb or through limited system analyses, cf. Fernandez-Lacruz et al. (2015). The **competing internal demand for forest biomass as feedstock for industry products** like sawnwood and pulp, which offer a higher price than energy producers, is most often handled with assumptions of static and fixed roundwood demand levels, with the left-overs available as an energy feedstock (Swedish Forest Agency, 2015b).The **external competition with other, non-forest renewable energy sources** is sensitive not only to market forces but also policy decisions on the super-national, national and/or sub-national levels. Finally, if all previous issues do not constrain biomass harvesting at a particular site, **ecological constraints** to the harvesting of tops, branches and stumps that are related to negative effects on soil nutrient status and/or biological diversity, are largely regulated via a common practice for where and when tops, branches and stumps may be harvested in connection to ordinary stemwood harvest (Swedish Forest Agency, 2008). However, certain researchers have suggested that the current recommendations may need updating (de Jong, et al., 2017). These issues are explicated and addressed to various extents within this thesis.

Table 1. *Review summary of recent BT potential assessment studies and a selection of forest sector models. A broader review of European biomass supply studies was conducted by Bostedt et al. (2016), whereas Latta et al. (2013) reviewed forestry PEMs in detail.*

								BT results, TWh × yr^{-1}	
Authors	Spatial scope	Temporal scope	Initiation of forest management activities	Forest representation	Techno-economical detailedness	Internal market model	Ecological perspective	Short-term[a]	Long-term
Nordfjell et al. 2008	Sweden	Snapshot	External	Detailed	Basic	-	-	23.85	-
Trømborg & Solberg, 2010	Norway	Long-term	External	Basic	Basic	Detailed	Basic (indirect)	(BT not studied)	
Kong et al. 2011	Mid-Sweden	Short-term	External	Detailed	Basic	Detailed	Basic (indirect)	(BT not studied)	
Carlsson 2012	Sweden	Snapshot	External	Basic	Detailed	Detailed	Basic (indirect)	(BT not studied)	
Eriksson et al. 2013, BAS	Sweden	Long-term	Internal	Detailed	Detailed	Detailed	Basic	2.8	2.02
Wetterlund et al. 2013	Sweden	Snapshot	External	Basic	Detailed	Detailed	Basic (indirect)	(BT not studied)	
Olsson et al. 2014	Sweden	Snapshot	External	Basic	Intermediate	Detailed	Basic (indirect)	(BT not studied)	
Fernandez-Lacruz et al. 2015	Sweden	Snapshot	External	Detailed	Basic	-	Basic	20.47[b]	-
Hynynen et al. 2015	Finland	Long-term	Internal	Detailed	Intermediate	-	Basic	15[c]	15[c]
Lundmark et al. 2015	Sweden	Long-term	External	Detailed	Detailed	Basic	Basic	(BT results aggregated with final felling)	
Swedish Forest Agency 2015	Sweden	Long-term	Internal	Detailed	Basic	Basic	Basic	14.65	18.02
Athanassiadis et al. 2017	Sweden	Snapshot	External	Detailed	Detailed	Basic	Basic	9.45	-
Baul et al. 2017	Finland (part)	Long-term	Internal	Detailed	Basic	-	Basic	(BT results aggregated with final felling)	

[a] Snapshot distributed across an arbitrary time period in the papers, or mean over first ten year for long-term studies [b] Example result for whole trees, 70% of all areas [c] Rough visual assessment of graphical results

It is expected that forest biomass will be increasingly used in the production of both new solid materials and liquid fuels; cellulose-based materials may replace non-renewable materials in e.g. packaging solutions (BillerudKorsnäs, 2018) and refined biofuels from forest biomass may replace petroleum-based fuels (Demirbas, 2009). By 2030, the total energy use of domestic and foreign transportations is predicted to reach 109 TWh yr^{-1} and the Swedish demand for forest biomass energy purposes is expected to increase by about 30 TWh yr^{-1} until the year 2030 (Swedish Energy Agency, 2014; Börjesson, et al., 2017). This increase can be explained by liquid biofuels and feedstocks required by the chemical and petrochemical industries, i.e. the scope of the presented energy demand somewhat overlaps the demand for other products.

To sum up, several aspects imply a possible significant role for BT in Swedish forestry. However, a universal synthesis of these aspects is missing, along with crucial elements such as generally applicable BT productivity and cost models.

1.4 Objectives

The overall objective of this thesis is to analyse the impact of new harvesting technology for forest biomass recovered in thinning of young dense forest stands (biomass thinning – BT) with regards to recovery costs, forest management and national forest biomass supply.

The scopes and focus areas of the different papers I-IV are visualized in Figure 2.The specific objectives relating to papers I-IV are:

I) i) to study how different harvesting techniques, stand factors and thinning methods affect time consumption (TC) for both present and future BT harvesting systems, and ii) to obtain productivity functions for such systems that can be used in cost calculations and scenario analyses.

II) to assess the utility of the presented deductive framework (DF) approach for modelling TC in forwarding, with a focus on new combinations of machines and environments and calculating the cost of forest operations.

III) to present the details of the SweFor partial equilibrium model – PEM – for the Swedish forest sector that was used in Paper IV, and assess the performance of SweFor with regards to two characteristics that are critical to forest sector PEMs, namely, how to describe forest owner behavior and saw log supply.

IV) to analyse i) optimal forest management and ii) the long-term national potential of BT with novel systems and techniques in Swedish forestry.

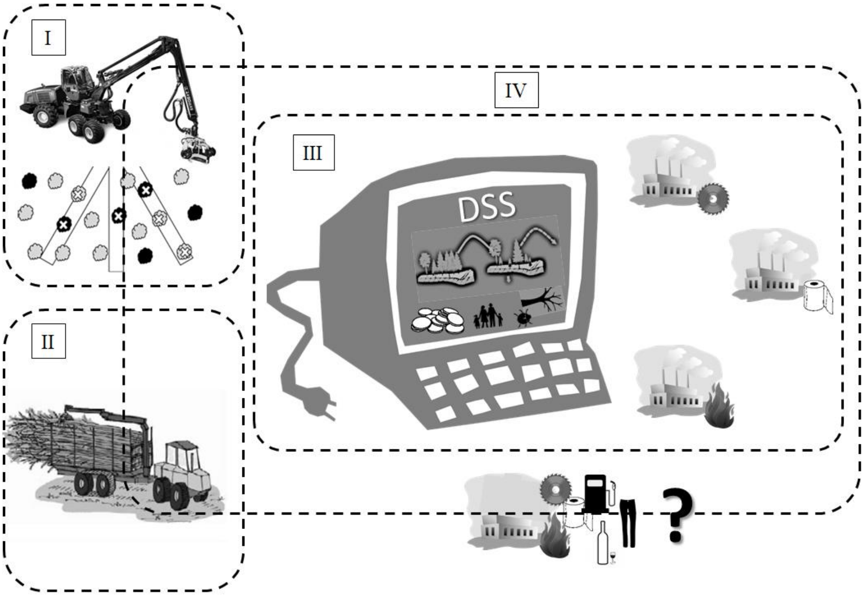


Figure 2. Schematic illustration of the scope and focus areas of the four papers in this thesis. *Copyrights: © CablePrice NZ Ltd, Juha Varhi – Metsäteho Oy, Microsoft, p2p2p2.com, mariafresa.net*

2 Methods and material

Many of the scenarios analysed in the research underlying this thesis are hypothetical in the sense that they include non-existing phenomena, such as the productivity and market impact of new and hypothetical BT machine systems and techniques. These phenomena would typically be analysed via empirical observations or empirically-based projection models. However, when such approaches are unavailable, the evaluation of novel technologies must instead rely on non-empirical, yet well-founded and reliable methods. All of the papers included in this thesis share the ambition to develop such robust methods that will provide reliable assessments of how the implementation of BT will affect the Swedish forest biomass supply. A tentative overview of methods relevant in the context of this thesis is given in Figure 3.

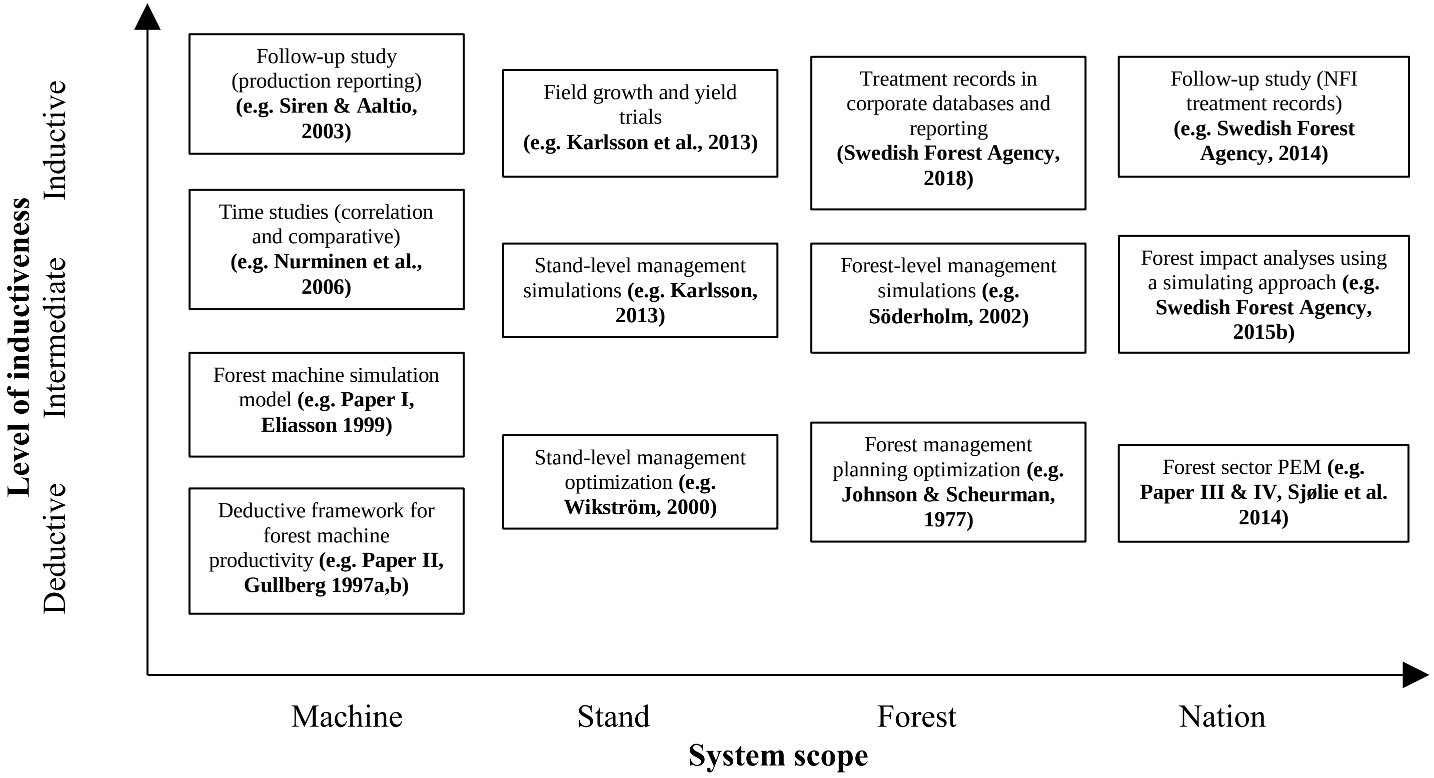


Figure 3. Tentative overview of important methodologies within the scope of this thesis, along with examples of publications thereof. The methodologies are roughly categorized as inductive or deductive, the former being based on empirical observations and actual events, and the latter being based on theoretical reasoning, projections or assumptions. For more details, confer Table 1, or Sängstuvall (2010).

2.1 Forest operations management and Forest work science

Forest operations management concerns the performance of forest operations and involves, among others, the quantification of economic performance of forest operations devices. Heinimann (2007) defined forest operations management as follows: *"It 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 (B2B) 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 location.".* The increased importance of the sustainability and climate mitigation benefits of forest biomass (Berndes et al., 2016) has been a key driver in the emergence of the concept of Sustainable Forest Operations (SFO), which is defined by Marchi et al. (2018).

The sub-discipline of *forest work science* concentrates on the productivity and cost of forest operations. The scientific methods used in this field may be categorized as either *inductive* or *deductive*. Inductive methods are based on empirical observations of a system (e.g. a forest machine), which are then analysed using statistical methods with the aim to predict the behaviour of the studied system. This application of inductive methods in forest work science is often referred to as *forest work studies*, and is well described by Sundberg & Silversides (1988) and Samset (1990). In contrast, a deductive approach provides predictions for the behaviour of a system based on theories, laws and models (Ford, 2000).To illustrate the difference between inductive and deductive reasoning in forest engineering, an inductive approach would entail measuring the TC of various work elements, e.g. the TC to cut and process a tree, and after which differences in TC are correlated to independent variables describing the forest and machine environments. Conversely, a deductive approach would use theoretical methods to analyse the work elements and identify the independent variables that affect the TC for specific work elements; these data could then be used to estimate the productivity of the entire system. For example, estimates of the cutting and processing speed of a certain machine could be used to compute how much time will be required to cut and process a tree of a given size. Inductive methods are more common since they are fairly straight-forward and will, if properly implemented, return reliable average productivity or cost estimates. However, inductive methods are limited in the sense that they require a functioning system as subject for the study, whereas deductive methods can be used to analyse e.g. forest machine systems that have not yet – or may never be – built in practice.

Forest work science often focuses on productivity, which is defined as the ratio of the input and output of a system. The input is typically calculated in terms of the working time (either of employees or machines), and the output is most often defined in terms of a produced quantity. Since TC per work element or work cycle is the most common measure of input, such studies are commonly referred to as time studies. There are two different kinds of time studies: comparative and correlation (Samset, 1990; Eliasson, 1998; Lindroos, 2010). In comparative studies, environmental factors are kept constant to facilitate comparisons between different working techniques, systems and methods. This type of time study is usually performed quite early in the life-cycle of a technique, system or method e.g. (Bergström, et al., 2010a). Correlation studies, on the other hand, evaluate how various factors influence a specific method, system or technique e.g. (Nurminen, et al., 2006; Laitila, et al., 2007). This type of time study is often performed during the later stages of the life-cycle, e.g. to provide a basis for a fair and general piece-rate-based salary system. A literature review of productivity estimations in cut-to-length forest operations was performed early during the course of doctoral studies to serve as a starting point for modelling BT productivity under varying conditions (Sängstuvall, 2010). Research on the productivity of harvesters and forwarders (a total of 14 and 8 studies, respectively) were categorized in terms of inductive/deductive research, comparative/correlation study and the independent variables that were used to explain variations in productivity. The estimated productivities of different systems were also compared under various conditions. Largely, most studies were inductive time studies: Roundwood harvesting operations were investigated through correlation studies whereas comparative studies were used to assess biofuel harvesting operations, and between-study variation in the estimated productivities could be observed.

One study on forwarder productivity stands out as deductive; Gullberg's deductive framework (DF) for TC for off-road extraction of shortwood (Gullberg, 1997a; Gullberg, 1997b). Gullberg attempted to describe the TC of a forwarder by using independent variables and deductive parameters: after a thorough review of previous studies, he identified and defined four main work elements and described them in terms of independent variables and coefficients. Gullberg validated his model for the loading work element against an inductive model (1997a), with the graphical presentations of the results showing good correspondence. He emphasized that rather than being the absolute truth, his model was intended to act as a framework or starting point for further deductive or inductive research.

As for harvester productivity, one simulation study (Eliasson, 1999) was included in the review by Sängstuvall (2010), but several others have been scrutinized during the writing of Paper I (Newnham, 1966; Santesson & Sjunnesson, 1972; AedoOrtiz, et al., 1997; Eliasson, 1999; Talbot, et al., 2003; Wang, et al., 2005; Ringdahl, et al., 2012). Simulation models of forest machines represent an intermediate between the inductive and deductive approaches. Their structures and inputs are designed using a combination of deductive and inductive reasoning, and their outputs are often interpreted as empirical observations and used as an alternative to time study results.

In the following sections, brief descriptions are given of the methods and materials used in Papers I and II. For more detailed descriptions of settings and assumptions, the reader is referred to those papers.

2.1.1 Paper I

Paper I employed a simulation approach to study how different harvesting techniques, stand factors and thinning methods on affect the TC of both current and future BT systems, as well as to obtain productivity functions that describe such systems. The simulations were performed using field data (Bredberg, 1972; Gustavsson, 1974) on individual tree characteristics and tree positions. The datasets comprised 47 first thinning type stands with an original size of 25 × 40 m^2 and nine pre-commercial thinning type stands with an original size of 25 × 20 m^2.

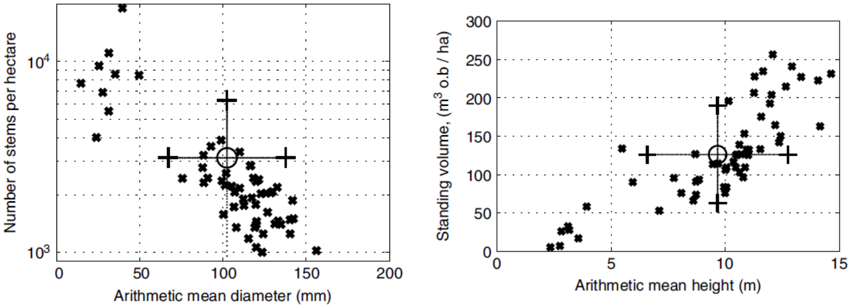


Figure 4. Characteristics of the 56 type stands used in Paper I, which were located at sites throughout Sweden and had not been subjected to a first commercial thinning. The diameter of the trees was measured at breast height, 1.3 m above ground, and o.b. refers to over bark. Xs indicate individual observations, Os indicate mean values and the distances along the lines that intersect the mean values indicate standard deviations. Note: the lower end of the interval for number of stems per hectare is outside the graph.

Computer programming and simulations were performed using MATLAB R2009b software (The MathWorks, Inc., Natick, MA, USA), and Minitab 15 (Minitab, Inc., PA, USA) was used for statistical analysis of the results.

The simulation model was based on the harvester simulation model developed by Eliasson (1999), with extended functionalities derived from other published simulation models e.g. (Santesson & Sjunnesson, 1972; Wang et al., 2005), felling operations in environments similar to those considered in the presented research e.g. (Bergström et al., 2007; Iwarsson Wide & Belbo, 2009) and harvester and forwarder working patterns e.g. (Gullberg, 1997b; Ovaskainen et al., 2004; Ovaskainen et al., 2006; Ovaskainen, 2008). Functions describing new machine systems that include boom-tip mounted, area-based felling devices and new working techniques were also implemented.

A total of 6 048 simulations were run on the 56 type stands, with six variations in thinning intensity and thinning ratio, and nine combinations of harvesting techniques and systems (Table 2). Every combination of stand, thinning and machinery was simulated twice with randomized machine starting positions. The type stands are graphically described in Figure 4, and the simulation model is briefly described in Figure 5.

Table 2. *Simulated thinning scenarios (felling mode and applied harvest pattern between strip roads) and the acronyms used hereafter. RW and FF refer to roundwood and forest biomass (denoted FF, for forest fuel, in Paper I), respectively. Corridor widths are provided for the geometrical harvest patterns. Abbreviations for thinning scenarios without parentheses are used in this thesis, whereas thinning scenario abbreviations within parentheses were used in the published version of Paper I.*

Thinning scenario				
Felling mode	Thinning pattern (between strip roads) and harvested assortment			
	Selective		Geometrical (corridor width)	
	RW	FF	FF (1 m)	FF (2 m)
Tree-based single-tree handling	TSRW$_{Sel}$			
Tree-based multi-tree handling	TMRW$_{Sel}$	TMFF$_{Sel}$	TMC$_1$ (TMFF$_{Corr1}$)	TMC$_2$ (TMFF$_{Corr2}$)
Area-based, felling 2m^2 at a time, multi-tree handling			2m^{2}C$_1$	2m^{2}C$_2$
Area-based, continuous felling, multi-tree handling			ContC$_1$ (CFF$_{Corr1}$)	ContC$_2$ (CFF$_{Corr2}$)

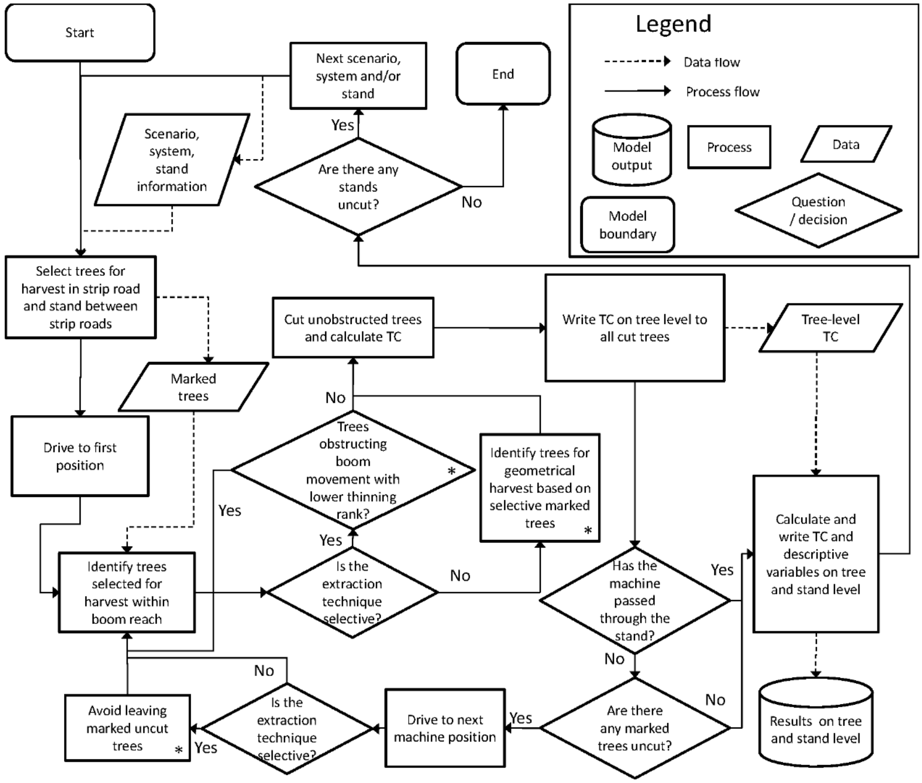


Figure 5. Flowchart for the simulation model in Paper I, that is based on work by Eliasson (1999), but including additional functionalities (marked by *). TC means time consumption.

The total TC per tree for harvester work was calculated using Eq. (1)

$$T_{Tot} = T_{BoomOutIn} + T_{BoomInt} + T_{Fell} + T_{LimbCut} + T_{Move} \qquad (1.)$$

where T_{Tot} is total TC, and the other terms denote TC per work element; $T_{BoomOutIn}$ is the TC for boom movements towards the first tree to be cut in a work cycle along with movements towards the processing spot after the last tree in a work cycle has been cut or towards the default harvester head is positioned in front of the machine, $T_{BoomInt}$ is TC for boom movements between trees to be cut in the same work cycle, T_{Fell} is the TC for felling trees, $T_{LimbCut}$ is the TC for processing (i.e. delimbing and cross-cutting) trees and T_{Move} is the TC for moving between machine positions. TC values were calculated at either the tree, work cycle or stand level, whichever was appropriate for the work element and thinning scenario (Table 2). TC per calculation unit was then distributed equally among all trees handled in the calculation unit under consideration.

Generic TC functions for the different thinning scenarios (cf. Table 2) were constructed using the simulated TC measures and independent stand and treatment variables as inputs in a regression analysis.

2.1.2 Paper II

In this paper, Gullberg's (1997b) deductive framework (DF) was implemented for two machine configurations that represented small- and medium-sized thinning forwarders with maximum load carrying capacities of 8.5 and 11 tonnes respectively. These machines were then simulated over a set of environments $\{X_m\} = \{X_1, X_2, \ldots, X_n\} \subset \mathrm{X}$ with a total of 16 different combinations of the independent variables included in the DF (forwarding distance, mean loading pile size, amount of piles along strip road, and unloading grapple volume). The simpler version of Gullberg's TC model for loading was used, i.e. only single-assortment loads were considered and it was assumed that all driving was done on strip roads. In the case of the small forwarder, the operation examined involved the hauling of whole trees for energy feedstock following mechanized felling during thinning (Laitila et al., 2007). For the medium-sized forwarder, the operation of interest was the hauling of pulpwood during thinning (Nurminen, et al., 2006). The two publications that described these tasks were analysed carefully to obtain accurate descriptions of relevant machine and environmental parameters, such as the grapple area or the mean pile size during the loading phase. Parts of the DF were adjusted in advance to match the conditions of the field studies. Estimated productivities $\{\hat{o}_{G_1}, \hat{o}_{G_2}, \ldots, \hat{o}_{G_n}\}$ for each machine were calculated using the DF, and the corresponding productivities $\{\hat{o}_1, \hat{o}_2, \ldots, \hat{o}_n\}$ were calculated using the work productivity functions presented by Nurminen et al. (2006) and Laitila et al. (2007).

The coefficients A_G of the DF were then altered in a bid to improve the accuracy of the DF in terms of conformity with the original work productivity functions. The adaptation was done by minimizing the squared sums (over the 16 combinations of independent variables, per forwarder type) of the differences between the productivity estimates and the observed productivity. This was performed separately for each machine by adjusting the default values in A_G, resulting in a new set of coefficients A_G' and the corresponding productivity estimates $\{\hat{o}_{G_1}', \hat{o}_{G_2}', \ldots, \hat{o}_{G_n}'\}$. No single coefficient in the adapted DF set (A_G') was allowed to deviate from its original value by more than 50%. All data management and calculations were performed with Microsoft Excel 2007 (Microsoft, 2007) using the Solver add-in.

2.2 Forest planning and impact assessment

Forest planning encompasses a decision making process in which e.g. the timing and type of forest management activities are chosen to fulfil the decision maker’s goals (cf. Bettinger et al. 2009), and the end of the planning process are decisions to be taken by a decision maker. Furthermore, a plan can be defined as a system of decisions (Mintzberg, 2000). Thus, whereas operations management could be interpreted to focus on processes and their interlinkage, planning is more concerned with decisions and their interrelatedness. Forest owners’ goals often involve economic criteria or measures; hence, accurate forest operations cost models are crucial in such forest *management* planning.

Forest impact assessment on the other hand involves elements similar to forest planning, such as projecting future forest conditions given different assumptions of e.g. forest management, but rather than being a plan the assessment informs about the consequences of one or several potential scenarios (cf. SKA 15 (Swedish Forest Agency, 2015b)), and is typically a component within policy processes. Forest impact assessment is typically performed on regional (sub-national) or national level. It has similar components as a planning process, such as definition and formulation of the problem, data collection, and generation and evaluation of alternatives.

Both papers III and IV reviewed and employed forest planning and impact assessment methods. This section briefly summarizes these two methodologies. Forest planning and impact assessment provides forest owners and stakeholders with the tools necessary to quantify and describe different values associated with forests and forestry, as well as to direct forest management in ways that maximizes the extent to which the forest owner’s objectives are fulfilled. Forest *utilization* problems (my addendum in *italics*) can be categorized according to six dimensions: temporal scale; spatial context; spatial scale; number of decision makers; number of objectives and types of goods and services provided, as described by the FORSYS Cost Action (Borges, et al., 2014). For example, the spatial scale of typical forest planning problems can range from stand, or even tree, level, to the regional, national and global levels, while the temporal scale ranges from months to hundreds of years.

A specific scale should be used with the appropriate context and/or forest utilization problem, for example, a stand-level analysis of optimal forest management under certain conditions will only return the optimal way to manage that particular stand. However, a forest management unit (e.g. the forests owned by a non-industrial private forest owner or a municipality) usually consists of different stands with different characteristics. The forest management unit typically has a certain set of preconditions that are related to forest characteristics and owner preferences, e.g., even harvest levels over time. Such super-stand criteria imply that the optimal stand-level forest management approach can not always be applied on the forest (management unit) level. On the regional/national level, variations among forest owners and stakeholders in their specific preferences and goals make it challenging to assess potential long-term sustainable forest growth and yield on the national level. A total of 432 combinations of categories to describe forest utilization problems exist across the six dimensions (Borges et al., 2014).

Decision support systems (DSS) are one alternative for solving or analysing various forest utilization problems. DSS are defined as *"computer based systems that represent and process knowledge in ways that allow the user to take decisions that are more productive, agile, innovative and reputable"* by Holsapple (2008), and *"tools providing support to solve ill-structured decision problems by integrating a user interface, simulation tools, expert rules, stakeholder preferences, database management and optimization algorithms"* by Muys et al. (2010). An example of a forestry DSS is the Heureka system (Wikström, et al., 2011), which compiles current Swedish knowledge and practices in forest growth and yield, biological processes related to forests, and forest operations, along with information from other disciplines. The Heureka DSS is relatively fixed towards the long- (and to some extent medium-) term end of the temporal scale, but allows for analyses across the other dimensions described by Borges et al. (2014). For example the spatial scale of forest utilization problems is already integrated into the Heureka system design, as the StandWise application addresses the stand level, while PlanWise and RegWise address the forest/estate and regional/national levels, respectively. Heureka is the DSS employed in the SKA 15 analyses (Swedish Forest Agency, 2015), which include a number of cutting scenarios for the entire Swedish forestry sector, modelled over 100 years using the Heureka RegWise application (Wikström, et al., 2011). Approximately 30,000 inventory plots, measured during the five-year period between 2008 and 2012 as part of the Swedish National Forest Inventory (NFI), were used to predict growth and yield at the plot level. Treatments were assigned to each plot using priority functions based on either per cent volume growth or probability functions describing historical landowner behaviour.

Consider the overall objective of this PhD-project the forest utilization problem at hand: *"to analyse the impact of new harvesting technology BT, with regards to recovery costs, forest management and national forest biomass supply".* This mere formulation leaves vast degrees of freedom on how to categorize the forest utilization problem along the six dimensions, and then select the materials and methods to solve it. Turning to the literature, a number of different approaches across the dimensions have been made (see also Table 1): Starting on stand level along the spatial scale, a number of studies have explored the profitability of BT-like treatments in arbitratry forest stands potentially suited for BT. In terms of the evaluation of net economic returns, many studies at hand fall on the forest operations side of the distinction between scientific disciplines, since they are based on a time study case, which is extended with economic measures and analyses, e.g. (Iwarsson Wide & Belbo, 2010). Alternatively, a couple of studies analysed BT in economic terms as part of the stand management over a rotation period (Heikkilä et al., 2009; Karlsson, 2013; Karttunen et al., 2016). However, these studies only use simulating approaches to solve the forest utilization problem, and thus, provide answers to the question *“What if we manage these particular stands with this particular BT management program under these specific conditions?”*. No studies that aim to optimize management objectives including BT at the stand level were identified in the literature review work underlying this thesis (cf. Table 1, Sängstuvall (2010)).

The intermediate level along the spatial scale – forest level – is often characterized by stand-level subunits in which the forest management takes place. Nevertheless, all of the stands (or subunits) are subjected to forest level conditions. At this level, it is common that the market prices are fixed, i.e. the way the forest is managed affects neither the input factor nor timber prices. Thus, this spatial resolution disregards regional and national phenomena such as market conditions. In this way, models on the forest level rarely consider competing supply from other forests or industrial sectors, or that demand for forest goods and services can change over time, in the form of e.g.: spatial allocation of industries; willingness to pay and price elasticity. The largest forest management companies in Sweden (and on the global scene) commonly use this approach because their assets are usually valuated on the basis of forest-level harvest prognoses and wood price assumptions. No studies on BT that were limited to the forest level were identified during the literature review underlying this thesis (cf. Table 1, Sängstuvall (2010)).

On the regional/national scale, the market aspect cannot be disregarded if the results of the forest utilization problem solving are to be useful. Another aspect – the diversity of forest owners within Sweden and across different regions – separates the forest level from the regional/national level in the Swedish context. Different forest owners manage their forests in different ways, either in accordance or conflict with their own forest management goals and objectives (Eggers, et al., 2014). In SKA 15, this is handled through an empirically based, owner-type specific random element within the priority functions mentioned above.

There are several tools that specifically address the ecological and techno-economical restrictions that are relevant to analyzing the role of forest biomass in the Swedish energy supply (section 1.3). As was the case in using a deductive approach to investigate forest operations, the internal and external market dynamics for forest products may also present unknown conditions – such as new market forces, policies and/or regulations – in the system environment. An inductive approach in this context usually entails either a) assuming constant supply and/or demand based on current knowledge, or b) disregarding demand criterias, i.e. assuming infinite demand. On the other hand, a deductive approach will handle these issues by gathering existing knowledge of market behaviour under different conditions, and transferring it into the analysis of the system at hand. In such a case, a sector model – which describes the supply and demand for different actors in the forest and/or energy sector – presents a powerful tool. According to Solberg (1986), a forest sector model is *"a model (numerical or strictly analytical) which takes into account both forestry and forest industries and the interaction between these two activities"*. A partial equilibrium model (PEM) is a kind of sector model. It is partial in the sense that relative prices from other sectors are given exogenously, and an equilibrium model in the sense that supplied and demanded quantities match, which implies that the sum of the consumer and producer surpluses is maximized. PEMs have been applied to various forest contexts around the world for several decades. Selected PEMs relevant to the scope of this thesis have been reviewed during the work of this project and are summarized in Table 1, along with other studies focusing on the potential of BT.

2.2.1 Papers III and IV

A Swedish sector model, SweFor, was developed in AIMMS modelling software (AIMMS, 2016) and originally used to explore the supply of wood fuel to the Swedish district heating industry under different market and technological assumptions (Eriksson et al., 2013). SweFor connects the management of Swedish forests with the demands of three branches: the sawmill industry; the pulp and paper industries; and the energy sector (represented by district heating plants). The model uses parts of the NFI plot data used in SKA 15 and the Heureka DSS to make growth and yield projections of the plots under different forest management scenarios. A tentative overview of the SweFor model is given in Figure 6, and the geographic dimensions of the supply and demand sides are shown in Figure 7. Papers III and IV provide more detailed formulations as well as the specific settings and assumptions of the model in the two different problem settings in the papers.

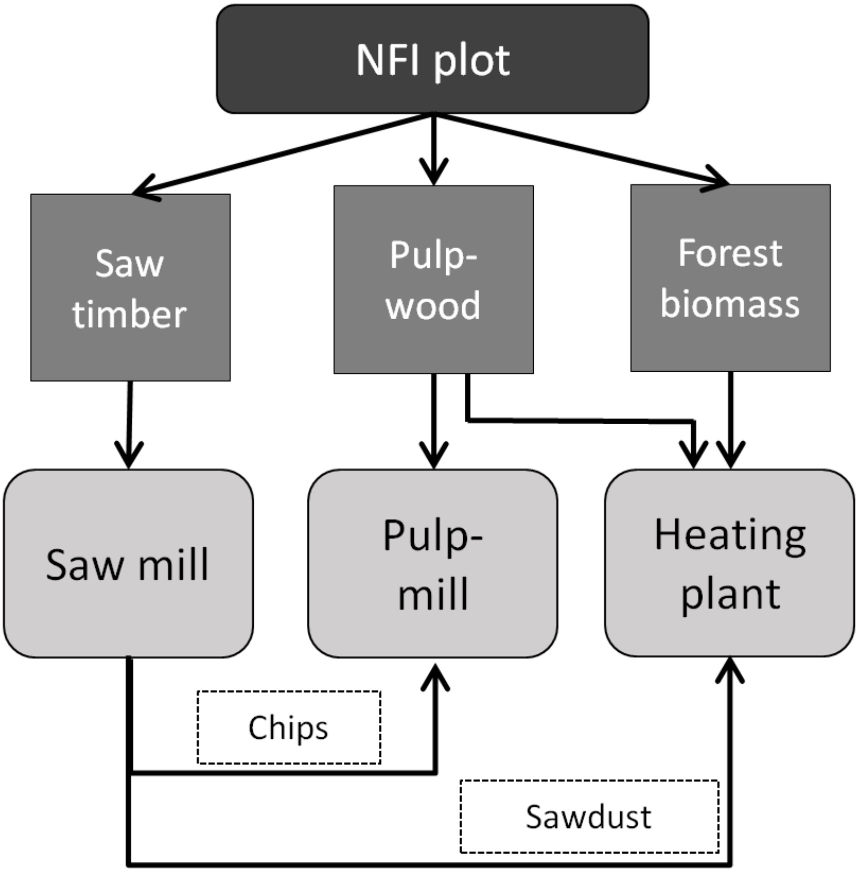


Figure 6. An overview of the SweFor material flow from the supply side (forests represented by NFI plots) to the demand side (different forest biomass consuming industry branches with individual industries represented as geographic units with specific demands). Internal use or refinement of by-products are not part of the model.

The demand function is given exogenously for each branch and time period and is defined by a point (a price and a demanded quantity, in SweFor defined using national statistics (e.g. Swedish Forest Agency, 2014)) and an elasticity that is assumed to be constant. As for the supply representation, Swedish NFI plots were used to represent the area of Swedish productive forestland (23.2 million ha). All 17,875 forest plots inventoried between the years 2010 to 2012 were used (Fridman et al., 2014).

The Heureka PlanWise application was used to generate growth and yield projections – excluding estimated climate effects on annual increment – for different management alternatives for all of the NFI plots and three alternative management regimes that correspond to three different BT technology scenarios:

- ordinary management with no BT (**NoBT**)
- management with the possibility to harvest forest biomass in 2 m wide geometrical boom corridors either with an accumulating multi-tree handling harvester head (Tree Multi Corridor, 2 m wide, **$\mathbf{TMC_2}$**)
- management that employs a fictional, idea-based continuously felling harvester head also operating in 2 m wide boom corridors (Continuous Corridor, 2 m wide, **$\mathbf{ContC_2}$**).

Harvester productivity functions for the TMC_2 and $ContC_2$ scenarios from Paper I and forwarder productivity functions obtained with a methodology similar to that in Paper II were included in the Heureka DSS so that BT could be integrated in the Heureka simulations and analyses. The simulations resulted in 0.5-1 million alternative management programs for the set of plots, which were then exported to SweFor along with the corresponding cost and yield information.

In SweFor, management programs and the subsequent transportation of the harvested wood assortments to different industries are assigned to each NFI plot in a way that maximizes the model objective. The target function in SweFor aims to maximize the sum of the net present (discounted) social surplus (NPS) across periods. The net surplus of a period can be obtained by calculating the area under the demand functions of the associated branches, for the supplied volumes, and subtracting the forest management costs (stand establishment and harvesting costs), transportation costs from harvest sites to the processing facility, and, in the case of forest biomass, the cost of comminution.

In Paper III, variations were made in the post-Heureka AIMMS stage to evaluate model characteristics related to forest owner behaviour and saw log supply. Different proxies for non-industrial private land owners' behaviour were evaluated, more specifically, amenity values given to old forests *(Amenity)*, random forest management program selection *(Random)* and strict age-control rules in final felling *(AgeCtrl)*. Furthermore, the impact of different saw log supply models was assessed. In the *Free* alternative, the merchantable volume could be freely distributed among sawmills, pulp mills, and heating plants, whereas in the *Dia* alternative, the merchantable volume was attributed a relative value based on the mean stand diameter at the time of harvest. In the

Theo alternative, theoretical bucking into saw logs and pulpwood, exogenously provided by the Heureka simulations, is followed when distributing the merchantable volume on sawmills and pulp mills.

In Paper IV, SweFor was employed and adapted to the forest utilization problem at hand in this thesis, whose final formulation include both BT effects and short- and long term aspects, namely, forest management and forest impact, along with how the potential supply of forest biomass from BT is affected by competition with other forest biomass sources.

The NoBT management program was used in Paper III, whereas the NoBT, TMC_2 and $ContC_2$ management programs were used in Paper IV.

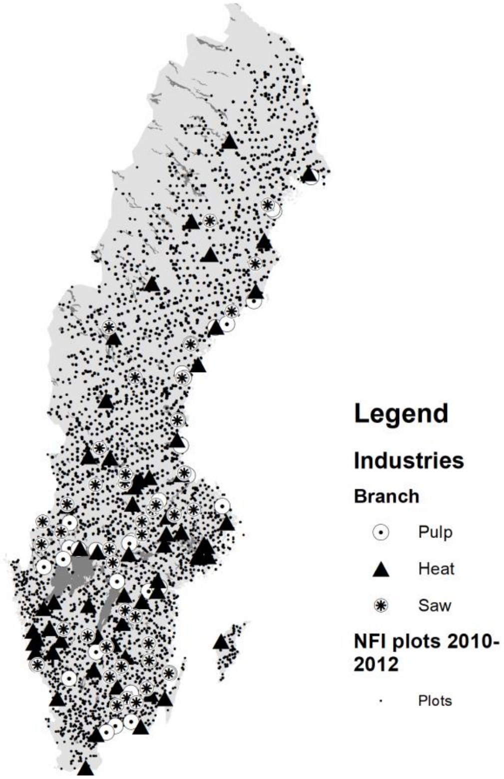


Figure 7. Inventory tract layout in the Swedish NFI in the years 2010–2012 (tracts are clusters of plots), and industry locations representing the wood-consuming industry branches in Sweden in the SweFor model.

3 Results and paper-wise discussion

3.1 Paper I

The research presented in Paper I demonstrated that BT, when exercised in a geometrical harvest pattern leads to increases in productivity, and more so using an area-based felling device. The productivity increases were of greatest magnitude in the stands with the smallest mean stem volumes (Figure 8). Direct comparisons among thinning scenarios are primarily valid within the same assortment (roundwood or forest fuel, cf. Table 2). In stands with mean stems volumes of up to 0.02 m^3ob, the machine systems and techniques that were further investigated in Paper IV, $ContC_2$ and TMC_2, showed productivities (expressed as tonnes dry matter (DM) per productive work hour (PWH)) that were 282% and 80% higher, respectively, than what was found for selective harvesting operations that involved multiple tree handling ($TMFF_{Sel}$). When the mean stem volumes were between 0.06 and 0.08 m^3ob, the productivity gains for $ContC_2$ and TMC_2 decreased to 44% and 10%, respectively, relative to $TMFF_{Sel}$. Parts of the observed increase in productivity when using a geometrical harvest pattern could be explained by the reduced selectivity in such treatments, leading to changes in the composition of harvested trees – i.e. the thinning ratio and thinning intensity could be altered. The positive effect of multiple-tree handling versus single-tree handling in a selective harvest pattern could be determined at 39% and 26% for the roundwood thinning scenarios at the same mean stem volumes.

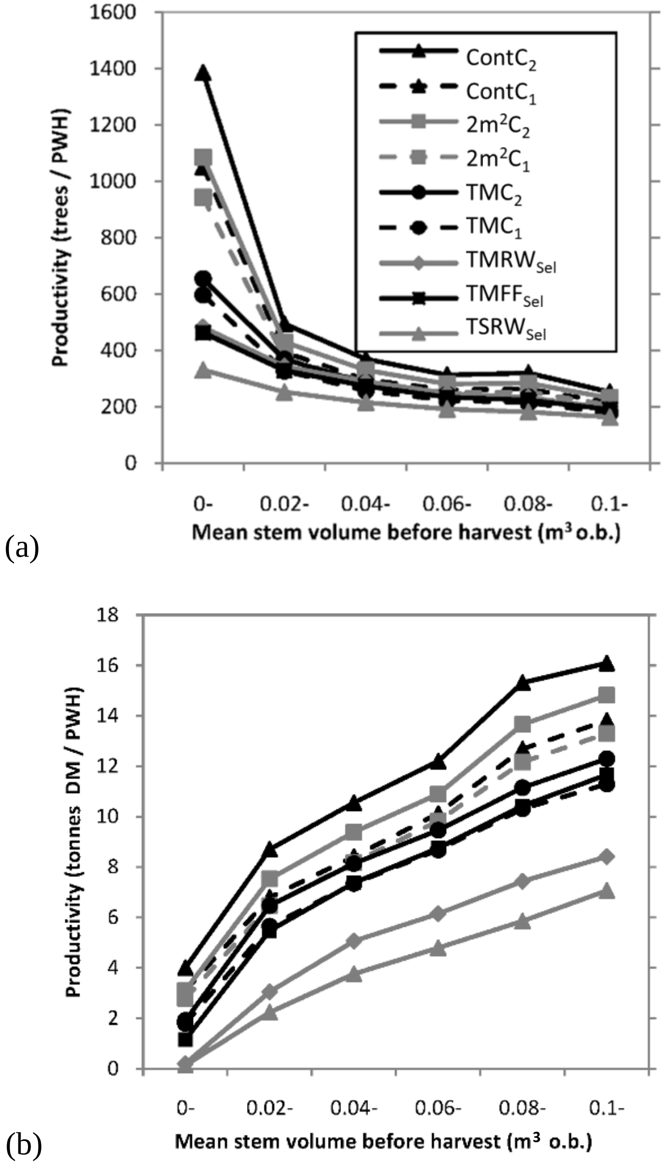


Figure 8. Mean productivity values, expressed as (a) trees harvested per productive work hour (PWH) and (b) tonnes dry matter (DM) of the given assortment harvested per PWH, obtained from the simulations for various classes of stand mean stem volume (in m^3 over bark (o.b.)) indicated on the x-axis. Different lines indicate values for different thinning scenarios, as explained in the legend (cf. Table II). The forest biomass assortment in the simulations illustrated in (b) comprises entire stems and 50% of other above-ground biomass. The simulations included all 56 studied type stands, with 9, 6, 9 14, 9, and 9 stands included in the mean stem volume classes from left to right, respectively.

The TC functions obtained with regression analysis were implemented in the Heureka DSS, to enable integrated analyses of BT in long-term forest planning. The functions contain a high number of independent variables. This facilitates – and requires – detailed analyses in e.g. the Heureka DSS, which include data for all selected independent variables. Other applications of the functions obtained in Paper I have been problematic, since some of the independent variables rarely are included in an ordinary forest management plan or stand inventory.

The simulation model was continuously verified during programming (by comparing model results to manual calculations), and the obtained results were validated by comparing them to three other datasets: another implementation of the simulation model (Eliasson, 1999); the most commonly used empirically based thinning productivity estimates in Sweden (Brunberg, 1997); and observed productivity in comparative time studies of similar BT operations (Bergström, et al., 2010a). In many cases, the simulation model used in Paper I somewhat underestimated TC, but that should be the case in a simulation (cf. Eliasson 1999). For example, the simulation model considered stem form expressed as tapering, but not the occurrence of difficult branches, forks and crooks, which, in practice, affects the potential of multiple-tree harvesting (Laitila et al., 2016).

3.2 Paper II

Both the original and the adapted DF yielded results that agreed well with what was produced by inductive time study functions adapted to the same environments (set of independent variables, n = 16 in this case). The difference between predictions of total TC per m^3 from the unadapted DF functions (A_G) and the time study functions ($\hat{A}$) for the tested environments were 6.1 % and 6.9 % relative root mean square error (RMSE) for the small and medium-sized forwarders, respectively.

The adapted DF (A'_G) yielded somewhat lower differences when the results were compared to the performance of time study functions ($\hat{A}$): differences, measured in relative RMSE, amounted to 4.1 % and 5.5 % for the small- and medium-sized forwarders, respectively. Two examples of productivity estimates obtained using the three sets of coefficients are given in Figure 9.

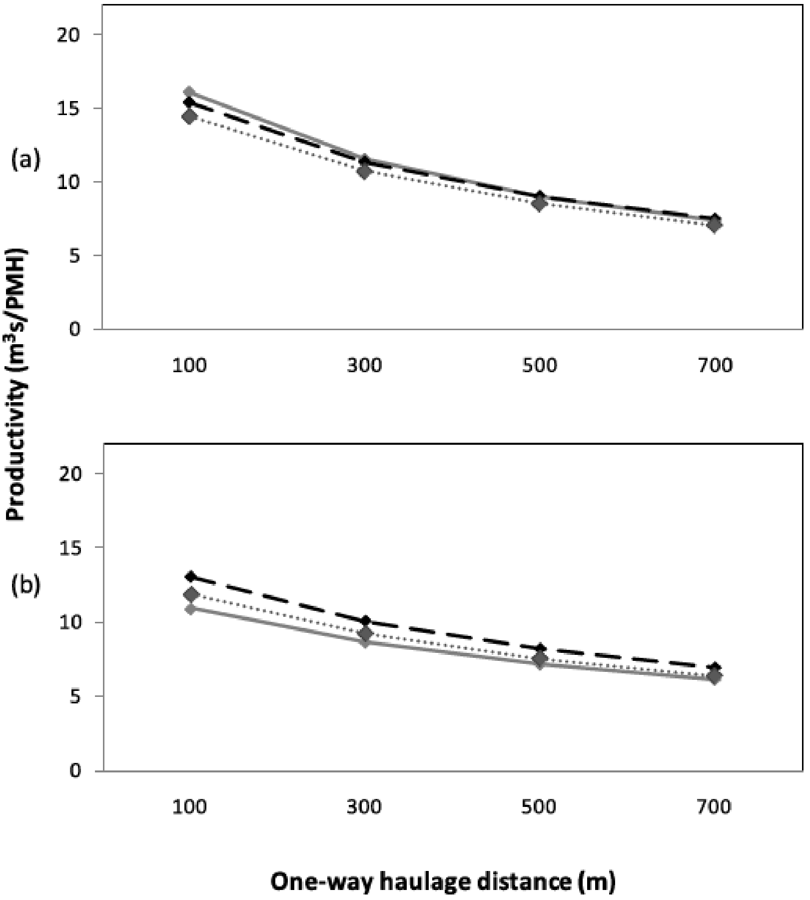


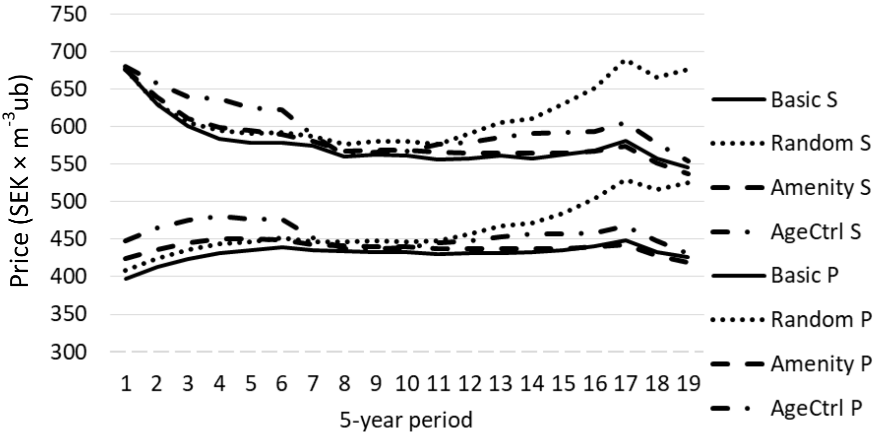
Figure 9. Productivity values from the work productivity functions ($\hat{A}$) of roundwood forwarding by Nurminen et al. (2006) (a) and whole-tree forwarding by Laitila et al. (2007) (b) are denoted by solid lines, while productivity values from the original deductive framework (DF) (A_G) are indicated by dashed lines (Gullberg 1997b). The productivity values from the adapted version of the DF (A_G') are indicated by dotted lines.

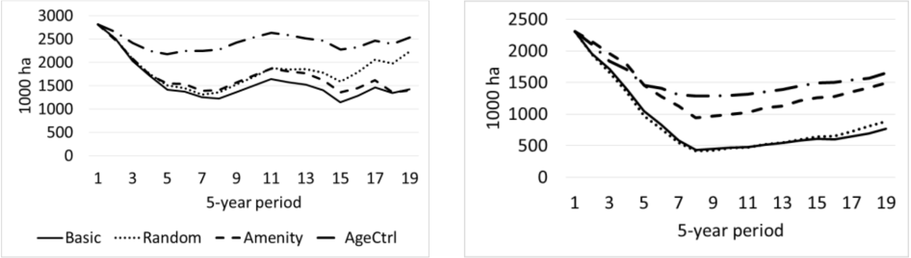
Observed differences between time study functions and the DF are smaller in the forwarding of roundwood (Figure 9a) than that of whole trees (Figure 9b). One possible explanation to this difference is the higher maturity level of roundwood versus whole-tree forwarding as a standard operation. In Paper II, n = 16 sets of independent variables were used as the empirical observations to which the DF was then fitted. However, the DF methodology allows for the number of observations to be much smaller. In fact, a single observation, obtained from the very first comparative time study of a new forwarder, would add valuable information to the DF, while the robustness of the DF would prevent the productivity model from returning totally unrealistic estimates. The DF employed in Paper II could be useful for improving predictions of hauling TC with a forwarder in several contexts. This, in turn, would lead to more accurate estimates of work amount and costs in forestry. Arguably, one could also combine the advantages of both the inductive and deductive approaches by using deductive reasoning to identify suitable independent variables for incorporation into work productivity functions based on time study results (Samset, 1990; Laitila et al., 2007).

Paper II provided a robust model that could be used to reliably predict the productivities, and as a result, the cost, of forest operations. More specifically, the DF was adapted to a set of comparative time study observations (n = 37 loads, performed by Skogforsk (e.g. Iwarsson Wide & Belbo 2009; 2010). The resulting DF was then implemented in the Heureka DSS as a productivity function for BT forwarding (Sängstuvall, 2018).

3.3 Paper III

In Paper III, the SweFor model is presented in detail, and two assumptions that influence the results presented in Paper IV are examined. One assumption refer to how a model could better reflect forest owner behaviour, or more specifically, how to capture the fact that old forests are not harvested to the extent that economic rationality would suggest. The desired effect is that forests older than 80 years should be less intensively harvested than what the maximization of NPV would suggest. Different proxies for non-industrial private forest owners' behaviour resulted in slightly different forest characteristics over time. The clearest difference between the approaches was observed for how forests older than 120 years were handled (Figure 10). Applying an amenity value of moderate size seems to give almost the same effect as conserving the area by a strict constraint. Saw log prices over time does not seem directly correlated with the amount of old forests, which could be said to represent the theoretical potential supply of saw logs. Various parts of this theoretical potential supply were however unavailable for harvest due to the hard constraints in behavioural assumptions *Random* and *AgeCtrl*.




Area 80–<120 years

Area ≥120 years

Figure 10. Prices for saw logs (per m^3 saw logs; marked with S) and pulpwood (per m^3 under bark; marked with P), and areas of old forest at two age classes (80-<120 years and ≥120 years) over time under different behavioural assumptions, with saw log supply model *Free*.

The other assumption investigated in Paper III refers to how different timber assortments are distributed between sawmills and pulp mills. The results in Paper IV were based on the behavioural assumption alternative *Basic*, i.e. no special provisions were made for securing old forest areas. Obviously, an approach like *Amenity* would have better reflected forest owner preferences. However, the fact that few output variables, except the area of old forest, showed any great differences when the *Amenity* alternative was applied in Paper III was reason to assume that the main results in Paper IV would not have changed much with the application of amenity values.

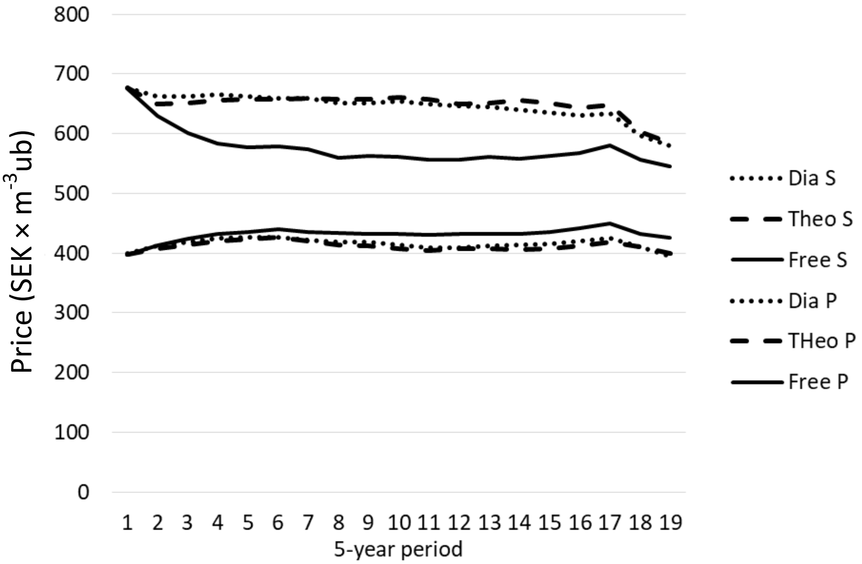


Figure 11. Prices for saw logs (per m^3 saw logs; marked with S) and pulpwood (per m^3 under bark; marked with P) over time, under different saw log supply models, with the behavioural assumption *Basic*.

The results in Paper IV were based on the saw log supply model *Theo*, i.e. a detailed bucking prognosis generated in the Heureka system was used to describe saw log supply per NFI plot in the SweFor model. *Theo* provides the lowest proportion of saw logs from the total harvested volume (data not shown), which is why *Theo* is associated with higher saw log prices (Figure 11). Saw log supply model *Diameter* performs in a similar way, whereas *Free* gives a higher proportion of saw logs and lower prices.

SweFor uses an optimization approach in which forest management is optimized on the national level for each unit—the NFI sample plot—in the forest supply representation. In contrast, SKA 15 employs a simulating approach in which treatment priorities are calculated for each unit in the forest supply representation, but treatments are assigned according to a routine that skips treatment in many prioritized plots (Swedish Forest Agency, 2015). This routine addresses several issues with using an optimization approach in regional or national forest consequence analyses, namely, differing landowner goals and behaviours, and the so-called plot-stand problem (Hägglund, 1982). The latter recognizes that the NFI data consist of plots of some few 100 m^2 area, whereas the smallest unit of treatment in Swedish forestry is typically some 1000 m^2, and often much more. NFI plots (or single sample plots from any inventory) often reflect a different forest state than that of the stand in which they belong, and will be managed in accordance with. This aspect is not fully addressed in Papers III and IV, and those results must be treated with that in mind. On the other hand, plots in SKA 15 for which a highly prioritized final felling is skipped in one period may be felled in the next period instead – this dynamic is comparable to the *Random* scenario. This leads to a depletion of older production forests over time (Swedish Forest Agency, 2015), whereas the other approaches evaluated in Paper III ensure a higher proportion of older forests over time.

3.4 Paper IV

The research showed that BT had little effect on NPS, and only to a limited extent contributed to the fulfilment of heat plant demands (Table 3, Figure 12).

Table 3. *Effects of biomass thinning (BT) on net present surplus (NPS), forest management regimes and heat plant supply for the Swedish forestry and forest sector.*

		Scenario				
Variable	Unit	NoBT	TMC_2	$ContC_2$	$TMC_2\infty$	$ContC_2\infty$
NPS at 3% interest rate	SEK × 10^9	287.13	288.70	288.97	296.34	297.52
Forest area managed in BT regime	1000 ha	0	2,707	3,064	12,996	13,499
	*%**	*0*	*13.8*	*15.6*	*66.2*	*68.7*
Heat plant supply from BT over 100 years	TWh	0	573.2	650.5	2,694	2,806
	*%***	*0*	*15.2*	*17.2*	*31.9*	*32.8*
BT proportion of all harvested forest biomass (including roundwood)	*%*	*0*	*3.0*	*3.3*	*12.2*	*12.8*

* Proportion of forest land available for production

** Proportion of the total supplied amount of energy to heat plants over 100 years

However, the contribution of BT varied between heat plants depending on the distance to competing heat plants, other industries and the available supply (Figure 16). If heat plant demand was considered infinite in terms of industrial capacity – as in scenarios $TMC_2\infty$ and $ContC_2\infty$ – then NPS increased considerably; this was dependent on BT as well as the increased removal of logging residues in final felling and increased use of pulpwood as an energy feedstock. Under these scenarios, BT became the dominant forest management regime in Sweden, as it was employed in two-thirds of the forest area (Table 3). Furthermore, the implementation of BT did not affect the ability to meet industry demands for pulpwood and saw logs; in the scenarios analysed in Paper IV, future harvest levels of roundwood were equal to or greater than the national long-term projections in SKA 15.

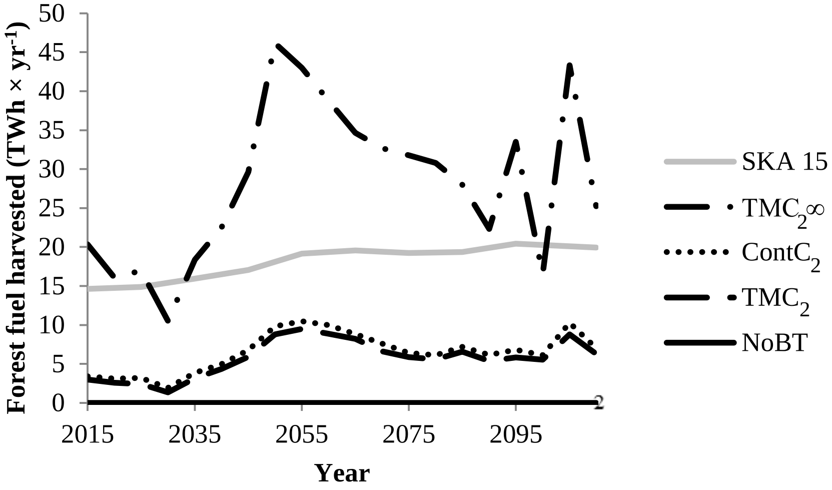


Figure 12. Annually harvested biomass for energy feedstock from biomass thinning (BT). Note: SKA 15 considers all harvest residues as biomass in all thinnings available according to ecological restrictions, but does not consider techno-economical restrictions. On the other hand, the scenarios analysed in Paper IV consider first thinnings and stem-wood biomass according to the same ecological restrictions, but also (through the selected approach) include techno-economical restrictions and market dynamics.

BT was more often the preferred management regime in richer sites, with higher growth potential at any given geographical location (Figure 13). Sites with higher growth potential can carry more basal area at a given top height before self-thinning occurs (Elfving, 2010), which may be an explanation for the dynamic observed in Figure 13. An increase in BT leads to less cleaning activity (Figure 14) and thinner trees at 15 meters mean height (Figure 15).

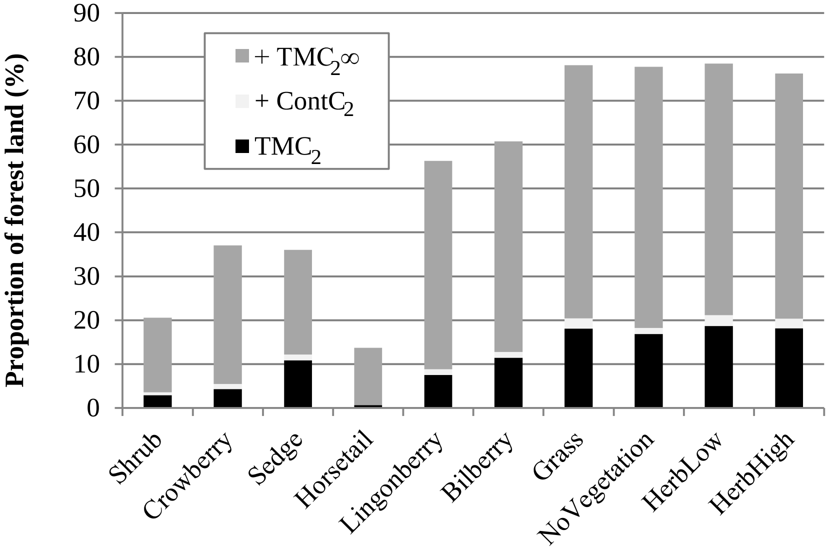


Figure 13. Proportion of forest land managed with different biomass thinning (BT) regimes over 100 years for various vegetation types, sorted from left to right with ascending growth potential (Hägglund & Lundmark, 1981). Scenario TMC_2 is indicated with black bars, and the additional contributions from scenarios $ContC_2$ and $TMC_2\infty$ are indicated with light and darker grey bars, respectively.

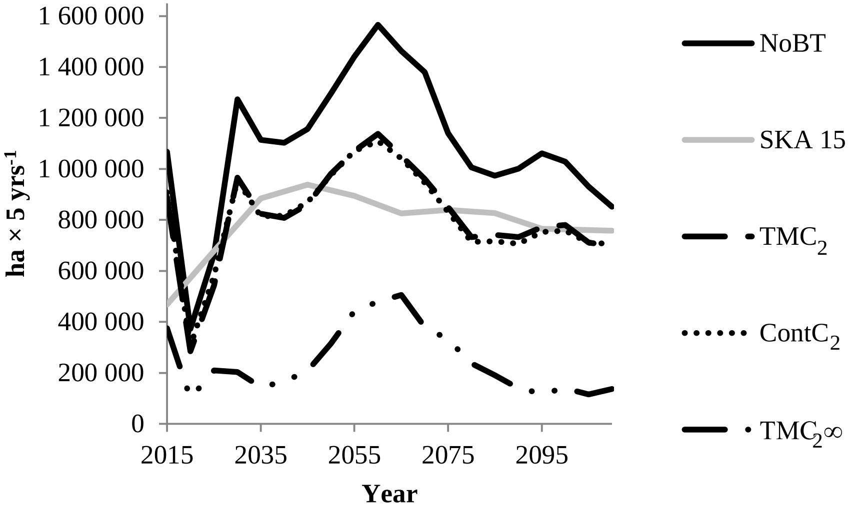


Figure 14. Pre-commercial thinning areas for five-year intervals for the different scenarios. Changes are shown over a 100-year study period.

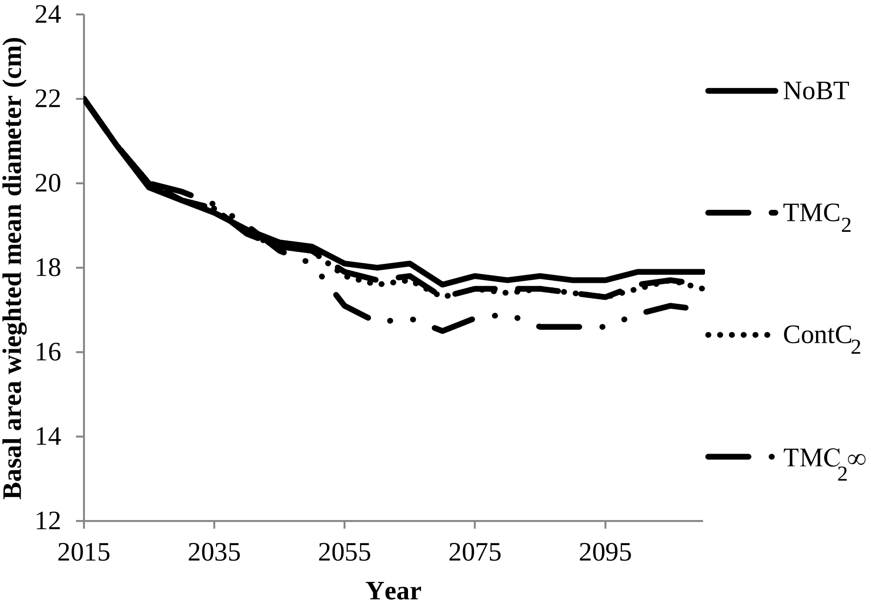


Figure 15. Diameter at breast height at a basal area weighted mean height of 15 m (i.e. post-first thinning), over five-year intervals for the different scenarios. Changes are shown over a 100-year study period.

The results revealed small differences between current and proposed future thinning systems (TMC_2 versus $ContC_2$, and $TMC_2\infty$ versus $ContC_2\infty$, respectively). This suggests that improvements in BT harvester productivity will only have a marginal effect on forest management. However, the BT harvester in the $ContC_2$ scenario was assumed to be more expensive than the conventional thinning harvesters used in the NoBT and TMC_2 scenarios due to required investments in the development and engineering of the $ContC_2$ harvester head, as well as a presumably heavier and more expensive carrier. This assumption obviously affected the competitiveness of the $ContC_2$ machine system. A limited sensitivity analysis with regard to harvester cost was carried out, with the results indicating that equal hourly costs for TMC_2 and $ContC_2$ harvesters would increase BT area for the $ContC_2$ scenario with 6.7% compared to the figure shown in Table 3. Furthermore, variations in the cost of harvesting and forwarding were considered in detail, but the comminution cost per unit was kept constant. In practice, different comminution systems have specific niches (Laitila, 2008), which further increases the complexity of the problem.

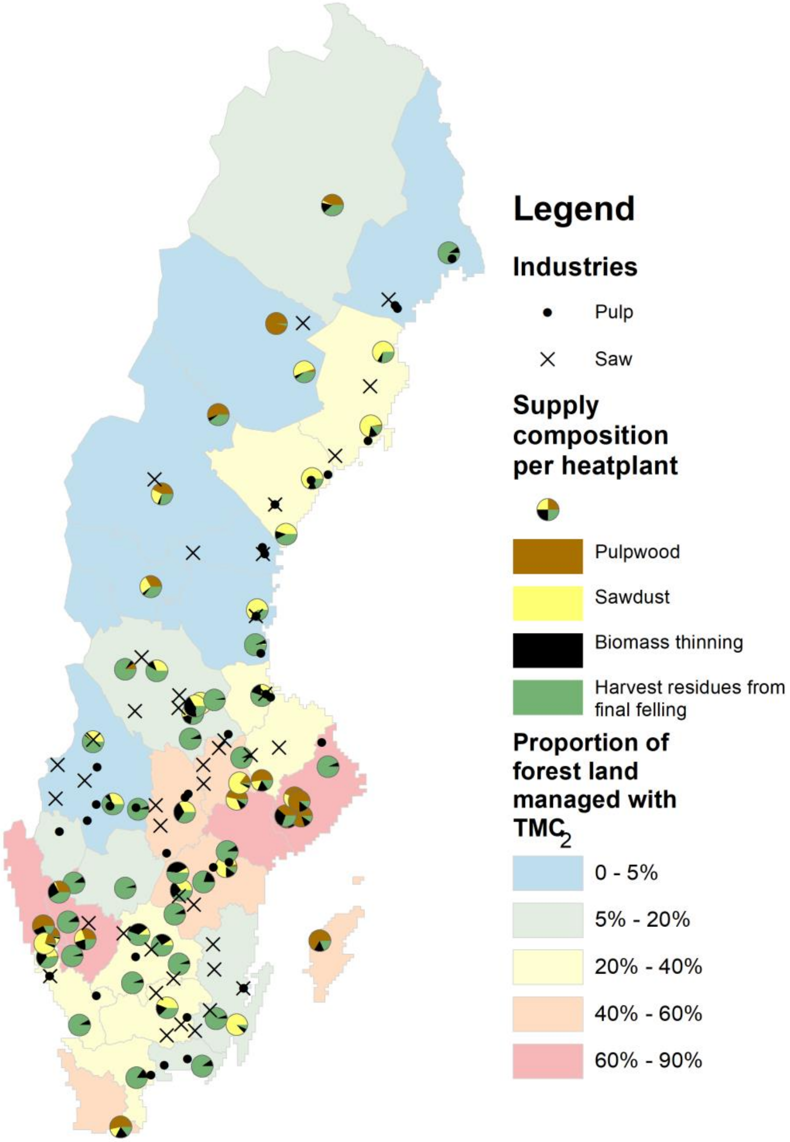


Figure 16. Geographic visualization of the TMC$_2$ scenario results. The supply compositions of heating plants and the proportion of forest land managed with biomass thinning (BT) per National Forest Inventory (NFI) region, expressed as mean values over the entire 100-year period.

In the analyses, the TMC_2 and $ContC_2$ systems were applied to first thinnings up to a mean height of 15 m, which corresponds to the tree size scope reported in Paper I. In the TMC_2 scenario, BT was most commonly applied to a mean tree height of around 12–14 m mean tree height and a mean stem volume of 0.06 m^3ob, both of which are similar to the values for the first thinning when harvesting roundwood (Anon., 2017). The results showed that BT stands out as an alternative to ordinary thinning rather than as a hybrid between cleaning and thinning. However, the performance and durability of a $ContC_2$ machine for this set of tree sizes should be investigated further, as $ContC_2$ treatments were applied to tree sizes that were similar to those handled by the TMC_2 system (data not shown). The additional costs associated with development and/or the heavier carrier machine may well be higher than the assumed 100 SEK $h^{-1}{}_{E15}$ (productive machine time including stops up to 15 minutes, measured in hours) compared to an ordinary thinning harvester with an accumulating, multiple-tree handling harvester head.

In NFI regions with low population density or low demand for pulpwood, BT activity was very low since pulpwood would be available for the limited local demand for energy. Correspondingly, densely populated areas with a high demand for biomass for energy showed a higher proportion of forest land managed with BT. Near the large urban areas of Stockholm and Gothenburg, BT was heavily utilized as an energy feedstock, as was pulpwood (Figure 16). Our results are expected in the sense that the availability and competitiveness of alternative biomass sources can be assumed to have a large effect on the demand for biomass from BT.

In comparison to SKA 15, the results in Paper IV revealed lower levels of bioenergy harvesting from Swedish forests. SKA 15 considered technical and biological restrictions to bioenergy harvesting, but not the market conditions. Hence, according to SKA 15, the available amount of bioenergy would be larger than what is finally utilized. The PCT activities in Paper IV were of the same magnitude as what was presented in SKA 15 (Figure 14), which could be attributed to a fairly low proportion of forest land that is managed with a BT regime (Table 3), with the exception of the $TMC_2\infty$ scenario, in which cleaning was clearly less preferred over time.

When compared with the results of Olsson & Lundmark (2014), the results in Paper IV indicate higher recovery of logging residues in final fellings, and in addition, an active supply of bioenergy from young dense forest stands (Figure 11). The difference in biomass utilization might stem from the selected modelling approaches. The detailed forest supply and industry demand descriptions in Paper IV—including geographical aspects—often limit the supply of by-products which can be readily used in a particular heat plant — in favour of nearby logging residues or bioenergy from BT.

The baseline scenarios showed that BT has limited implications for current forest policy and practice. Nevertheless, the impact and importance of BT could grow with an increase in demand (Table 3). Theoretically, BT could sustainably provide 5% or more of Sweden's total energy demand if market conditions were altered (e.g. through higher capacities or governmental subsidies).

Differences in the amount of material that BT can supply heat plants with (Table 3) between TMC_2 and $TMC_2\infty$, and between $ContC_2$ and $ContC_2\infty$, respectively, suggest that BT can supply industries that consume biomass (heat plant, biorefineries or other consumers) with feedstock if these industries would increase their demand for biomass. When these results are compared with what has been previously reported, e.g., Nordfjell et al. (2008) and Fernandez-Lacruz et al. (2015), the magnitude of the difference demonstrates that simpler approaches are poor at estimating the potential of BT. If such a overoptimistic potential estimate is used for decisions on investment in machinery and/or the development of new machine equipment—such as a $ContC_2$ harvester head—there is a risk that such investments will be unprofitable because the actual demand for forest biomass from BT is rather low.

The SweFor framework gives indirect indications for where industrial capacities could be altered (Figure 16). The development and introduction of an investment model that adjusts capacity based on profitability would be an important task in the future development of SweFor. Further research and development efforts could also be directed at using SweFor to analyse other forest management or silvicultural aspects, further develop the detail at which the industrial sectors are described in SweFor, e.g. considering multiple assortments per industry, integrating terminals and multiple transport solutions in the transportation model, or including saw mill and pulp mill bark production and use.

Growth reduction related to removal of nutrients in tops, branches and needles in thinnings was addressed in Paper IV using the standard Heureka settings, i.e. 5% reduced growth for the next 15 years following BT. This is in line with the conclusions by Egnell (2017) in his review on the subject – but wide variations in the reviewed results stresses the need for long-term studies Furthermore, Paper IV assumed that a proportion of the branches and needles would remain in the forest following extraction of the biomass assortment. A limited Finnish field experiment has suggested that the occurrence of wind and snow damage is positively correlated with the quota tree height / tree diameter at breast (Zubizarreta-Gerendiain et al., 2012). This quota increases over time, and most so for the BT intensive scenarios (cf. Figure 15). Forsell (2009) showed that adapting forest management to high wind damage risks leads to increases, however small, in net present value compared to business-as-usual forest management. Conversely, managing the forest in a more wind-sensitive way could potentially reduce NPV, yet the magnitude of this effect is unknown. Since neither adaptations of management nor adjustment for major storm occurrences were implemented it is possible that the models discussed in this thesis overestimate BT supply and advantages. Chudy et al. (2016) propose a structured method to incorporate risk in a broader sense – including stochastic events as well as data quality – in forest sector modelling by using an iterative sensitivity analysis based on known probabilities for risks and data errors. As for the ecological aspect, de Jong et al. (2017) concluded that BT impacts forest production at all harvest levels, but it was not explicitly mentioned to have negative effects, e.g. acidification or the release of toxins.

4 Synthesis

4.1 Methodological aspects

Papers I and II applied forest work science methods to obtain generic productivity functions for BT harvesters and forwarders. The research presented in both papers selected methods which ensured that no real, palpable forest machine was necessary for the analyses; as such, they may be entirely based on hypothetical forest machine systems with assumed associated properties. Considering the proposed future felling modes studied in Paper I (e.g. $2m^2C_2$, $ContC_2$ (Table 2)), the only alternative to the described approach would have been the construction of a physical piece of machinery to perform a time study with. This would have required substantial investments in product development and operator training if the study were to provide a fair and reliable comparison to existing felling modes. For this reason, an initial analysis of non-existing phenomena in the early stages of forest machinery innovation is a resource-efficient way to provide information on the benefits that may be provided by new systems, and prevent the unnecessary development costs for forest machine systems that in the end would have turned out to be less successful. Development resources may then instead be directed to other, more promising forest machine systems. One could therefore argue that a simulation model such as the one used in Paper I is the obvious method of choice in such cases. As for Paper II however, the forest machine under study was a forwarder used in, and perhaps adapted to, the forwarding of tree sections or whole trees in BT. Such forwarders exist in practice, and have been studied using inductive forest work science methods (Laitila, et al., 2007; Iwarsson Wide & Belbo, 2009; Iwarsson Wide & Belbo, 2010). Clearly, to fulfil the objectives of Paper II, other approaches, both a simulation model as well as an inductive approach – e.g. a correlation time study – could have been used instead. However, great variations in the productivity reported in previous time studies were observed, and it was decided that current BT forwarding practices are too heterogeneous to be generically described with reasonable means. On the other hand, the combination of a DF and the available comparative time study observations facilitated cost-effective, fairly accurate yet still empirically influenced BT forwarding productivity estimations. An empirical correlation-type validation of the productivity functions estimated using the methodology in Paper II should be performed in the future.

As for Papers III and IV, an alternative approach would have been addressing forest management issues – relevant on the stand or forest level – and national potential supply in two different studies applying entirely different methodologies. Such an approach would have given insight that was only valid for those spatial scales that the separate studies investigated. In other words, the forest level results would have lacked the market dimension, and the national results would not provide information as to in which stands or when BT should be applied. Moreover, the national study would not have taken into account recursive forest management dynamics. The selected approach was chosen precisely for this reason; it provides robust results on both levels, as the detailed forest representation and internal initiation of forest management activities (cf. Table 1) integrate forest management dynamics into the national supply problem. Turning to market-forest interactions, as shown in Figure 15, increased BT activity led to smaller mean diameter at a mean height of 15 m. Such a change in forest management practices will also influence the proportion of saw logs, and is captured using either *Theo* or *Diameter* saw log supply models, described in Paper III.

Since a detailed forest representation – including variations in management activities – was required to solve the investigated forest utilization problem, a mechanism for determining forest management activities was essential. Modelling forestry activities based on historical land owner behaviour, as is the case in SKA 15, is only valid for current management practices – and thus current market dynamics. Landowner behaviour associated with the harvesting of bioenergy from logging residues in final felling is described by Roos & Bohlin (2002), but was not implemented in SKA 15. Currently, BT is rarely applied in Swedish forestry and thus both scientifically founded management guidelines involving BT as well as the necessary empirical data are missing. In this way, BT analyses using the SKA 15 framework would require unfounded assumptions of market dynamics; that is, an arbitrary share of the theoretically available biomass from BT would have to be assumed as utilized. With such an approach, results concerning the impact of various forest management regimes (Figures 13 – 15) would directly reflect the assumptions of utilization rather than a projection of what BT utilization degree and forest management impacts to expect. The lack of market models in SKA 15 also makes it difficult to assess how new approaches for satisfying, for example, bioenergy demand will affect national forest management trends, i.e. new practices will affect growth, costs and revenues, which, in turn, affects supply, which in turn affect markets that feed back on forest management. In contrast, an optimization approach allows analytical variations of forest management activities that may be outside of the empirically known boundaries, but requires detailed and accurate formulations of the goals and constraints for the results to be adequate as support for decision-making or policy assessments.

The overarching aim of Paper IV deemed PEM the method of choice since this approach offers vast degrees of freedom regarding which aspects or issues of a forest utilization problem should be considered on the regional or national scale. However, the inclusion of multiple detailed aspects makes the model and its results more sensitive to errors in any of the underlying assumptions. For precisely this reason, one of the key deliverables of Paper III was investigating the validity of the model and identifying some potential errors – including land owner behaviour associated with the timing of final felling – in the PEM eventually employed in Paper IV.

When the research presented in this thesis is compared with similar Swedish studies, the method used in this thesis boasts the highest resolution across the different properties identified in Table 1. Nevertheless, ecological constraints were only addressed to a small extent, and external market dynamics (by definition) were kept constant. It is possible to modify SweFor to include additional ecological aspects, and extend the “partial” limit for which market dynamics are internal, but such changes represent a trade-off not only with model accuracy and sensitivity to errors, but also resolution in the currently addressed issues; e.g. all of the other reviewed PEMs (Table 1) except for NorFor (Sjølie et al., 2011, Sjølie et al., 2014) are rougher on the forest representation end. The observed difference between the TMC_2 and $TMC_2\infty$ scenarios provides the best proof of the contribution of the PEM approach in relation to simpler market models or market assumptions: when competing supply from other forest fuels in fulfilling the current district heating demand is included in the model, projected BT activity decreases to 20% of what is expected when competition between forest fuels is not considered.

4.2 Summarizing discussion of the results

A harvester performing BT was found to be more productive than a harvester that extracts only roundwood assortments. This is because the BT harvester utilizes a larger proportion of the harvested trees' total above-ground biomass without any additional TC (Paper I). To some extent, this gain in BT harvester productivity could be seen as lost in the BT forwarding activity (Paper II), since the BT assortment has a lower density than roundwood assortments (Bergström et al., 2010b). A geometrical harvest pattern led to higher harvester productivity than selective treatments (Paper I), and this dynamic was most pronounced for the wider 2 m boom corridors. This increase in harvester productivity was correlated with the amount of biomass accumulated by the harvester head per work cycle. Forwarder loading productivity also increased with larger piles (Paper II); in this aspect, BT with wide boom corridors favours both harvester and forwarder productivity. To summarize, BT operations seem to be a competitive alternative to roundwood harvesting operations, with regards to TC per harvested unit biomass.

The impacts of BT on forest management were identified and quantified in Papers I and IV; a geometrical harvesting pattern reduced selectivity in BT compared to an ordinary selective first thinning, and the increased BT activity was preceded by reduced PCT activity. These factors imply higher stem densities, and thus thinner trees, throughout the rotation period – and especially so up until the time of first (biomass) thinning. Nevertheless, saw log as well as pulpwood demands could be fulfilled in the different simulated scenarios in Paper IV, without compromising the sustainability of the forestry.

Paper IV analysed whether BT could be used to supply the district heating industry in Sweden. As has been put forth, forest biomass is expected to be increasingly used in new kinds of products, both solid materials and liquid fuels. SweFor can be used to analyse such scenarios, i.e. the heating plant industry (Figure 6) could be expanded to include all forest biomass consuming industries. The infinite demand scenarios (Table 3) hint that the industries that consume forest biomass have the potential to expand. The results in Paper IV revealed that BT has more potential than has been estimated in prior studies (Table 1). This finding can be attributed to several aspects, namely, BT was scheduled later in the rotation period, the analyses included the extraction of whole trees instead of only the harvesting residues, and the SweFor model considering both forest management activities as well as their effects, i.e. reduced PCT activity translates to more available biomass.

4.3 Extended use of SweFor and its results

SweFor could be used to analyse potential locations for new forest biomass consuming industries, such as the Metsä Äänekoski bioproduct mill, launched in August 2017. Although its main products are *"softwood and birch pulp for board, tissue, printing paper and speciality products"*, it is being marketed as *"the world's first next-generation bioproduct mill"*. Notable by-products (albeit many arise to some extent from the production in any arbitrary pulp mill) are tall oil, turpentine, bioelectricity, product gas, sulphuric acid and biogas (Metsä, 2018). Locations analyses could be performed either by starting with manually identified potential locations which are then evaluated iteratively, or deducing optimal sites using GIS analyses of the SweFor results, and/or spatial optimization. Other studies on localization of new forest biomass consuming industries – or terminals for transportation rationalization – can guide future extensions of the SweFor analyses (e.g. Forsberg et al., 2005; Pettersson et al., 2015; Athanassiadis & Nordfjell, 2017).

Revisiting the business innovation process aspect, the results in Paper IV indicated that an area-based felling device, such as ContC$_2$, had limited effects on additionally supplied biomass from BT, or NPS (Table 3). The differences in NPS between TMC$_2$ versus ContC$_2$, and TMC$_2$∞ versus ContC$_2$∞ amount to 270 and 1,180 million SEK respectively. When converted to annual net cash flow with a simple assumption of equal annual real-term net return, these differences in NPS corresponds to additional annual surpluses of 8.1 and 35.4 million SEK, respectively. This annual margin can be seen as a bonus associated with the development and usage of area-based felling devices. In Paper IV, it was assumed that a ContC$_2$ machine hour would cost 10% more than a TMC$_2$ machine hour to reflect the development costs of the new technology as well as the higher costs associated with a more complex area-based felling device and carrier. However, this assumed cost difference may not entirely reflect the cost of development as well as the associated risks. For speculative purposes, the additional annual surpluses derived from the NPS values in Paper IV should be interpreted as the possible reward for successfully developing (and marketing) an area-based ContC$_2$ felling device. However, the cost estimations should cover for one additional aspect that was not included in the ContC$_2$ system costs (Paper IV): the relocation of machines, both in BT and other forest management regimes. This approach is standard in strategic level forestry analyses, and the problems of relocation and aggregation of harvesting sites are usually considered on the tactical and operational levels. The spatial result in Figure 16 reveals regions with low BT activity. In those regions, it is likely that the relocation cost for specialized BT machinery (i.e. an area-based felling device) will outweigh the productivity benefits. Furthermore, forest harvesting machines are commonly used in an area that has a maximum radius of about 100 km from the owners' and operators' residences, and this distance is often much less. If one piece of machinery is not fully utilized its action range, the hourly cost of an expensive and specialized BT harvester will increase even further. It is likely that these unconsidered costs will restrain BT harvesting with area-based felling devices in some regions. However, according to the TMC and TMC∞ scenarios, relocation will have a negligible effect on BT harvesting as this forestry operation can use conventional machinery to apply an altered harvest pattern (Table 2). Finally, errors in e.g. the cost assumptions underlying this kind of assessment can be considered a risk factor, just as stochastic damage events or random errors in input descriptive data. The Monte Carlo approach proposed by Chudy et al. (2016) could in fact be a mean to cover also this aspect.

5 Conclusions

The main outcomes of this thesis can be concluded as:

- The productivity of biomass thinning (BT) harvesters increases with multiple-tree handling, geometrical harvest patterns and area-based felling devices, compared with a selective, single-tree handling thinning scenario. Productivity increases were greater in denser stands with smaller trees.

- Simulation and deductive productivity modelling seems to offer cost-efficient means for analysing the productivity of novel harvester and forwarder machine systems and techniques.

    - Inventions and new applications of existing equipment can be assessed already at a theoretical stage, early in the innovation process, as empirical data are not required in this approach. The results of such analyses may guide the continued innovation process in a more auspicious direction, but must be handled with consideration of the results' sensitivity to errors in descriptive data and assumptions.

- The SweFor partial equilibrium model (PEM) performs expectedly with regards to forest owner behaviour and saw log supply. This implies that other aspects – e.g. BT – analysed with SweFor can be expected to perform in a reliable way.

- The potential contribution of BT to Sweden's energy supply – given the current demand – is minor on national level, but may be of significant importance on the regional level.

- Although $\mathrm{ContC_2}$ is superior to $\mathrm{TMC_2}$ in terms of productivity in small-diameter stands, the contribution of $\mathrm{ContC_2}$ to additionally supplied biomass, i.e. the increase in net present surplus (NPS), is small relative to $\mathrm{TMC_2}$.

- BT activity seems positively correlated with high site qualities, high demand and lack of either alternative fuels or regional demand for pulpwood. Increased BT activity leads to reduced pre-commercial thinning (PCT) activity and a greater decrease in mean diameter at 15 m height over time.

- A PEM seems to be a useful tool for integrating the market aspect in the innovation process of novel machine systems and techniques. The results suggest that the predicted impact of BT, and the associated machinery, will vary greatly depending on whether or not the model takes into account market factors (total demand and competing supply with its associated costs). This implies two alternative consequences:

    - Ignoring the market aspect during the innovation process may lead to unnecessary investment in the development and implementation of machine systems that will ultimately be less successful than productivity or simple potential estimates predicted.

  or

    - The significant difference between the current market and infinite demand scenarios present a huge potential for the increased utilization of forest biomass in new products. In this way, an increase in the demand for forest biomass would increase net social surplus in the forest sector and a new doctrine for Swedish forest management.

6 References

AedoOrtiz, D., Olsen, E. & Kellogg, L. (1997). Simulating a harvester-forwarder softwood thinning: A software evaluation. *Forest Products Journal*, 47(5), pp. 36-41.

Ahnlund Ulvcrona, K., Bergström, D. & Bergsten, U. (2017). Stand structure after thinning in 1–2 m wide corridors in young dense stands. *Silva Fennica*, 51(3), pp. 1-15.

AIMMS (2016). AIMMS B.V., The Netherlands.

Anerud, E. (2012). *Stumps as Fuel – the influence of handling method on fuel quality. Acta Unversitatis agriculturae Sueciae 2012:85,* Uppsala: SLU.

Anon. (2017). *INGVAR - beslutsstöd för gallring och röjning (Decision support for thinning and cleaning). In Swedish.*. [Online]
Available at: https://www.skogforsk.se/produkter-och-evenemang/verktyg/ingvar/
[Accessed 4 December 2017].

Athanassiadis, D. & Nordfjell, T. (2017). Regional GIS-based evaluation of the potential and supply costs of forest biomass in Sweden. *Frontiers of Agricultural Science and Engineering*, 4(4), pp. 493-501.

Baul, T. K., Alam, A., Ikonen, A., Standman, H., Asikainen, A., Peltola, H. & Kilpeläinen, A. (2017). Climate Change Mitigation Potential in Boreal Forests: Impacts of Management, Harvest Intensity and Use of Forest Biomass to Substitute Fossil Resources. *Forests*, 8(11).

Berg, S. (2014). *Technology and Systems for Stump Harvesting with Low Ground Disturbance. Acta Universitatis agriculturae Sueciae 2014:95.* Umeå: SLU.

Bergström, D., Bergsten, U. & Nordfjell, T. (2007). Simulation of geometric thinning systems and their time requirements for young forests. *Silva Fennica 41(1),* pp. 137-147.

Bergström, D., Bergsten, U. & Nordfjell, T. (2010a). Comparison of boom-corridor thinning and thinning from below harvesting methods in young dense Scots pine stands. *Silva Fennica, 44(4),* pp. 669-679.

Bergström, D., Nordfjell, T. & Bergsten, U. (2010b). Compression Processing and Load Compression of Young Scots Pine and Birch Trees in Thinnings for Bioenergy. *International Journal of Forest Engineering*, 21(1), pp. 31-39.

Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G., Lindner, M., Marelli, L., Paré, D., Pingoud, K. & Yeh, S. (2016). *Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy 3.*, s.l.: European Forest Institute.

BillerudKorsnäs (2018). *The Paper Bottle project.* [Online]
Available at: https://www.billerudkorsnas.com/about-us/the-paper-bottle-project
[Accessed 19 08 2018].

Bohlin, F. & Roos, A. (2002). Wood fuel supply as a function of forest owner preferences and management styles. *Biomass and Bioenergy*, 22(4), pp. 237-249.

Borges, J., Nordström, E.M., Garcia-Gonzalo, J., Hujala, T. & Trasobares, A. (2014). *Computer-based tools for supporting forest management. The experience and the expertise world-wide,* Umeå: SLU, Dept. for Forest Resource Management. ISBN (electronic): 978-91-576-9237-5

Bostedt, G., Mustonen, M. & Gong, P. (2016). Increasing forest biomass supply in northern Europe – countrywide estimates and economic perspectives. *Scandinavian Journal of Forest Research*, 31(3), pp. 314-322.

Bredberg, C.-J. (1972). *Type stands for the first thinning, Research Notes No. 55.* Stockholm: Royal College of Forestry. Dept. of Operational Efficiency.

Brunberg, T. (1997). *Basic data for productivity norms for single-grip harvesters in thinning, Redogörelse No. 8.* Uppsala: Skogforsk.

Börjesson, P., Hansson, J. & Berndes, G. (2017). Future demand for forest-based biomass for energy purposes in Sweden. *Forest Ecology and Management*, Volume 383, pp. 17-26.

Chudy, R., Sjølie, H. & Solberg, B. (2016). Incorporating risk in forest sector modeling – state of the art and promising paths for future research. *Scandinavian Journal of Forest Research*, 31(7), pp. 719-727.

Dees, M. & Rettenmaier, N. (2009). *Overview of European studies of biomass resource assessment - BEE.* [Online]
Available at: http://www.eu-bee.eu/_ACC/_components/ATLANTIS-DigiStore/dees_biomass_potential5501.pdf?item=digistorefile;144642;837&params=open;gallery
[Accessed 13 08 2018].

Demirbas, N. (2009). Biorefineries for biofuel upgrading: A critical review. *Applied energy*, Volume 86, pp. 151-161.

Domsjö Fabriker (2018). *Domsjö Fabriker Sustainability.* [Online]
Available at:
http://www.domsjo.adityabirla.com/Documents/Hallbarhetsredovisning/Domsjo_hallbarhetsredovisning.pdf [Accessed 19 08 2018].

Eggers, J., Lämås, T., Lind, T. & Öhman, K. (2014). Factors influencing the choice of management strategy among small-scale private forest owners in Sweden. *Forests*, 5(7), pp. 1695-1716.

Egnell, G. (2017). A review of Nordic trials studying effects of biomass harvest intensity on subsequent forest production. *Forest Ecology and Management*, Volume 383, pp. 27-36.

Elfving, B. (2010). Natural mortality in thinning and fertilisation experiments with pine and spruce in Sweden. *Forest Ecology and Management*, Volume 260, pp. 353-360.

Eliasson, L. (1998). *Analyses of Single-Grip Harvester Productivity, Acta Universitatis agriculturae Sueciae, Silvestria, 1998:80*. Umeå: SLU.

Eliasson, L. (1999). Simulation of thinning with a single-grip harvester. *Forest Science*, 45(1), pp. 26-34.

Eriksson, L.O., Athanassiadis, D. & Öhman, M. (2013). *Ett energioptimerat skogsbruk i Sverige. Rapport 2013:17.,* Stockholm: Svensk Fjärrvärme.

Fernandez-Lacruz, R., di Fulvio, F., Athanassiadis, D., Bergström, D. & Nordfjell, T. (2015). Distribution, characteristics and potential of biomassdense thinning forests in Sweden. *Silva Fennica,* 49(5), pp. 1-17.

Ford, E. (2000). *Scientific Method for Ecological Research,* Port Chester, NY: Cambridge University Press.

Forsberg, J. & Wennberg, R. (2011). *Teknikutveckling av aggregat för kontinuerligt ackumulerande skörd i unga skogar. Examensarbete.,* Luleå: Luleå Tekniska Universitet.

Forsberg, M., Frisk, M. & Rönnqvist, M. (2005). FlowOpt - A Decision Support Tool for Strategic and Tactical Transportation Planning in Forestry. *International Journal of Forest Engineering,* 16(2), pp. 101-114.

Fridman, J., Holm, S., Nilsson, M., Nilsson, P., Hedström Ringvall, A. & Ståhl, G. (2014). Adapting National Forest Inventories to changing requirements - the case of the Swedish National Forest Inventory at the turn of the 20th century. *Silva Fennica, 48(3).*

di Fulvio, F., Kroon, A., Bergström, D. & Nordfjell, T. (2011). Comparison of energy-wood and pulpwood thinning systems in young birch stands. *Scandinavian Journal of Forest Research*, 26(4), pp. 339-349.

Geissdoerfer, M., Bocken, N. M. & Hultink, E. J. (2016). Design thinking to enhance the sustainable business modelling process - A workshop based on a value mapping process. *Journal of Cleaner Production*, Volume 135.

Ghaffariyan, M., Brown, M., Acuna, M., Sessions, J., Gallagher, T., Kühmaier, M., Spinelli, R., Visser, R., Devlin, G., Eliasson, L., Laitila, J., Laina, R., Iwarsson Wide, M. & Egnell, G. (2017). An international review of the most productive and cost effective forest biomass recovery technologies and supply chains. *Renewable and Sustainable Energy Reviews*, Volume 74, pp. 145-158.

Gullberg, T. (1997a). A deductive time consumption model for loading shortwood. *Journal of Forest Engineering,* 8(1), pp. 35-44.

Gullberg, T. (1997b). *Time consumption model for off-road extraction of shortwood, Papers and Results, No. 297.* Garpenberg: SLU.

Gustavsson, L., Haus, S., Lundblad, M., Lundström, A., Ortiz, C.A., Sathre, R., Truong, N.L. & Wikberg, P-E. (2017). Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels. *Renewable and Sustainable Energy Reviews,* Volume 67, pp. 612-624.

Gustavsson, R. (1974). *Type stands for cleaning, Research Note No. 70.* Garpenberg: Royal College of Forestry. Dept. of Operational Efficiency.

Heikkilä, J., Siren, M., Ahtikoski, A., Hynynen, J., Sauvula, R., Lehtonen, M. (2009). Energy Wood Thinning as a Part of the Stand Management of Scots Pine and Norway Spruce. *Silva Fennica, 43(1),* pp. 129-146.

Heinimann, H.R. (2007). Forest operations engineering and management - the ways behind and ahead of a scientific disipline. *Croatian Journal of Forest Engineering,* 28(1), pp. 107-121.

Holsapple, C. (2008). Decision and knowledge. In: F. Burstein & C. Holsapple, eds. *Handbook on Decision Support Systems.* Berlin: Springer, pp. 21-53.

Hynynen, J., Salminen, H., Ahtikoski, A., Huuskonen, S., Ojansuu, R., Siipiletho, J., Lehtonen, M. & Eerikäinen, K. (2015). Long-term impacts of forest management on biomass supply and forest resource development: a scenario analysis for Finland. *European Journal of Forest Research*, 134(3), pp. 415-431.

Hyytiäinen, K., Tahvonen, I. & Valsta, L. (2005). Optimum juvenile density, harvesting, and stand structure in even-aged Scots pine stands. *Forest Science, 51(2),* pp. 120-133.

Hägglund, B. (1982). Some remarks on the plot-stand problem in forest inventory. In: *Statistics in theory and practice: Essays in honour of Bertil Matérn.* Umeå: Swedish University of Agricultural Sciences, Section of Forest Biometry, pp. 137-157.

Hägglund, B. & Lundmark, J.-E. (1981). *Handledning i bonitering med Skogshögskolans boniteringssystem. 124 pp. (In Swedish.),* Jönköping, Sweden: National Board of Forestry .

Iwarsson Wide, M. & Belbo, H. (2009). *Jämförande studie av olika tekniker för skogsbränsleuttag - Skogsbränsleuttag med Naarva-gripen 1500-40E, Bracke C16.A och LogMax 4000, Mellanskog, Färila. Working papers no. 679.* Uppsala: Skogforsk.

Iwarsson Wide, M. & Belbo, H. (2010). *A comparative study of different techniques for forest fuel extraction in very small forests - Forest fuel extraction with the Naarva 1500-40E grip and LogMax 4000, Mellanskog, Simeå. Working papers no. 709.* Uppsala: Skogforsk.

Johnson, K.N. & Scheurman, H.L. (1977). Techniques for prescribing optimal timber harvest and investment under different objectives – Discussion and Synthesis. *Forest Science Monograph 18.*

de Jong, J., Akselsson, C., Egnell, G., Löfgren, S. & Olsson, B.A. (2017). Realizing the energy potential of forest biomass in Sweden – How much is environmentally sustainable?. *Forest Ecology and Management*, Volume 383, pp. 3-16.

Jylhä, P. & Laitila, J. (2007). Energy wood and pulpwood harvesting using a prototype whole-tree bundler. *Silva Fennica 41(4),* pp. 763-779.

Karlsson, L. (2013). *Silvicultural regimes and early biomass thinning in young, dense pine stands, Acta Universitatis agriculturae Sueciae, Doctoral thesis No. 2013:90. Faculty of Forest Sciences.* Umeå: SLU.

Karlsson, L., Bergsten, U., Ulvcrona, T. & Elfving, B. (2013). Long-term effects on growth and yield of corridor thinning in young Pinus silvestris stands. *Scandinavian Journal of Forest Research. 28.,* pp. 28-37.

Karttunen, K., Laitila, J. & Ranta, T. (2016). First-thinning harvesting alternatives for industrial or energy purposes based on regional Scots pine stand simulations in Finland. *Silva Fennica, 50(2).*

Laitila, J. (2008). Harvesting technology and the cost of fuel chips from early thinnings. *Silva Fennica*, 42(2), pp. 267-283.

Laitila, J., Asikainen, A. & Nuutinen, Y. (2007). Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. *International Journal of Forest Engineering 18(2),* pp. 29-39.

Laitila, J., Niemistö, P. & Väätäinen, K. (2016). Productivity of Multi-Tree Cutting in Thinnings and Clear Cuttings of Young Downy Birch (Betula pubescens) Dominated Stands in the Integrated Harvesting of Pulpwood and Energy Wood. *Baltic Forestry*, 22(1), pp. 116-131.

Latta, G. S., Sjølie, H. K. & Solberg, B. (2013). A review of recent developments and applications of partial equilibrium models of the forest sector. *Journal of Forest Economics 19*, pp. 350-360.

Lindroos, O. (2010). Scrutinizing the theory of comparative time studies with operator as a block effect. *International Journal of Forest Engineering*, 21(1), pp. 20-30.

Lindroos, O., La Hera, P. & Häggström, C. (2017). Drivers of Advances in Mechanized Timber Harvesting – a Selective Review of Technological Innovation. *Croatian Journal of Forest Engineering*, 38(2), pp. 243-258.

Lundmark, R., Athanassiadis, D. & Wetterlund, E. (2015). Supply assessment of forest biomass - A bottom-up approach for Sweden. *Biomass and Bioenergy*, Volume 75, pp. 213-226.

Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P.S., McEwan, A., Brink, M. & Laschi, A. (2018). Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. *Science of the Total Environment*, Volume 634, pp. 1385-1397.

Melin, Y. (2014). *Impacts of stumps and roots on carbon storage and bioenergy use in a climate change context. Acta Universitatis agriculturae Sueciae 2014:79*, Umeå: SLU.

Metsä (2018). *Metsä Group's Bioproduct mill.* [Online]
Available at: https://www.metsafibre.com/en/about-us/Bioproduct-mill/Pages/default.aspx#
[Accessed 13 09 2018].

Microsoft (2007). Microsoft, Redmond, WA.

Mintzberg, H. (2000). *The rise and fall of strategic planning.* London: Pearson Education.

Muys, B., Hynynen, J., Palahí, M., Lexer, M.J., Fabrika, M., Pretzsch, H., Gillet, F., Briceño, E., Nabuurs, G.J. & Kint, V. (2010). Simulation tools for decision support to adaptive forest management in Europe. *Forest Systems*, Volume 19, pp. 86-99.

Newnham, R. (1966). A simulation model for studying the effect of stand structure on harvesting pattern. *Forest Chronicle*, Volume 42, pp. 39-44.

Nordfjell, T., Nilsson, P., Henningsson, M. & Wästerlund, I. (2008). *Unutilized biomass resources in Swedish young dense forests.* Proceedings of the World Bioenergy Conference and Exhibition on Biomass for Energy, Jönköping, Sweden, 27-29 May 2008, The Swedish Bioenergy Association, pp. 323-325.

Nurminen, T., Korpuhnen, H. & Uusitalo, J. (2006). Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fennica, 40(2)*, pp. 335-363.

Oikari, M., Kärhä, K., Palander, T., Pajuoja, H. & Ovaskainen, H. (2010). Analyzing the Views of Wood Harvesting Professionals Related to the Approaches for Increasing the Cost-Efficiency of Wood Harvesting from Young Stands. *Silva Fennica, 44(3)*, pp. 481-495.

Olsson, A. & Lundmark, R. (2014). Modelling the Competition for Forest Resources: The Case of Sweden. *Journal of Energy and Natural Resources*, 3(2), pp. 11-19.

Ovaskainen, H. (2008). *Timber harvester operators working technique in first thinning and the importance of cognitive abilities on work productivity, Dissertationes Forestales 79.* Joensuu: University of Joensuu.

Ovaskainen, H., Uusitalo, J. & Sassi, T. (2006). Effect of edge trees on harvester positioning in thinning. *Forest Science*, 52(6), pp. 659-669.

Ovaskainen, H., Uusitalo, J. & Väätäinen, K. (2004). Characteristics and significance of a harvester operators' working technique in thinnings. *International Journal of Forest Engineering,* 15(2), pp. 67-77.

Pettersson, K. et al. (2015). Integration of next-generation biofuel production in the Swedish forest industry – A geographically explicit approach. *Applied Energy,* Volume 154, pp. 317-332.

Pettersson, N. (1993). The Effect of Density after Precommercial Thinning on Volume and Stucture in Pinus Sylvestris and Picea Abies stands.. *Scandinavian Journal of Forest Research, 8.,* pp. 528-539.

Ringdahl, O., Hellström, T. & Lindroos, O. (2012). Potentials of possible machine systems for directly loading logs in cut-to-length harvesting. *Canadian Journal of Forest Research*, 42(5), pp. 970-985.

Routa, J., Asikainen, A., Björheden, R., Laitila, J. & Röser, D. (2013). Forest energy procurement: state of the art in Finland and Sweden. *Wiley Interdisciplinary Reviews-Energy and Environment, 2(6),* pp. 602-613.

Samset, I. (1966). Loven om den sprangvise vikling (The law of discontinuous evolution). *Norsk Skogbruk*, Volume 12, pp. 737-741.

Samset, I. (1990). *Some observations on time and performance studies in forestry, Communication No. 43.5.* Ås: Norwegian Forest Research Institute.

Santesson, M. & Sjunnesson, S. (1972). *Simulation model for thinning machines, Research Notes, No. 49.* Stockholm: Royal College of Forestry, Dept. of Operational Efficiency.

Siren, M. & Aaltio, H. (2003). Productivity and costs of thinning harvesters and harvester-forwarders. *International Journal of Forest Engineering* 14(1), pp. 39-48.

Sjølie, H. K., Latta, G. S., Gobakken, T. & Solberg, B. (2011). *NorFor - a forest sector model of Norway. Model overview and structure,* Ås: Department of Ecology and Natural Resource Management, Norwegian University of Life Sciences.

Sjølie, H., Latta, G. & Solberg, B. (2014). Impacts of the Kyoto Protocol on boreal forest climate change mitigation. *Annals of Forest Science*, Volume 71, pp. 267-277.

SLU, 2016. *Heureka Wiki.* [Online]
Available at: http://heurekaslu.org/wiki/Main_Page
[Accessed 09 08 2016].

Solberg, B. (1986). Forest sector simulation models as methodological tools in forest policy analysis. *Silva Fennica*, 20(4), pp. 419-427.

Sundberg, U. & Silversides, C. (1988). *Operational Efficiency in Forestry: Analysis (Vol. 1),* Springer.

Swedish Energy Agency (2014). *Scenarier över Sveriges energisystem, ER 2014:19,* Eskilstuna: Swedish Energy Agency.

Swedish Energy Agency (2015). *Production of unprocessed wood fuels 2014. ES 2015:08,* Eskilstuna: Swedish Energy Agency.

Swedish Energy Agency (2017). *Trädbränsle- och torvpriser Nr 4 / 2017,* Eskilstuna: Swedish Energy Agency.

Swedish Energy Agency (2018). *Energiläget i siffror 2018.* [Online]
Available at: http://www.energimyndigheten.se/nyhetsarkiv/2018/nu-finns-energilaget-i-

siffror-20182/
[Accessed 03 10 2018].

Swedish Forest Agency (2008). *Rekommendationer vid uttag av avverkningsrester och askåterföring,* Jönköping: Swedish Forest Agency.

Swedish Forest Agency (2009). *Stubbskörd - kunskapssammanställning och Skogsstyrelsens rekommendationer. (Meddelande no. 4:2009.),* Jönköping: Swedish Forest Agency.

Swedish Forest Agency (2014). *Swedish Statistical Yearbook of Forestry,* Jönköping: Swedish Forest Agency.

Swedish Forest Agency (2015a). *Rundvirkes- och skogsbränslebalanser för år 2013 - SKA 15. Meddelande 3:2015.,* Jönköping: Swedish Forest Agency.

Swedish Forest Agency (2015b). *Skogliga konsekvensanalyser 2015 - SKA 15. Rapport 10:2015.,* Jönköping: Swedish Forest Agency.

Swedish Forest Agency (2016). *Prices on roundwood in 2015.* [Online]
Available at:
http://www.skogsstyrelsen.se/Global/myndigheten/Statistik/Statistiska%20meddelanden/2016/SM_Rundvirkespriser_2016-01-28.pdf
[Accessed 01 08 2016].

Swedish Forest Agency (2017). *Nationella sektorsrådet, minnesanteckningar 2017-09-26.* [Online]
Available at: https://www.skogsstyrelsen.se/globalassets/om-oss/radgivande-grupper/nationella-sektorsradet/20170926/minnesanteckningar-sektorsrad-170926.pdf
[Accessed 28 09 2018].

Swedish Forest Agency (2018). *Statistik efter ämne.* [Online]
Available at: https://www.skogsstyrelsen.se/statistik/statistik-efter-amne/
[Accessed 07 09 2018].

Swedish Forest Industries Federation (2017). *Statistics - International - Forest Industry.* [Online]
Available at: http://www.forestindustries.se/forest-industry/statistics/international/
[Accessed 06 08 2018].

Sängstuvall, L. (2010). *Estimates of the productivity of logging operations with a focus on forest fuel extraction. Arbetsrapport 261.,* Umeå: SLU. Department of Forest Resource Management.

Sängstuvall, L. (2018). *Tidsåtgångsfunktioner för skotning av träddelar med mellanstor skotare. [In Swedish],* Umeå: SLU. Manuscript.

Söderholm, J. (2002). *The planning system of Swedish forest companies. Arbetsrapport 98.,* Umeå: SLU. Department of Forest Resource Management and Geomatics.

Talbot, B., Nordfjell, T. & Suadicani, K. (2003). Assessing the utility of two integrated harvester-forwarder machine concepts through stand-level simulation. *International Journal of Forest Engineering,* 14(2), pp. 31-43.

Trømborg, E. & Solberg, B. (2010). Forest sector impacts of the increased use of wood in energy production in Norway. *Forest Policy and Economics,* 12, pp. 39-47.

Wang, J., LeDoux, C. & Li, X. (2005). Simulating cut-to-length harvesting operations in Appalachian hardwoods. *International Journal of Forest Engineering,* 16(2), pp. 11-27.

Varmola, M. & Salminen, H. (2004). Timing and intensity of precommercial thinning in Pinus sylvestris stands. *Scandinavian Journal of Forest Research, 19(2),* pp. 142-151.

Wetterlund, E., Pettersson, K., Mossberg, J., Torén, C., Hoffstedt, A. & von Schenck, A. (2013). *Optimal localisation of next generation biofuel production in Sweden, 2013:8,* Göteborg: Swedish Knowledge Centre for Renewable Transportation Fuels (F3).

Wikström, P. (2000). A Solution Method for Uneven-Aged Management Applied to Norway Spruce. *Forest Science. 46(3),* pp. 452-463.

Wikström, P. et al. (2011). The Heureka Forestry Decision Support System: An Overview. *Mathematical and Computational Forestry & Natural-Resource Sciences. 3(2)* , pp. 87-94.

Popular science summary

Forest biomass is used as feedstock for forest products as well as for bioenergy. The current Swedish roundwood utilization is near the sustainable maximum, and so increased forest biomass consumption in Sweden must utilize additional parts of the trees already harvested, and/or that small trees not utilized today must be harvested. New ways to harvest such small trees, including stems, tops, branches and needles – biomass thinning (BT), were developed over the years 2005-2010. Harvesting in a geometrical pattern (boom-corridors, Figure 1), with a conventional harvester head or a specialized area-based felling device, was described and tested. After promising tests, more research was needed to see if the results were valid under other conditions than those tested. The overall objective of this thesis is to analyse the impact of new BT harvesting technology with regards to recovery costs, forest management and national forest biomass supply. A popularized and sharpened question at issue in this thesis is

"Should we stop doing pre-commercial thinning, and instead grow dense young stands with small trees, which can be harvested for energy or other use with new and efficient harvesting techniuque?"

Harvester and forwarder productivity in new kinds of BT operations were modelled, and the results were implemented in the Heureka decision support system, to allow long-term forest planning analyses of BT. Forest management programs simulated with Heureka were used in the SweFor sector model, where forest industry demand is balanced with potential supply from the forest, and the consequences of industry consumption in one period affects the forest development in the following periods. SweFor was tested for a couple of assumptions other than BT, and worked expectedly there. As for BT, it was the preferred management regime on about 15% of the managed Swedish forest area, and provided 15% of the total supply to heat plants. If the forest industries could consume endless amounts of biomass, for present or new uses and products, BT activity could increase with 300%.

In conclusion, the answer to the popularized question asked is

"It depends, on market conditions as well as forest characteristics".

Populärvetenskaplig sammanfattning

Biomassa från skogen används som råvara för såväl skogsprodukter (papper, massa, sågade trävaror) som bioenergi. Den svenska avverkningen av rundvirke ligger nära den högsta hållbara nivån. Detta innebär att ökat utnyttjande av biomassa från den svenska skogen till del måste baseras på andra delar av de träd som redan avverkas, och/eller småträd som inte tillvaratas idag. Nya metoder och tekniker för att tillvarata sådana träd utvecklades under åren 2005-2010. med hjälp av befintlig eller ny drivningsteknik. Gallring i ett geometriskt mönster (krankorridorer, Figur 1), med ett vanligt skördaraggregat eller en specialbyggd arealbaserad fällningsutrustning, beskrevs och testades. Efter lovande tester behövdes mer forskning för att se om testresultaten blev de samma under fler förutsättningar. Det övergripande syftet med denna avhandling är att analysera effekterna av nya tekniker och metoder för biomassagallring, med avseende på drivningskostnad, skogsskötsel och nationell biomassaförsörjning från den svenska skogen. En populariserad och tillspetsad frågeställning i avhandlingen kan låta såhär:

“Ska man sluta röja skogen, och istället odla unga täta bestånd med klena träd, som kan avverkas som energiråvara eller för annan användning, med ny och effektiv drivningsteknik?”

Skördar- och skotarproduktivitet i nya typer av biomassagallring modellerades, och resultaten implementerades i beslutsstödssystemet Heureka, så man kunde göra långsiktiga analyser av biomassagallring. Skogsskötselprogram som simulerats med Heureka användes sedan i sektorsmodellen SweFor, där skogsindustrins efterfrågan balanseras med möjlig försörjning från skogen, och konsekvenserna av industrins förbrukning av råvara från skogen i en period påverkar skogens sammansättning och utveckling i de kommande perioderna. SweFor testades för ett par antaganden som inte rörde biomassagallring, och fungerade som förväntat. Biomassagallring var det bästa skötselalternativet på ungefär 15% av den brukade skogsmarksarealen, och stod för ungefär 15% av försörjningen av skoglig biomassa till de svenska fjärrvärmeverken, med dagens marknadsförutsättningar. Med obegränsad efterfrågan på skoglig biomassa, givet dagens prisnivåer, ökar den nyttjande volymen från biomassagallring med 300%, som kan gå till nya typer av användning och produkter.

Sammanfattningsvis är svaret på den populariserade frågeställningen

“Det beror på, marknadsläget och de skogliga förutsättningarna”.

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