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Forest Refine, 2012-2014

– Efficient forest biomass supply chain management for biorefineries

Synthesis report

Editors: Dan Bergström, Magnus Matisons

Rapport 18 2014

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Abstract

Current biorefining activities and plans for new biorefineries in Sweden and Finland are largely concentrated on the production of liquid biofuels for the transport sector. However, the pulp industry (and other players) are also developing new biorefinery processes, for example to: convert pulp fibers into new types of materials and products (e.g. textiles, diverse composites and nanocellulose); upgrade residue streams to deliver marketable products (e.g. via black liquor gasification, lignin extraction, fermentation of hemicellulose, and gasification or hydrolysis of fibre sludge); implement processes for co-production of process steams and marketable products (e.g. gasification and pyrolysis); and extract useful substances from incoming raw material (e.g. pre-extraction of hemicellulose). Thus, for example tall oil from pulp mills is increasingly being used as feedstock for both motor fuels and various chemicals. The raw material requirements of future biorefineries (in terms of abundance, quality and timing of supplies) may radically differ from those of traditional forest industries and energy plants, demanding equally radical adjustment of the supply chains. Thus, it is vitally important to harmonize research and development goals in parts of northern Sweden and Finland in the Botnia-Atlantica (BA) region with the development of efficient and sustainable supply chains for forest raw material. Hence, the overall objective of this project was to acquire knowledge of ways to optimize biomass supplies for refineries in the BA region from existing, planned or potential procurement areas.

An overall conclusion from the studies is that supply costs can be significantly reduced by integrating supplies of pulpwood and residual assortments rather than providing them via separate supply chains. However, assessing the costs and benefits of possible systems is not straightforward as they are influenced by complex interactions between supplies of multiple feedstock assortments and demands from multiple users. Furthermore, the costs of separating stemwood from residues at a later point in the chain may reduce or eliminate the benefits of integrated harvest. Hence, the advantages would be greatest for applications in which there is little gain from separating these assortments. Available amounts of feedstock could also be increased by pre-treatment operations, which could make previously non-viable assortments available. However, any cost reductions thus achieved from increasing supplies should be weighed against the additional pre-treatment costs. Overall, the options studied in the project indicate that new practices could potentially reduce supply costs by around 10%, compared to current best practices, under certain conditions.

Another critical factor is to ensure that supplies of biomasses with various qualities can be rapidly adjusted and adapted to meet shifts (potentially unpredictable) in demand. Terminals can play a key role in the provision of such flexibility. Current terminals are mainly used as transition points, where little upgrading is done apart from comminution. Since raw forest biomass cannot be transported long distances, due to its relatively low value, robust value-upgrading at terminals closer to terminals before long distance transportation is likely to be necessary. Such terminals must be quite sophisticated in order to serve as flexible/semi-mobile refineries, i.e. they will need to have access (*inter alia*) to appropriate infrastructure, electricity, water and personnel. As most of the unexploited forest biomass resources are located in inland areas, particular attention should be paid to developing terminal-refinery-integrated supply chains in these areas for supplying industry-dense areas for further refining or direct use in processes.

Keywords: bioenergy; biofuels; bio-based economy; lignocellulosic; upgrading; wood procurement

Foreword

The “Forest Refine” project is the fourth cross-border project between partners in Sweden and Finland with the overall objective to analyze and improve the forest fuel supply chain.

The first was the 2-year “Bioenergy from forest 1” project, launched in 2003 with a budget of 860 000 € financed by the European Union’s Interreg kvarken mittskandia program, County Administrative Board of Västerbotten and Regional Council of Central Ostrobothnia. The participating partners were the Central Ostrobothnia Rural Institute (Kannus unit), Chydenius Institute, Swedish University of Agricultural Sciences (SLU: Department of Forest Management and Unit for Biomass Technology and Chemistry), Finnish Forest Research Institute (METLA) and Central Ostrobothnia Forest Owners Association. The project compiled existing knowledge of the forest fuel supply chain, and identified knowledge gaps. Studies were carried out to analyze and improve technology and methods for extracting logging residues, including innovative systems for multi-tree handling and corridor harvests. Possibilities to harvest, dry and pelletize wood from young trees were also studied and evaluated. Pellets produced were characterized and combusted. The knowledge gained in the project was disseminated to forest owners, machine operators, energy entrepreneurs, and energy experts in municipalities and universities via cross-border seminars, field demonstrations and distribution of information sheets. The project established a fertile cross-border partnership for information exchange. Some of the identified knowledge gaps were filled but several new gaps were identified that were to be studied in subsequent projects.

In 2005 a 2-year follow-up project, “Bioenergy from forest 2”, was launched with the same partners and a budget of 1 000 000 € from the same providers. Building on the knowledge gained from the previous project, extensive studies were carried out to analyze and improve technology and methods applied at all steps in the forest fuel supply chain: harvesting, handling, storing and transportation of young trees from the forest to small-scale heating cooperatives. New logistical solutions adapted to regional conditions and their environmental impact on poor soils were evaluated. Possible ways to improve the fuel quality of young trees were considered, including various means of debarking, delimbing, processing and storing them. Local solutions for using pellets produced from young trees instead of fuel chips were also addressed, and both chips’ and pellets’ physicochemical characteristics and combustion properties were analyzed. Studies were carried out in close cooperation with forest owners, entrepreneurs and local heating plants’ staff, who also participated in seminars and field excursions. Information from the project was also communicated in international seminars and exhibitions, and through extensive distribution of information sheets.

In 2009 the 3-year “Forest Power” project was launched with a budget of 4 400 000 €. The project was partly financed by the European Union’s Botnia-Atlantica (BA) program (ERDF, Interreg IV A), the Regional Council of Ostrobothnia, and the County Administrative Boards of Västerbotten and Västernorrland. There were also contributions from several Norwegian sources, including the State of Norway, Nordland County, the County Governor’s Office in Nordland and the Norwegian Ministry of Agriculture and Food. Participating partners were: METLA, Centria, Central Ostrobothnia Rural Institute (Kannus unit), Central Ostrobothnia Forest Owners association, SLU (Department of Forest Resource Management and Unit of Biomass Technology and Chemistry), Umeå University (Department of Applied Physics and Electronics), BioFuel Region, AllSkog and the Norwegian Forest and Landscape Institute (Skog og Landskap). The project investigated the whole energy wood procurement and conversion chain from forest to energy and heating plant. Thus, it generated information on new and more efficient ways for procuring forest fuel, improving the quality management of raw material, improving conversion processes at small-scale heating plants, and developing new business models for self-employed energy wood contractors. The project had a marked impact in the following ways. Utilization of renewable energy increased in private households, farms, enterprises, cooperatives and district heating plants in the BA region. New heating plants were established during the project period and more were expected to start up subsequently. Utilization of forest biomass reserves improved, by exploiting small-diameter stems, crown biomass and stumps. The ability of energy cooperatives to price the heat they produced (reflecting the productivity of the whole procurement chain), energy efficiency and feedstock quality all improved. Heating plant staff were more aware of the factors that affect boiler efficiency and emissions, and their competence in adjusting boiler behavior increased. General knowledge of renewable forest energy sources and utilization within the BA region was also enhanced. Forest companies, forest owners and entrepreneurs received information and help to support their activities in the region, and new machine entrepreneurs initiated ventures. New contacts were established, which stimulated abundant networking, information exchange, new initiatives and new project ideas. Contacts with actors in the forest and energy sectors were also established via collaboration with participants in other EU projects.

The first two projects focused mostly on small-scale forest energy systems and pelletizing while the "Forest Power" project focused more on large-scale supply of various energy assortments (logging residues, stumps and young trees). Extensive R&D particularly addressed young energy thinnings. In cooperation with forest machine manufacturers, it provided robust scientific foundations for developing innovative new felling heads and commercial development is under way. The projects fostered a strong cross-border network of forest energy experts, with multiple links to forest and energy stakeholders and participants in other projects addressing related issues. This ongoing cooperation has stimulated further efforts to develop and implement means to improve and exploit renewable energy sources. A highly pro-active communication strategy has disseminated information to targeted stakeholders and contributed to increased knowledge about the forest energy resources and utilization within the BA region. The projects have enhanced numerous aspects of the forest fuel supply chains, helping the region to reach and surpass the renewable energy goals and greenhouse gas emission targets set by the EU. Sweden reached the 2020 goal of meeting 49% of its energy demand from renewable sources by 2012, with a 132 TWh per year contribution (32% of total energy consumption) from biomass. The use of biomass has increased in all sectors, but the biggest increase has been in district heating, where it rose from 29 TWh in 2002 to 45 TWh in 2012 (Swedish Energy Agency 2014). However, it is more difficult to find renewable solutions for the transport sector, and both Sweden and Finland are still heavily dependent on imported fossil fuels. To contribute to renewable solutions for the transport sector and the development of forest biorefineries, the Forest Refine project was launched in 2012.

Biorefining is being extensively researched in Sweden and Finland, and interest in production of new products and biofuels from forest biomass for transport is steadily growing. The "Forest Refine" project's overall goal has been to develop more efficient supply chains for emerging biorefineries. Since the start of the project, global demand for newsprint and printing paper has decreased dramatically, forcing several pulp and paper mills to close in Scandinavia. This trend has considerably increased the interest in forest biorefineries. The 3-year project started in 2012 and was financed with 2 500 000 € from the European Union's BA -program (ERDF, Interreg IV A) together with the Regional Council of Ostrobothnia, the Regional Council of Central Ostrobothnia, the County Administrative Board of Västernorrland and RegionVästerbotten. Participating partners were SLU, METLA, SP Processum, the Kokkola University Consortium Chydenius, Centria University of Applied Sciences, Central Ostrobothnia Rural Institute, Central Ostrobothnia Adult Education Institute, and BioFuel Region (see Appendix I for more details of the organizations).

Replacing fossil fuels with renewable energy sources has been the core strategy to meet the EU´s renewable energy and climate goals. For Sweden and Finland increasing the use of forest biomass in a sustainable manner has been the main element of the strategy. The two countries have shown that it is possible to increase the use of forest biomass and the standing volume of forest biomass simultaneously. Exploitation of forest biomass in biorefineries could also be potentially increased in the near future. However, there are fears that future EU policies may not favor the use of forest biomass to meet climate and renewable energy targets. This is partly because misleading results from excessively narrow analyses of the role of forests in the carbon cycle are being presented to decision-makers by various lobbies, which may postpone transformation of the energy systems to the next generation. Claims are being made that trees from the boreal forest should be left in the forest as carbon sinks. This analysis ignores the established facts that: mature trees occupy space that could otherwise be utilized by younger, more rapidly growing trees; old trees eventually become carbon emitters rather than carbon sinks; and leaving trees in the forests reduces amounts of forest products and energy that could be used to reduce dependence on fossil fuels. Claims are also being made that burning biomass creates a carbon debt, but these claims are not credible as they are based on the unrealistic assumption that trees are first burned and then grown. If the carbon cycle of a forest is analyzed over a short time period rather than a whole rotation, or single-stand rather than landscape perspectives are applied, key interactions over time and space can be overlooked, and the conclusions can be highly misleading. To raise awareness of these unrealistic claims there is an urgent need for forest stakeholders and our politicians to engage more actively in lobbying and the debate. Therefore, a lobbying network including the major forest industry and forest owner stakeholders in Sweden has been formed during the project. The overall goal is to promote long-term and stable energy policies to stimulate investments in forest biorefineries. The network is focusing on the role of forests in a future climate perspective and energy policies. Several meetings and information activities have been organized, resulting in several published articles in press. The network's activities will continue after the project has ended and a sister network is being established in Finland. Thanks to the network, interest in the Forest Refine project has widened and various important stakeholders have received information and results from the project.

This report describes the research and development efforts during the Forest Refine project, discusses practical implementations and limitations of the results, and considers aspects that require further attention to stimulate ongoing development of the forest biomass supply chains. The reader must judge the success of the project, but to my knowledge it is unique in its aim and scope. Through bringing together researchers from several countries with multi-disciplinary perspectives it has, I believe, generated important new insights and fostered important progress. I sincerely hope that the results presented here will play an important role in developing the nascent bio-based economy in the BA region.

Magnus Matisons, project manager
Biofuel Region

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Units, definitions, abbreviations and conversion rates

barrel, 1 barrel=x m^3, 1 barrel of oil ~ x MWh
BA, Botnia-Atlantica
CHP, combined heat and power plants
DBH, diameter at breast height (1.3 m above ground)
D, diameter
DM, dry matter
EROEI, energy return over energy invested, calculated as produced wood fuel over consumed diesel fuel per unit time.
EU, European Union
GIS, Geographical Information System
h, height
IEA, International Energy Agency
L, liter
M, Mega
MC, moisture content, wet basis
m^3 l, loose volume
m^3 s, solid volume
NFI, National Forest Inventory
OD, oven-dry
PCT, pre-commercial thinning
PMH_0, productive hour of machine work, excluding delay time
PMH_{15}, productive hour of machine work including delay times shorter than 15 min
sd, standard deviation
RPM, revolutions per minute
SDC, Swedish Forest Industry's IT Company
SFA, Swedish Forest Agency
t, metric tonnes, 1000 kg
T, Terra, 1 T = 1000 G (Giga) = 1000 000 M
VMF, Swedish wood measuring association
Wh, watt hour = 3600 J (joule)

1 SEK=USD 0.154= Euro 0.108

Introduction

Demand for energy is continuously increasing globally, due (*inter alia*) to increases in industrialization and population. More than 80% of the energy we currently use comes from fossil fuels and about 98 % of carbon emissions originate from fossil fuel combustion. Petroleum is the largest single source of energy consumed by the world`s population. Unfortunately, however, there are severe risks of petroleum shortages within coming decades, and fossil fuel consumption is widely acknowledged as the major contributor to anthropogenic climate change (IEA 2010). Thus, the growth of the world's energy demands raises urgent problems. Furthermore, the largest petroleum and natural gas reserves are located in a small group of countries. For example, the Middle East countries have 63% of the known global reserves and are currently the main petroleum suppliers. This energy system is unsuitable because of equity issues as well as environmental, economic and geopolitical concerns with far-reaching implications. It is more difficult to find renewable solutions for the transport sector than for heat and electricity production. Nevertheless, the IEA predicts that use of biofuels – transport fuels derived from biomass – will continue to increase from about 1 million barrels per day in 2010 to 4.4 million barrels per day in 2035, due to rising oil prices and government support, e.g. subsidies to shift from fossil fuels to biofuels (Swedish Energy Agency 2011).

The Swedish government decided to establish a new climate and energy policy in 2009, according to which the share of renewable energy should reach at least 50% of the total energy use by 2020. This is in line with a target set in the EU RES Directive for the contribution of renewables to the energy consumed in the transport sector to rise from 5% in 2009 to 10% by 2020. Current progress towards this target is heavily dependent on imported biofuels (mainly ethanol). However, switching from importing fossil fuel (mainly gasoline and diesel) to importing biofuel is not a long-term solution. In 2010, 183 TWh (~108 million barrels) equivalents of fossil-based products were used in Sweden (a major share in the transport sector) and 130 TWh equivalents of biofuels (mainly solid wood fuels), amounting to 32% of the total consumed energy. Most of the latter was used in the forest industries and heating plants for heat and electricity production (Swedish Energy Agency 2011).

The EU RES-directive binds Finland to increase the share of renewable energy sources from 28.5% in 2010 to 38% by 2020. This is a challenging obligation, and its realization depends on reducing final energy consumption. Finland's vast natural resources provide ample potential to increase the use of renewable energy, but exploiting them to help meet the obligation will require more effective subsidy and steering systems. According to the national climate and energy strategy, intense increases in the use of wood-based energy, waste fuels, heat pumps, biogas and wind energy will be promoted. As part of this strategy, Finnish law promotes the use of biofuels in transportation by requiring distributors of transport fuels to supply biofuels for consumers, and stipulates that the contribution of biofuels to the total energy content of distributed gasoline, diesel oil and biofuels must be increased from the current level of 5.8% to at least 20% by 2020. However, if a biofuel is produced from wastes or inedible cellulose or lignocellulose, its energy content is considered two-fold in this calculation. Therefore, the legislation promotes the production of "second generation" biofuels over the somewhat controversial "first generation" fuels. The doubling of the energy content of second generation fuels in the calculations also means that the true contribution of biofuels to the total energy content of distributed fuel may be only 10% in 2020, if the target is met and all of the biofuels are produced from such fuels, e.g. forest biomasses (IEA 2010).

Forest resources

The major biomass resource in Sweden and Finland, especially in the BA region, is forest biomass, also referred to as lignocellolusic feedstock. Sawn timber products and pulp and paper products have dominated use of this resource for a long time, but the use of forest biomass for energy purposes has grown rapidly in recent decades.

The area of productive forest land in the Swedish BA region totals 47 900 km^2, and hosts a productive forest volume of 198 million m^3 of wood, with an annual wood increment of 19.5 million m^3 (Finnish

Forest Research Institute 2012). Forest biomass resources have provided the basis for significant industrial activities in Sweden and Finland for more than a century.

The total standing volume of Swedish forests is currently around 3 200 million m^3, with annual growth of about 120 million m^3. In 2012 the annual gross felling volume amounted to 84.8 million m^3 and the net felling volume to 68.9 million m^3 (excluding bark), of which sawlogs, pulpwood, fuelwood and other roundwood accounted for 32.0, 30.5, 5.9and 0.5 million m^3, respectively (Swedish Forest Agency 2013). In Sweden it has been estimated that the total energy content of annually produced logging residues, stumps and small-diameter thinning wood amounts to more than 100 TWh, of which approx. 40 TWh could potentially be extracted under present ecological, economic and technical restrictions. The current use of primary forest fuels (obtained directly from the forest) amounts to approx. 15-20 TWh. Forest-based fuels (including streams directly from the forest and industrial residues) contributed 132 TWh to the energy used in Sweden in 2012, 32% of the total (Swedish Energy Agency 2014).

Currently, stem volume growth of the Finnish forests exceeds extracted volumes by about 30 million m^3 per year. 90% of the raw wood used annually (ca. 70 mill m^3 in 2010) is allocated to the wood product and pulp industries, and the rest is directed to energy production in small-scale housing and heating plants. Wood energy is also produced from logging residues and stumps from clear-cuts, small-diameter thinning wood, and some by-products of the wood and pulp industries, such as bark, sawdust and chips. It has been estimated that the gross annual potential production of forest chips from logging residues, stumps and small-diameter thinning wood is ca. 48 million m^3 in Finland. However, most of this potential resource is unusable due to ecological, economic or technical restrictions, so the practical potential forest chip production amounts to ca. 14-20 million m^3 annually. Thus, there is clearly scope for increasing the utilization of non-roundwood forest biomasses from the volume of forest chips currently used (6.8 million m^3 in 2011). In addition, more than 9.9 million m^3 of forest biomass-derived industrial by-products was used in energy production in 2011. Most of this, 6.6 million m^3, consisted of bark, and the rest of wood residue chips, sawdust, recycled wood, pellets and briquettes. There is no precise information on quantities of by-product supplies, but they are probably already extensively utilized in energy production. For instance, ca. 70 million m^3 of raw wood is used annually, up to 10% of which could be bark. This would amount to roughly 7 million m^3 of bark, which is close to the quantity already used in combustion. Hence, use of these by-products in biorefining processes could be in direct competition with energy generation (Demibras 2010).

Biorefining

A biorefinery is a facility that integrates conversion processes to produce (for instance) liquid and gaseous fuels, power and value added chemicals from biomass. The biorefinery concept is analogous to today`s crude oil refineries, which produce multiple fuels and other products (see Fig. 1). Although only about 4% of the fossil oil use is for non-fuel purposes, petroleum-derived bulk chemicals have considerable value, for example their estimated value in Europe was ca. 240 billion euros, while the value of the fuel uses was roughly 400 billion euros, assuming an oil price of 100 euros per barrel, in 2010 (Demibras 2010).

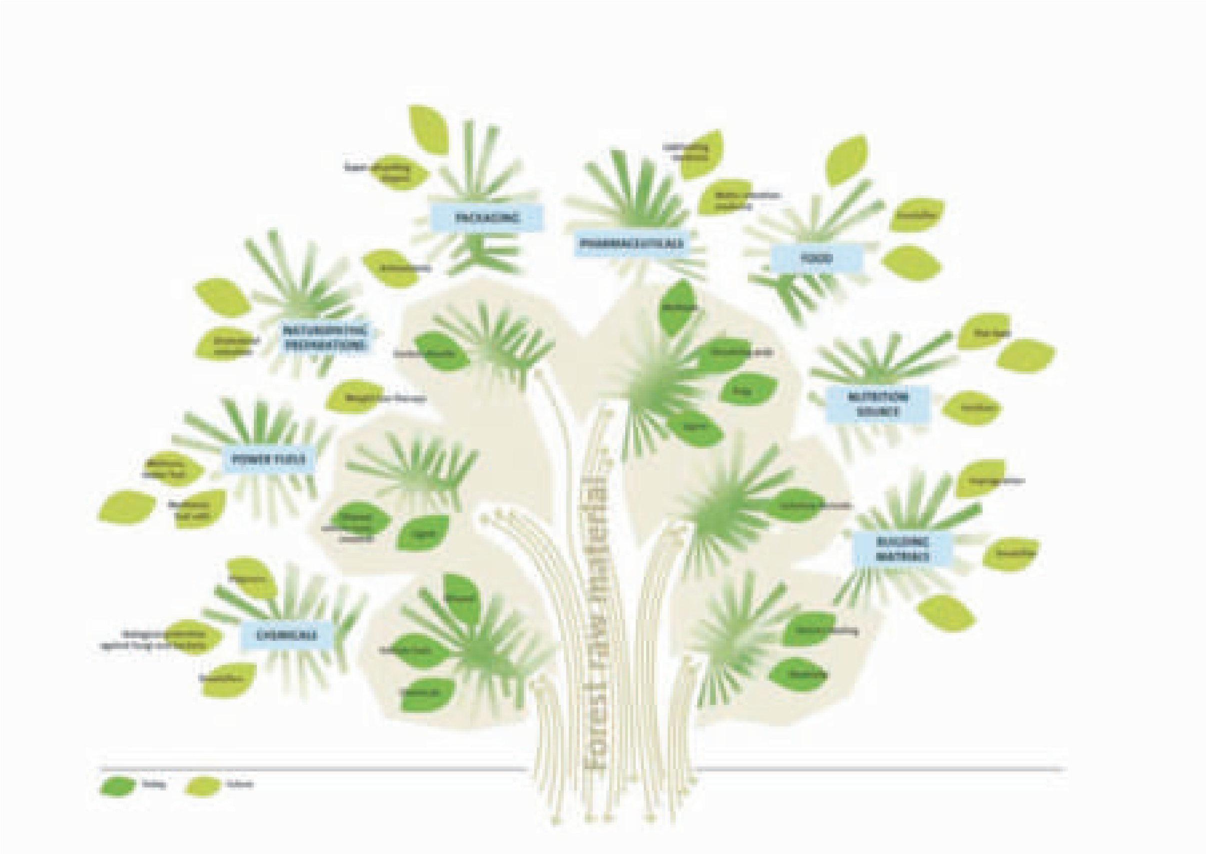


Figure 1. Flow of forest biomass into **a** biorefinery and potential outputs (Source: SP Processum)

Present activities and plans for new biorefineries in Sweden and Finland are currently concentrated on facilities for producing liquid biofuels for the transport sector. Gaseous and liquid biofuels can be produced from forest biomass through two radically different processing routes: biochemical and thermochemical. Thermochemical conversion technology includes pyrolysis, gasification and torrefaction, while biochemical technology is based on the use of enzymes or microorganisms as catalysts. Both concepts are based on breaking down the lignocelluloses in wood to molecules that are subsequently used as “raw material” to synthesize new chemicals. Currently, it is unclear which (if either) is the optimal technological pathway; every strategy has specific pros and cons, thus the ideal raw material properties are highly dependent on the application and processes selected in each biorefinery (Joelsson & Tuuttila 2012).

A fundamental process in the biorefinery system is fractionation, where raw materials are separated according to selected characteristics. Mechanical fractionation is applied to separate (*inter alia*) tree components and/or different fiber/particle structures, while chemical fractionation is used to separate wood components, e.g. celluloses from lignin. Desired qualities are enriched in certain fractions and impurities are discarded by using appropriate sorting/separation methods. Both biomass and fossil oil consist of diverse molecular fractions that can be separated and converted into useful products in refineries. However, the processes involved in fractioning biomass are more complex than those used in petrorefineries. The vast majority of biorefinery conversion technologies require the forest biomass to be reduced to particles smaller than a few mm (powders). In practice, this usually involves comminution of wood pieces and reduction of their sizes in several steps, e.g. chipping/crushing at landings or terminals followed by milling at industrial sites. Specific biorefinery processes require particles with certain qualities for optimum performance, and the choice of chipping/crushing and milling technology strongly influences the resulting particles’ characteristics, e.g. their size distribution and shapes (geometry). The use of appropriate characterization methods is highly important for market-oriented labeling of the different material assortments. Higher degrees of refining enhance the value and unit price of forest biomass, hence the wider establishment of biorefineries will transform requirements and specifications for forest (and other) biomasses as raw materials. It has been suggested that biomass should be utilized in a similar manner to crude oil; i.e. use large amounts as fuels, and further refining smaller but economically significant amounts to generate higher value products. The ultimate goal in biorefining is to isolate all the added value components from biomass feedstock with minimal waste. This would not only improve its economic viability, allowing it to compete with the petrochemical industry, but also reduce the overall environmental impact.

Forest biomass characteristics

The proportions (and both chemical and physical properties) of tree biomass components are highly dependent on the tree species (Fig. 2). For example, the crown components (branches and needles) account for a higher proportion of total biomass in spruce (ca. 20-30%) than in pine or birches (15-25%). Tree size is also a significant determinant of the ratios of biomass components. Proportions of stem wood and roots increase as trees grow, while proportions of the crown components, bark and stumps correspondingly decline, thereby affecting yields of desired biomasses.

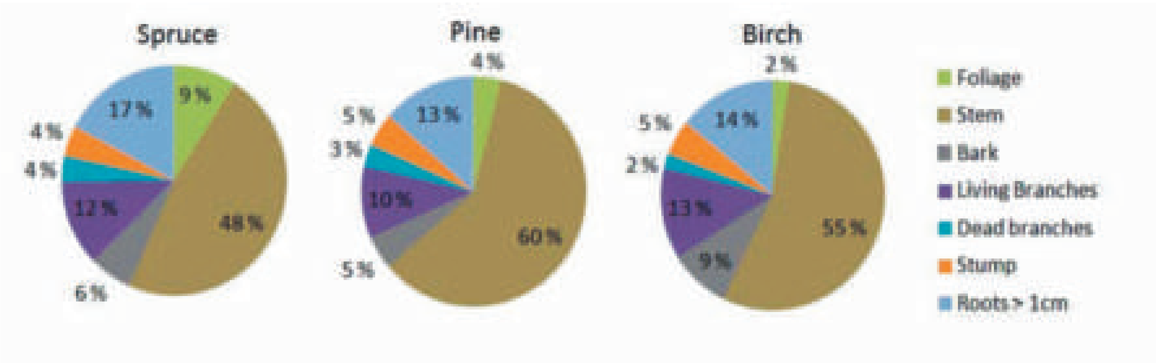


Figure 2. Proportions of indicated biomass components in spruce (D = 20cm, h = 17m), pine (D = 20cm, h = 17m), and birch (D = 20cm, h = 16m) trees, calculated from data presented by Repola (2008, 2009).

The tree stem, excluding bark, is a relatively homogeneous material and its chemical and physical properties are well known, while bark and crown components have a much more heterogeneous chemical composition Thus, for many refining processes stem wood is arguably the most straightforward production material. Wood consists mainly of cellulose, hemicelluloses and lignin with small amounts of extractives, in ratios that vary substantially amongst both biomass components and tree species. Crown components have much higher contents of extractives and various other compounds than stem wood, which is a significant determinant of the suitability of feedstock materials for biorefining processes.' Stump wood is quite similar to stem wood, except that it has higher concentrations of extractives, especially wood of old pine stumps. However, using stump and root biomass as a feedstock can be problematic because harvested stumps always contain soil residues, such as sand and rocks, which may hinder some refining processes. The wood components also include lipids, proteins, simple sugars, starches, water, hydrocarbons, ash-forming elements and other compounds. Proportions of these components vary significantly among tree species, individuals, trees of different ages, seasonally and (especially) among tree parts, i.e. the stem wood, bark, needles/foliage, stump and roots. For example, compared to wood and bark, foliage usually contains considerably more extractives (e.g. terpenes, resin, acids, starch, fats, waxes, tannins and polyphenols). The amount of extractives in woody materials is 2-5% of the feedstock dry solids in stemwood (Alén 2000).

Forest industries produce huge quantities of bark, which is a potential source of green chemicals but at present is mainly burned for energy production (Gandini et al. 2006). For example, birch logs contain about 11.4% of bark (3.4% outer bark and about 8% inner bark) (Pinto et al. 2009, Holmbom 2011). A birch kraft pulp mill, with an annual pulp production of 400,000 t/year, generates about 28,000 t of outer bark. According to Holmbom (2011), silver birch outer bark is composed of about 40 % of extractives, 45% suberin, 9 % lignin, 4 % hemicelluloses and 2% cellulose. Among bark components the suberin hydroxy and epoxy derivatives of fatty acids, some of which are relatively rare in nature, may be interesting precursors for chemicals with diverse applications (Miranda et al. 2013), such as skin-care, anti-aging, hair-care, biodegradable plastic polyesters, drug leads, dietary supplements, anti-cholesterol, and anti-obesity products (Krasutsky 2011). In addition, suberinic ω-acids salts could be used in customized washing materials, shampoos for diverse applications, and hair care products.

Many initial extracts suitable for potential applications are either rather volatile or chemically unstable. Thus, extractive contents start to decrease immediately after tree felling and this degradation continues during storage (Alén 2000, Ekman 2000). This also means that the chemical composition of the extractives-based fraction gradually changes. For example, after felling a tree, the resin content starts to decrease immediately and its chemical composition changes (Alén 2000). Several factors influence the nature and rate of changes in the properties of wood resin (Ekman 2000). These include the type of harvesting, transportation, storage and inventory-control systems of the wood used at the mill. The properties also depend on the tree species available, time in storage, physical form of the wood, and the weather and other environmental factors during all phases of the wood-handling process. The major chemical changes in resin during wood storage can be divided into three groups (Ekman 2000). Firstly, rapid hydrolysis of triglycerides accompanied by slower hydrolysis of waxes, especially steryl esters. Secondly, oxidation, degradation and /or polymerization of resin acids, unsaturated fatty acids and to some extent other unsaturated compounds. Thirdly, evaporation of volatile terpenoids, especially monoterpenoids. It should be noted that these reactions are markedly faster when the wood is stored as chips rather than logs (Alén 2000). Promberger et al. (2004) concluded that the faster deterioration of compounds in wood chips is due to the larger surface area, which increases their accessibility. Increasing ventilation, and thus increased access of atmospheric oxygen in the chip pile, further fastens evaporation and oxidation reactions (Ekman 2000). For example, the cited author found that the degree of hydrolysis of triglycerides in chips after eight weeks of outdoor storage was similar to the degree in roundwood after a year of storage. In addition, chip piles autonomously generate heat, at rates that are influenced by the pile construction, freshness of the wood, wood species and season.

Lignocellulose is the most abundant renewable biomass on earth. It is composed mainly of cellulose, hemicellulose and lignin. Both the cellulose and hemicellulose fractions are polymers of sugars and, consequently, potential sources of fermentable sugars. However, the usability of lignocellulosic material is reduced by its recalcitrant structure. In a pre-treatment step, most of the hemicelluloses are released and the recalcitrant structure of the lignocellulose is opened up to make it accessible for a subsequent hydrolysis step to produce fermentable sugar molecules. Several methods are used for pre-treating lignocellulosic material: physical, physicochemical, chemical and biological. In addition to effective release of cellulose in the pre-treatment step, it is important to minimize the formation of degradation products because of their inhibitory effects on subsequent hydrolysis and fermentation processes.

The supply chain

Forestry is a co-production system, i.e. several products are produced simultaneously, such as saw logs, pulpwood and logging residues. Therefore, the potential amounts of the different assortments are not independent. Calculating production costs for one product in a co-production system is not straightforward. Generally, there is no unambiguous way to allocate costs between the different products in an operation. For example, costs of harvesting a tree and cutting it into pulpwood and saw logs cannot be easily split into costs of producing pulpwood and saw logs, although saw logs are the most valuable assortment in terms of revenues for the land owner. The supply of forest feedstock depends on numerous factors. In the short term, the quantity of feedstock supplied to the market depends on decisions of individual forest owners whether to perform harvesting operations or not. The existing forest stock also constrains amounts that can be supplied in the short term. Furthermore, forestry is regulated by legislation intended to secure the productivity of the forest land and environmental values with specific restrictions. In the longer term, factors influencing forest growth are important. In addition to domestic wood, imported wood can also contribute to amounts available on the market. Forest owners' decision-making is influenced by several factors, including (*inter alia*) market prices of forest products, their current financial circumstances and the strength of their desire to pass on a well-managed forest estate to the next generation (Lidestav & Nordfjell 2005).

The costs of harvesting, transporting, storing and handling the biomass are prime determinants of overall biorefining costs both locally and regionally. Thus, it is vitally important to develop local forest biomass supply systems that can efficiently supply biorefineries with sufficient raw material that meets their specific quality and seasonal demands. However, the geographical accessibility of specific types of forest biomass (logging residues, stumps, young trees and round wood) within the project region is not well known. Thus, it is important to acquire detailed information about both current and anticipated extractable biomasses in specified timeframes (e.g. 10 to 20 years from now).

Conventional Nordic forestry regimes include a pre-commercial thinning (PCT) when the trees reach heights of ca. 5 m to reduce stand density. A first thinning for pulpwood is generally applied when the tree heights are ca. 8-10 m. However, PCTs are often neglected, resulting in biomass-rich and diametrically heterogeneous stands at the time of first thinning, in which most of the biomass is unsuitable for pulpwood production. An alternative to this treatment is to apply an early whole tree thinning instead of a PCT when the tree height is ca. 6-7 m, removing whole trees by selective or (for instance) boom-corridor harvesting methods (cf. Bergström et al. 2009). The whole tree biomass harvested from small trees is a bulky material, and in order to optimize its transportation some densification is needed. According to current end users' quality demands, trees in the Nordic countries are harvested and handled by the cut-to-length method. Harvesters are used to fell, delimb and cross-cut the trees into separate piles of pulpwood, sawlogs and logging residues (branches and tops). Forwarders transport the logs to the roadside, then the pulpwood is transported to pulp mills and timber to sawmills by trucks. Logging residues can be bundled in-stand to increase transportation efficiency if there are long distances to the mills, but are mostly forwarded loose to roadside for seasonal storage and then comminuted before transportation to industrial sites. The stumps are harvested as a separate assortment by excavators, the stump biomass is subsequently forwarded to roadside then either crushed, or transported to industrial sites as a loose material.

Forest biomass terminals play a key role in current supply systems, and their importance is likely to increase in a coming bioeconomy. Not only do they provide key transit points, where forest biomass harvested within relatively short distances (<50 km) is gathered, but also sites where the biomass can be comminuted, sorted and refined or upgraded in accordance with users' requirements before further transport by train or trucks to end users. In the Swedish part of the BA region demand for forest biomass (both traditional round wood and fuel wood) is mainly concentrated in coastal area (the main location of industrial facilities). However, the biomass is dispersed over vast forest areas, creating substantial logistical challenges to effectively harvest and transport raw materials from the forest to the industrial sites. These challenges are especially pronounced when handling different forest fuel assortments like logging residues, which often have a bulky and troublesome nature. Normally such assortments are transported by trucks up to 100-150 km to industrial sites.

Potential benefits of terminals depend on their type and placement, but generally include the following. Firstly, they allow cost- and energy-efficient comminution (chipping and crushing). Large-scale machinery can comminute forest biomass 2-3 times more cost- and energy-efficiently than smaller roadside machinery. At many terminal locations electricity can be used to power large comminuting machinery, rather than relying on the diesel-powered machinery used when comminuting closer to the forest. Secondly, they allow different fractions of raw material to be sorted and mixed according to the requirements of the end-user (which for a biorefinery will depend, *inter alia*, on whether it stands alone or is integrated with other processing facilities and the type of raw material required, e.g. whole tree biomass or specific tree components). Different plants will also have different quality requirements, as can already be seen in current forest industries. To reduce overall transport costs it can be advantageous to sort and mix fractions of raw material according to specific plants' quality requirements as early as possible in the supply chain. Thirdly, terminals can enhance storage and cleaning capacities. Forest harvesting operations normally take place year-around, but for heat and power plants (among others) the demand for supplies rises during winter time. This creates an imbalance between supply and demand, and hence requirements for storage of the biomass. Currently, large volumes of forest fuels are stored mainly at roadside landings, but increasing volumes are being stored at terminals, where there are opportunities to equilibrate supply and demand in addition to meeting specific users' quality requirements. Fourthly, terminals are often used to transfer forest biomass to trains for long-distance (>150 km), which is more cost- and energy efficient than truck transport. Today more than 300 GWh equivalents of forest fuels are transported to end users outside the Swedish part of the BA region, and these volumes are likely to increase annually. Finally, terminals greatly enhance possibilities for refining/upgrading forest biomasses to obtain more energy dense products that can be more cost-efficiently transported.

Starting point

It is generally acknowledged that future biorefineries' raw material quality requirements will differ from those of those of traditional forest industries or energy plants, and that this will influence the raw material supply chains. Important activities in the supply chain include harvest, terrain transport and storage at landing, terminal handling and fractionation, characterization of different fractions, and some specific biorefining. To avoid increasing competition and biomass shortages, new biomass terminals, in which the biomass is fractionated into various assortments and supplied to different biorefineries, might be required to optimize utilization of every component of the biomass.

New biorefining facilities would compete for raw material supplies with current users of woody biomasses. Nationally, there is a wide margin between amounts of wood assortments harvested today and the maximum amounts that could be sustainably harvested, but there may not be sufficient raw material for every potential or desired purpose in every location locally. Without specifying exact forest-derived raw material types needed for a biorefinery, its raw material demands could potentially be met by reallocating current biomass flows. This could mean redirecting pulpwood, energy wood or industrial by-product flows into new processes. Trade cycles and changes in the production capacity of forest industry are reflected in the volume of harvested roundwood. This could lead to temporary or even permanently free potential supplies of harvestable roundwood, namely pulpwood that could be utilized in a new biorefining facility. However, redirecting current energy wood and industrial by-product flows would create a corresponding deficiency in the raw material supply for energy production, which should be compensated in some way. In principle, switching renewable raw material from energy production to biorefining and replacing it with fossil materials, such as coal, would not be very appealing. However, another option to meet the raw material demands for biorefining would be to enhance utilization of existing biomass resources, which would only be limited by the economic and ecological sustainability of forest management and, naturally, the quantity of the biomass reserves. In order to evaluate potential harvestable forest biomasses and their components, harvesting restrictions must be considered. Stem wood harvesting is only restricted by the limits imposed by the sustainability of forest management and nature values, but when harvesting tree crowns and stumps, possible nutrient losses or damage to the remaining or future tree population must also be considered.

A biorefinery plant can either be a stand-alone unit or integrated with other plants, such as a pulp and paper mill and/or a heat and power plant. These new industrial concepts, in conjunction with increasing competence in refining technology and forest biomass supply chain management, create new business opportunities and foundations for substantial regional, national and international developments. However, current infrastructure and supply chains are mainly oriented towards production of sawn timber, pulp, paper, heat and power. Thus, they may not be optimal for biorefineries. The optimal technology and conversion process used, and plant size, will depend on the available local feedstock and the supply system used. If raw material is upgraded (e.g. by fractioning tree components) at a terminal, the raw material supply area can be increased, thereby allowing larger-scale refining processes. The proportion of extractives in a tree is normally only a few percent, but these components can be upgraded into highly valuable products. Thus, it is important to utilize all the available raw material efficiently. Optimum use requires identification of the advantages and disadvantages of each component of the forest biomass (e.g. stem wood, bark, foliage, stumps and roots of the available species) for each application. For example, in contrast to current heating plants' quality demands (e.g. low proportions of needles in the fuel), a future biorefinery may require a high proportion of fresh needles to maximize the extraction of valuable chemicals.

Clearly, it is vitally important to harmonize research and development goals in parts of northern Sweden and Finland in the BA region with the development of efficient and sustainable forest raw material supply chains. To ensure the future expansion and prosperity of the region's forest industries, particularly viable forest biomass-based biorefineries, the ability to access raw material further away than some current sources (which will require establishment of terminals close to raw material sources) is also critical.

Project objectives

The overall objective of this project was to acquire knowledge of ways to reduce costs of supplying biorefineries in the BA region with a given forest biomass by at least 15%. The specific objectives were to:

- investigate the chemical balances and concentrations for all tree components of the major species growing in the Swedish and Finnish part of the Botnia Atlantica area;
- assess the geographical potential of different forest biomasses (logging residues, stumps, small diameter trees and round wood) for biorefineries within the project region;
- study conventional and innovative systems in the whole supply chain from the forest to delivery to a biorefinery. This includes harvest, terrain transport and storage at landing, terminal handling, fractioning and storage of different types of fractionized biomass;
- characterize different biomass fractions according to their physical and chemical properties;
- define the future quality requirements of the forest biomass assortments for various types of biorefineries;
- design and analyze the cost and energy demands for current and future forest biomass supply chains to biorefineries in both countries in accordance with their biomass quality and quantity requirements and geographical location with respect to biomass resources and infrastructure.

Chemical balances and potentially available forest biomasses for biorefineries

Basic chemical composition of pine, spruce and birch biomass components

Objectives
The objective of this part of the project was to compile literature data on the chemical composition (the most common organic compounds) of the most common tree species in the focal region.

Background and Materials & Methods
The review of the chemical composition of tree biomasses focused on the most common groups of organic compounds in woody biomasses: cellulose, hemicelluloses, lignin and extractives. The polysaccharides cellulose and hemicelluloses consist of long carbohydrate molecules and function as structural components in diverse plant tissues. Lignin is also a structural component, of plant cell walls, that strengthens wood and enables the formation of tree stems. Extractives include highly diverse compounds with multiple non-structural functions in plants, for instance as defenses against herbivores or other damage-causing agents. However, trees also contain varying quantities of numerous other compounds, including other polysaccharides (such as starch and pectins), proteins, nucleic acids and various other nitrogenous molecules. The absolute quantities and proportions of these other compounds depend partly on the biomass component. For example, bark may contain large amounts of suberin and some polyphenols, which are not usually included in extractives. Published literature was reviewed to establish the chemical composition of stem wood, stem bark, branches, needles or leaves, stumps and roots. Only literature sources reporting the composition of a biomass component comprehensively, and information on the proportions of the carbohydrates, lignin and extractives were included in this review. Medians (i.e. the numerical values separating the higher halves of reported values from the lower halves) of all the concentrations or percentages published in the selected literature were calculated, when more than two values were available. This was because medians are less sensitive to extreme values than means, which were occasionally found. The literature values were quite variable for some biomass components, especially bark and branches, partly due to variations in the physical properties, origin or age of the analyzed material, and partly due to differences in the analytical methods used in different studies. The variability of the literature values was described by their median absolute deviation (m.a.d: median of the absolute deviations from the data's median), which is a robust measure of dispersion and more resilient to outliers than the standard deviation.

Results & Conclusions
The composition of stem wood is generally well known due to its long industrial use. The variation in literature values is also quite small since wood is a relatively homogeneous material compared to the other biomass components. The largest difference in the basic chemical composition of wood between the tree species is that silver and downy birch (*Betula pendula* and *B. pubescens*) wood contains less lignin than wood from the conifers pine (*Pinus sylvestris*) and spruce (*Picea Abies*). Pine wood is also slightly richer in extractives than the other species. The chemical composition of stem bark is significantly different from that of stem wood, extractives being the most abundant compound group in all species. However, “other compounds” comprise a large proportion of bark’s chemical contents. In pine, bark cellulose, hemicellulose, lignin and extractives comprise ca. 70% of the chemical composition, according to the literature, while these compound groups account for 80% of spruce bark and only 60% of birch bark. Branches consist of both wood and bark, the ratio between them being influenced by branch size. Hence, determining the chemical composition of tree branches can be challenging and the conclusions drawn can only be very general. Just one study describing the cellulose and hemicellulose concentration of branches was found for each species, and only a few for the other compound groups. However, the chemical composition of branches appears to be intermediate between that of stem wood and bark, which is not surprising since branches are composed of these materials. Pine and spruce needles, and birch leaves, are the most extractives-rich components of the respective trees’ biomass. Unfortunately,

no literature was found on the cellulose and hemicellulose contents of birch leaves. The chemical composition of tree stumps and roots have not been extensively studied – only one report describing contents of these components of pine and birch trees was found, and two for spruce trees. Use of this underground biomass has been mainly restricted to burning of spruce stumps for energy to date. The few available reports indicate that the chemical composition of stumps (including bark) is similar to that of stem wood, apart from higher concentrations of extractives. The chemical composition of roots depends on their size, but is quite similar to that of branches. The medians (and their deviations) of the proportions of the studied chemical compound groups are presented in Table 1. The values of the compound groups do not necessarily total 100% and may even exceed it, due to the variability in the literature values and the fact that the concentrations of other compounds are not included in the presented data.

Table 1. Proportions of the main chemical compound groups (%) within the indicated biomass components of Scots pine, Norway spruce and birch trees. Presented values are medians of values found in the literature, with median absolute deviations in parenthesis if more than two values were obtained from the literature sources.

Tree species	**Cellulose**	**Hemicelluloses**	**Lignin**	**Extractives**
Scots pine				
Stem wood (1-7, 11, 12, 27)	40.7 (0.7)	26.9 (0.6)	27.0 (0.0)	5.0 (1.0)
Bark (7-12, 27)	22.2 (3.2)	8.1 (0.4)	13.1 (5.4)	25.2 (5.2)
Branches (11-14, 27)	32.0	32.0	21.5 (5.9)	16.6 (7.1)
Needles (3, 11, 12, 27)	29.1	24.9	6.9 (0.8)	39.6 (1.3)
Stump (12)	36.4	28.2	19.5	18.7
Roots (12)	28.6	18.9	29.8	13.3
Norway spruce				
Stem wood (3-6, 15-18, 27)	42.0 (1.2)	27.3 (1.6)	27.4 (0.7)	2.0 (0.6)
Bark (9-12, 17, 19, 20, 27)	26.6 (1.3)	9.2 (1.1)	11.8 (0.9)	32.1 (3.8)
Branches (11, 12, 14, 17, 27)	29.0	30.0	22.8 (1.7)	16.4 (2.6)
Needles (3, 11, 12, 27)	28.2	25.4	8.4 (2.1)	43.3 (2.3)
Stump (12, 21)	42.9	27.9	29.4 (1.8)	3.8 (0.2)
Roots (12)	29.5	19.2	25.5	15.7
Silver/Downy birch				
Stem wood (1, 5, 11, 12 15, 18, 22, 27)	43.9 (2.7)	28.9 (3.7)	20.2 (0.8)	3.8 (1.3)
Bark (11, 12, 23-25, 27)	10.7 (0.3)	11.2 (0.5)	14.7 (3.9)	25.6 (1.1)
Branches (11, 12, 26, 27)	33.3	23.4	20.8 (3.9)	13.5 (3.0)
Leaves (11, 12, 27)	N/A	N/A	11.1 (0.0)	33.0 (0.0)
Stump (12)	29.5	19.4	13.4	4.7
Roots (12)	26.0	17.1	27.1	13.5

1) Alén (2000); 2) Kilpeläinen et al. (2003); 3) Hakkila (1989); 4) Korhonen (1997); 5) Sjöström (1993); 6) Viikki (1995); 7) Saarela et al. (2005); 8) Valentín et al. (2010); 9) Peltonen (1981); 10) Dietrichs et al. (1978); 11) Nurmi (1993); 12) Nurmi (1997); 13) Vávřová et al. (2009); 14) Lassi & Wikman (2011); 15) Fengel & Wegener (1989); 16) Bertaud & Holmbom (2004); 17) Rhén (2004); 18) Willför et al. (2005); 19) Wainhouse et al. (1990); 20) Spiridon et al. (1995); 21) Anerud & Jirjis (2011); 22) Willför et al. (2005); 23) Ukkonen & Erä (1979); 24) Pulkkinen & Nurmesniemi (1980); 25) Pinto et al. (2009); 26) Krutul et al. (2011); 27) Voipio & Laakso (1992).

Sources of forest biomass for biorefining in Finland

Objectives

The objective of this part of the project was to compile information from the Finnish nationwide MELA-simulations on current harvesting levels and biomass potentials.

Results & Conclusions (Routa et al. 2012, Tomppo et al. 2012, Ylitalo 2011a, Ylitalo 2011b)

The nationwide MELA-simulations indicate that there is substantial potential for sustainably increasing harvesting levels of forest biomass, especially stumps, in Finland. They also indicate that there is significant potential for increasing pulpwood harvests, with a difference between current and estimated maximum sustainable annual harvests of ca. 7.7 million m^3 for the period 2009- 2018 (Fig. 3). It is probably not economically viable to harvest all of the potential volume, but these findings indicate that there could be significant raw material reserves for new wood users.

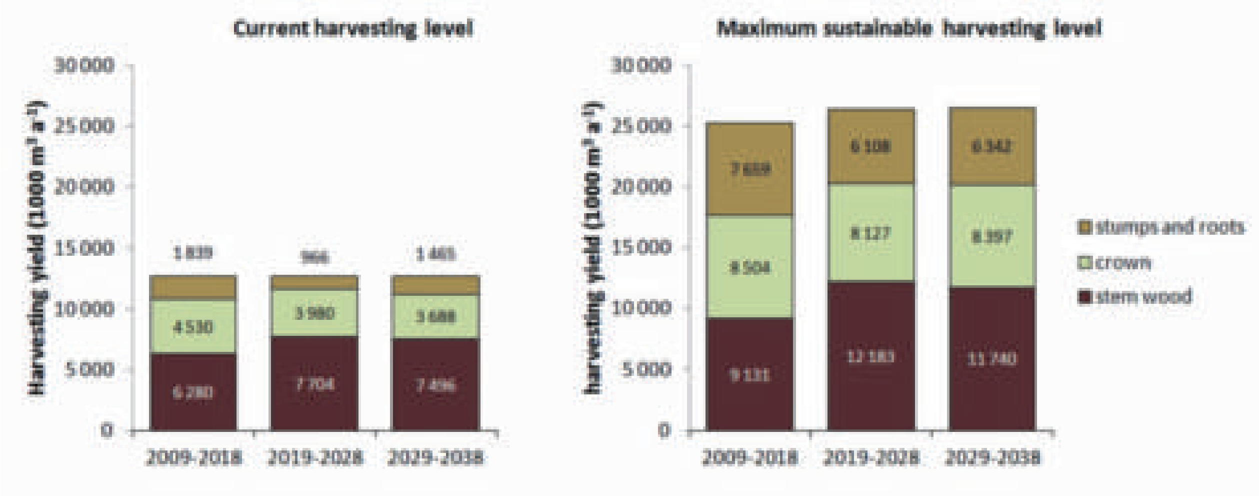
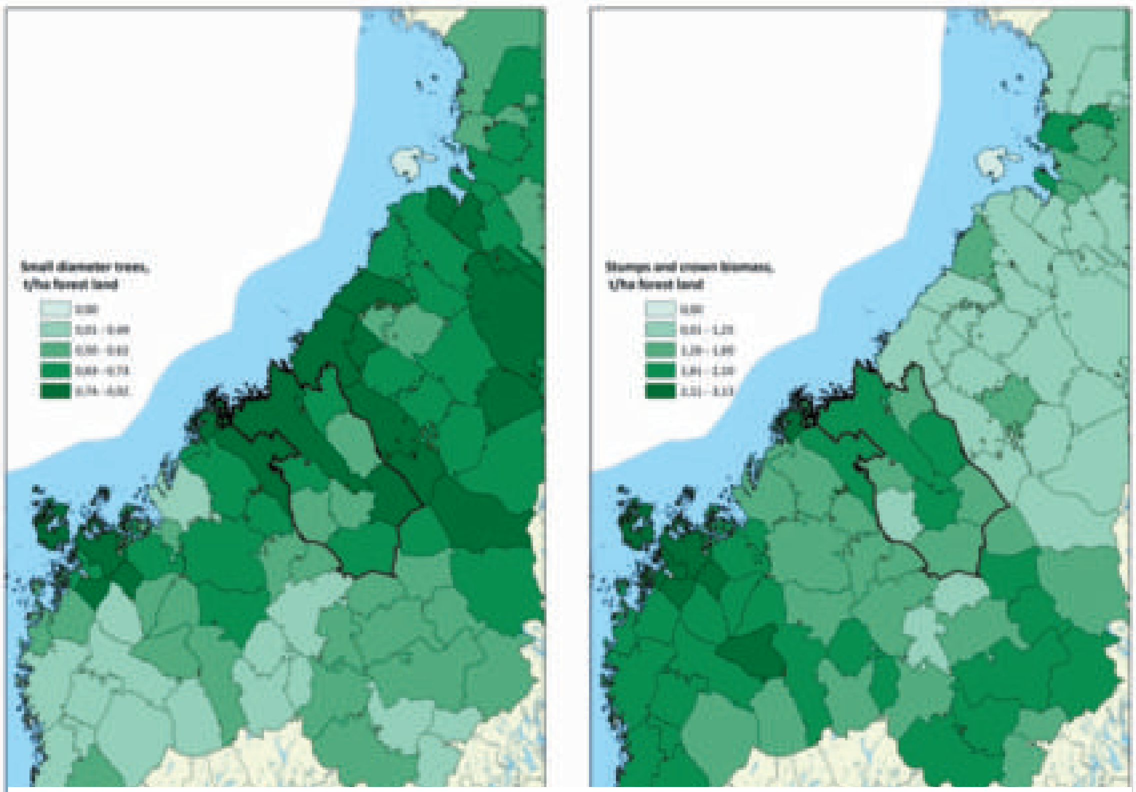


Figure 3. Annual harvesting yields in Finland of biomass components (non-roundwood) for three simulation periods using two harvesting scenarios. Source: Metla / MELA-group, June 19 2012.

These raw values may give the impression that abundant raw materials are available for new biorefining facilities. However, forest reserves are not evenly distributed throughout the country (Fig. 4), and competition for raw material may be more intense in some regions. Additionally, the availability of different forest biomass assortments is partly dependent on roundwood loggings. Quantities of logging residues, i.e. crown biomass from clear-cuts, and stumps are directly related to volumes of final fellings. Currently, the profitability of harvesting small-diameter trees is in some cases related to the roundwood yield in the same felling, although it is not necessary to harvest roundwood if the yields of other biomass assortments are sufficiently large.

The location and capacity of a biorefining facility are of key importance when the availability of raw material is considered. The location should be optimal with respect to the raw material reserves within a realistic procurement area. The type of the raw material reserves available should also match requirements set by the refining processes, and ultimately the capacity to pay for the raw material determines the eventual availability of forest biomasses for biorefining.



© National Land Survey of Finland MML/VIR/MYY/328/08 Forest data: 10th Finnish National Forest Inventory

Figure 4. Potential quantities (t /ha) of small-diameter trees (whole-tree biomass), stumps and logging residues that could be sustainably harvested in municipalities of Central Osthrobotnia (thick black line) and surrounding areas.

Potential, distribution and use of forest biomaterials in Finland

Objectives

The objective of this part of the project was to estimate the current utilized biomass, and the potential surpluses and geographical distributions of bark, stumps, logging residues and pulpwood in Finland, on the basis of the average roundwood harvesting levels of 2002-2011. Corresponding values for small diameter trees from thinnings were based on calculations presented by Anttila et al. (2013).

Materials and Methods

Bark is currently separated as a roundwood by-product in the forest industry. Therefore the quantity of available bark depends on current roundwood harvesting levels. The share of bark in roundwood was estimated using biomass models, which give estimates of all biomass components in relation to tree size (Repola 2008, 2009). The quantity of harvestable stumps is tied to the wood consumption of forest industries, i.e. volumes of final fellings. The volumes of harvestable stumps of the major tree species were estimated on the basis of harvested roundwood volumes using expansion factors, municipal-level tree species distribution information and considering certain ecological restrictions for stump harvesting. Most of the residual logging biomass at a final felling site consists of living and dead branches and needles or leaves, while tree tops with smaller diameters than roundwood comprise a smaller part of the total quantity. The proportions of these biomass components depend on the dominant tree species and the size of the harvested trees, which determine key variables such as the stem/crown-ratio and branch thickness. Sites supporting spruce-dominated stands are considered the best for removing logging residues as they have high yields, generating ca. twice as much harvestable crown biomass as Scots pine-dominated stands, for instance. The volumes of harvestable logging residues of pine, spruce and broadleaf species (mainly birches) have been estimated for the whole country on the basis of harvested roundwood volumes using expansion factors and municipal-level tree species distribution information. Furthermore, the ecological restrictions limiting the volume of harvestable logging residues have been considered. For instance, in the potential biomass calculations, the recovery rate of residues from a felling site was set to 70 %, as recommended in the current harvesting guidelines.

The volume of potentially harvestable non-roundwood biomass of young stands depends on the harvesting regime: it can be estimated for harvested stem wood alone, for whole tree biomass (i.e. tree stems including living crowns) or for the small-diameter stem wood (smaller than roundwood) in integrated thinnings. All of these options offer differing potential biomass volumes and are suitable for different thinning sites. For instance, harvesting delimbed stem wood is suitable for all sites regardless of the dominant tree species or site type, whereas whole tree harvesting is not recommended for sites of poor or high-risk nutrient status. However, the harvesting yield can be increased quite significantly by harvesting the crown biomass together with stem wood. Integrated harvesting may be a suitable option for thinning sites where the roundwood yield is sufficient.

Results & Discussion

The volume of roundwood harvested annually in Finland varied from 41 to 57 million m^3 during the years 2002-2011, averaging 52 million m^3 (including bark), and annual harvests of saw-timber ranged from 17 to 28 million m^3. The estimated total potentially harvestable volume of logging residues was 9.2 million m^3 nationally: with 5.6, 2.4 and 1.2 million m^3 contributions from Norway spruce, Scots pine and broadleaf species, respectively. On the basis of data and harvesting recommendations in the 10^{th} national forest inventory (NFI), Anttila et al. (2013) estimated that the total potentially harvestable volume of small-diameter thinning wood (including crowns) in Finland is 12.4 million m^3 per year: 5.1, 4.6 and 2.7 million m^3 of Scots pine, broadleaved species (mainly birches) and Norway spruce, respectively. The pulpwood harvesting volume averaged 30.1 million m^3 per year between 2002 and 2011: 13.7 million m^3 per year from pulpwood-sized pine stemwood, 8.4 million m^3 from Norway spruce and 8.0 million m^3 from broadleaf species. Roundwood harvestings have consistently been well below the annual volume growth of the forest reserves for many years.

<u>Bark</u>

Ca. 5.6 million m^3 of bark was harvested in Finland Annually between 2002 and 2011, 35, 41 and 24% of which was bark of pine, spruce and broadleaved species (mainly birches), respectively. In Central Ostrobothnia, the corresponding bark volume was 86 000 m^3. Some of the bark that is potentially available is not separated from stem wood, but utilized directly in energy production as part of wood chips made from small diameter thinning wood. In 2011, 4.3 million m^3 of small wood chips were used in energy production, ca. 0.6 million m^3 of which consisted of bark. The full harvesting potential of forest biomasses is currently not utilized. In other words, even at the maximum harvesting levels from the last decade surplus roundwood and bark is left in the forests. If the maximum harvesting potential, estimated from data and harvesting recommendations in the 10th NFI, was exploited the total national harvestable roundwood volume would be ca. 63 million m^3, with 6.9 million m^3 of bark, per year. Subtracting average harvesting levels indicates that a potential surplus of 1.3 million m^3 of bark remains annually in the forests (13 000 m^3 in Central Osthrobotnia). In 2011, 6.6 million m^3 of bark was separately used in energy production. Most of this was obtained from domestic roundwood harvestings, but the total quantity also includes bark from the ca. 10 million m^3 of wood that is imported annually. These data indicate that all of the harvested bark is fully used. The harvestable forest reserves of bark are concentrated in Southern and Eastern Finland as growing stock volumes are highest in these areas (Fig. 5). Areas close to the western coast also have high bark potential. However, roundwood fellings (and thus bark harvests) are most intensive in the east and south-eastern parts of the country, and the unused bark potential is highest in areas close to the western and southern coasts.

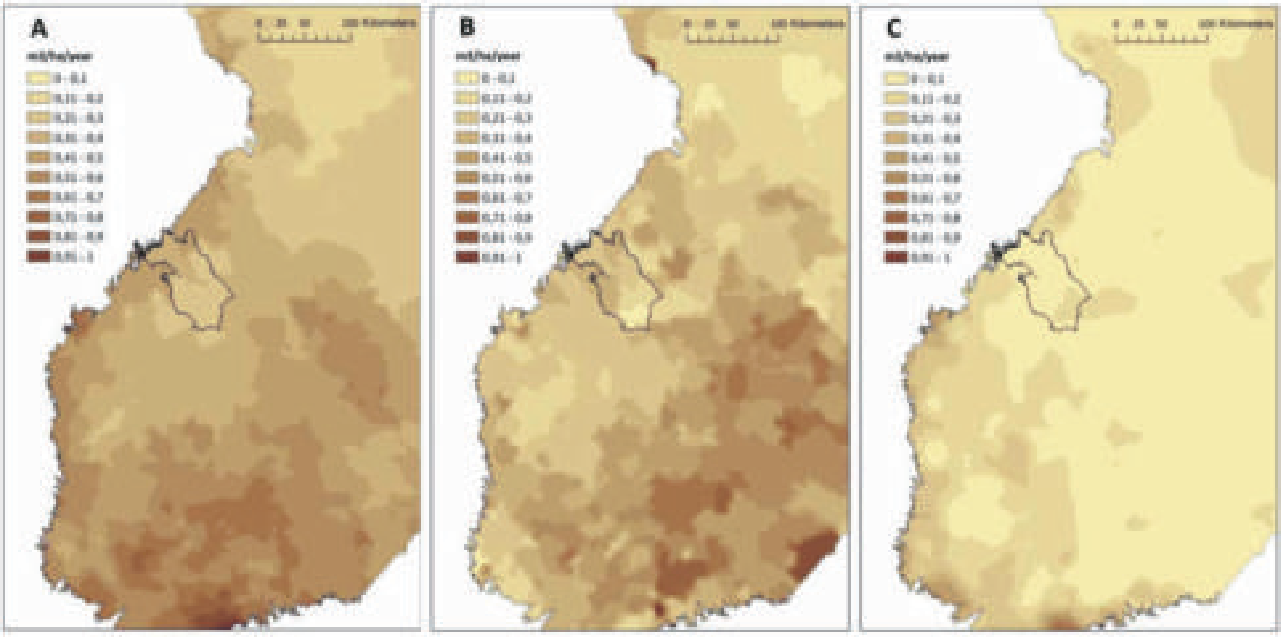


Figure 5. (A) Bark harvesting potential (volume per unit area of forest land) estimated on the basis of data and harvesting recommendations in the 10th NFI. (B) Volume of harvested bark on the basis of the average harvesting level in 2002-2011. (C) Surplus bark, i.e. the full potential minus the harvested volume. The province of Central Osthrobotnia is outlined in the maps. Harvesting statistics applied in the calculations for (B): Metla/MetINFO.

Stumps

The total estimated volume of potentially harvestable stumps was 6.7 million m^3 nationally, with Norway spruce, Scots pine and broadleaf species (mainly birches) accounting for 3.0, 2.5 and 1.3 million m^3 of the total, respectively. Thus, as 1.3 million m^3 of stump biomass was annually used in energy production in Finland between 2002 and 2011, the maximum potentially harvestable stump volume would be ca. 8.0 million m^3 (3.5, 3.0 and 1.5 million m^3 of spruce, pine and broadleaf stumps, respectively), and less than a fifth of the total potential is used. However, only spruce stumps have been commonly extracted from clear-cuts, thus the pine and broadleaf stump potentials remain unexploited. The remaining potential volume of spruce stumps has been estimated by subtracting the mass of stumps used (in 2011) from the total volume of potentially harvestable spruce stumps estimated from the 2002-2011 average harvesting level. This results in an annual surplus potential of 1.6 million m^3 for the whole country. The geographical distribution of potentially available stump biomass depends on the estimation basis (Figs. 6, 7, 8). Based on the average harvesting levels, spruce and broadleaf stumps are most abundant in Southern and Eastern Finland (although there are also high densities of pine stumps in Western parts of the country). Estimates based on the NFI data indicate that the maximum stump potential for all considered tree species is concentrated in the Western coastal areas in addition to the Eastern and Southern parts of the country. The free potential of spruce stumps is limited to Southern and Eastern Finland. In Western Finland, the full potential of spruce stumps appears to be used on the basis of the average harvesting levels.

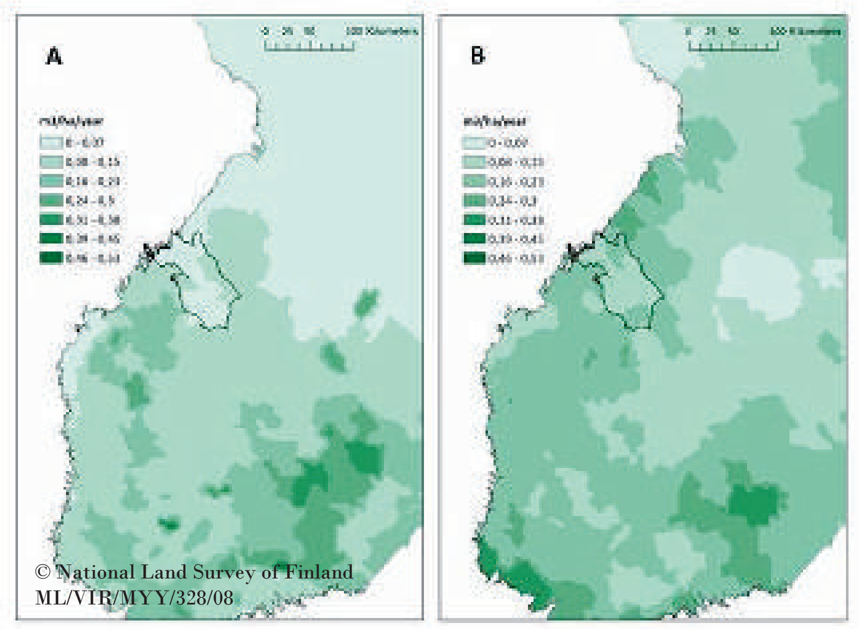


Figure 6. (A) Volumes (per hectare of forest land) of harvestable Scots pine stumps based on the average harvesting level in 2002-2011. (B) Technically feasible potential harvesting volumes of pine stumps estimated on the basis of data and recommendations in the 10th NFI. Total pine stump volumes in the province of Central Osthrobotnia (outlined in the maps): 32 400 m^3 in (A) and 59 400 m^3 in (B). Harvesting statistics (A): Metla/MetINFO

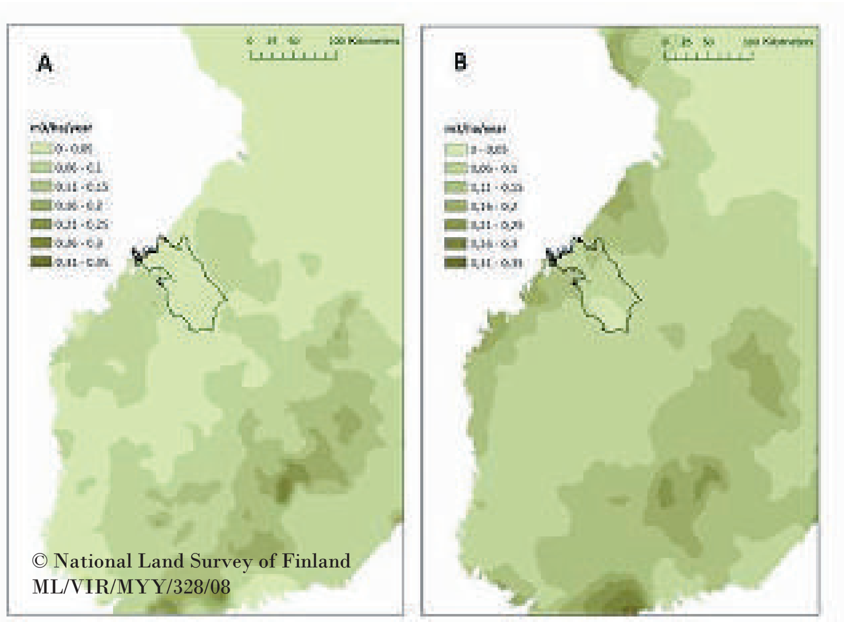


Figure 7. (A) Volumes (per hectare of forest land) of harvestable broadleaf tree (mainly birch) stumps based on the average harvesting level in 2002-2011. (B) Technically feasible potential harvesting volumes of broadleaf stumps estimated on the basis of data and recommendations in the 10th NFI. Total broadleaf stump volumes in the province of Central Osthrobotnia (outlined in the maps): 12 800 m^3 in (A) and 24 200 m^3 in (B). Harvesting statistics (A): Metla/MetINFO.

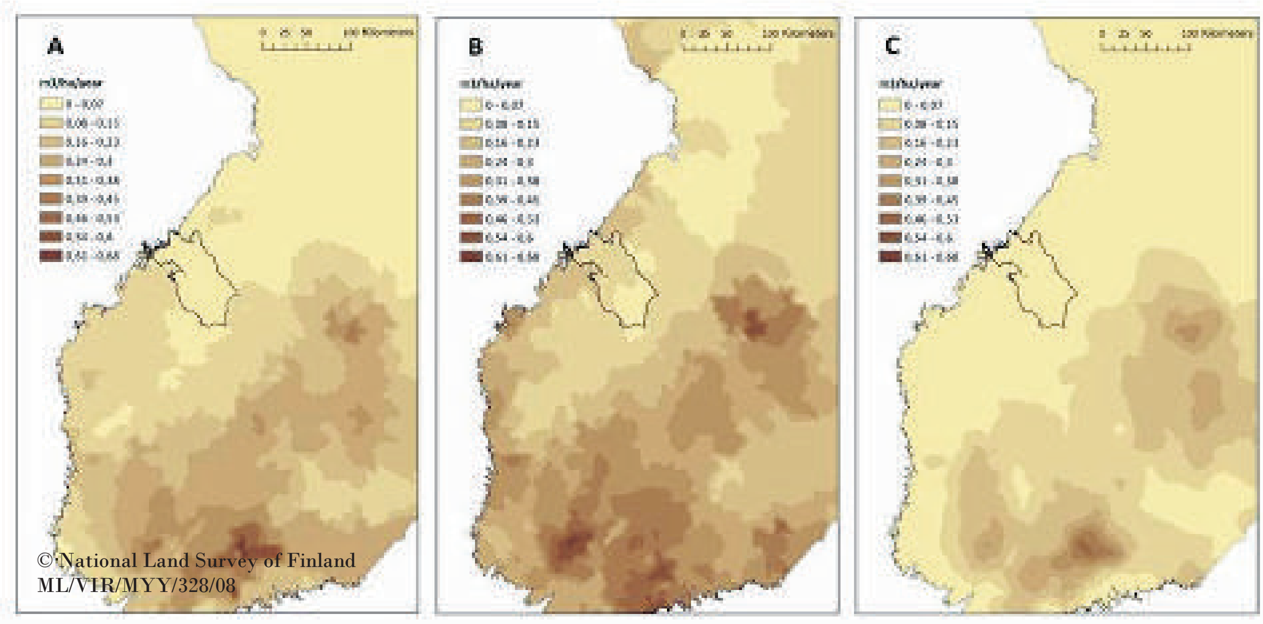


Figure 8. (A) Volumes (per hectare of forest land) of harvestable Norway spruce stumps based on the average harvesting level in 2002-2011. (B) Technically feasible potential harvesting volumes of spruce stumps estimated on the basis of data and recommendations in the 10th NFI. (C) Volumes of unexploited potentially harvestable spruce stumps, estimated by subtracting volumes currently used from the average harvestable volumes shown in (A). Total spruce stump volumes in the province of Central Osthrobotnia (outlined in the maps): 17 100 m^3 in (A), 32 400 m^3 in (B) and 0 m^3 in (C). Harvesting statistics (A): Metla/MetINFO. The geographical distribution of stump utilization was estimated by Anttila et al. (2013).

<u>Tree tops and delimbed branches from final fellings</u>

The maximum volume of potentially harvestable logging residues was 11.1 million m^3: 6.9, 2.8 and 1.4 million m^3 of spruce, pine and broadleaf residues, respectively. Logging residues are currently only used in energy production. In 2011, 3.7 million m^3 of logging residues were chipped and burned for energy in Finland. Almost all of this volume consisted of spruce residues, so the remaining free potential of spruce logging residues is reduced to 2.4 million m^3 at the average harvesting level (2002-2011) and that of pine residues to 2.1 million m^3. Broadleaf residues are not currently utilized at all, so all of the broadleaf potential is technically available. Despite the current utilization in energy production, the full potential of logging residues (and other biomass components) is naturally open to competition and if more productive or profitable applications are found, the biomass volumes from energy production could be reallocated. Based on the average harvesting levels in 2002-2011, spruce and broadleaf logging residues are most abundant in Southern and Eastern Finland (Figs. 9, 10, 11). In addition to these areas, pine residues are also concentrated in Western parts of the country. Based on the NFI data estimation, the maximum logging residue potential of all species is concentrated in the Western coastal areas and the Eastern and Southern parts of the country. If volumes of pine residues currently utilized are subtracted from the total potentially harvestable volumes, based on the average harvesting levels, the remaining unused potential volumes are concentrated in the Southeastern part of Finland. Similarly, the "free" potential volumes of spruce residues are concentrated in Southern and Eastern parts of the country, whereas in parts of Western Finland both pine and spruce residue potentials are currently in full use on the basis of the average harvesting levels.

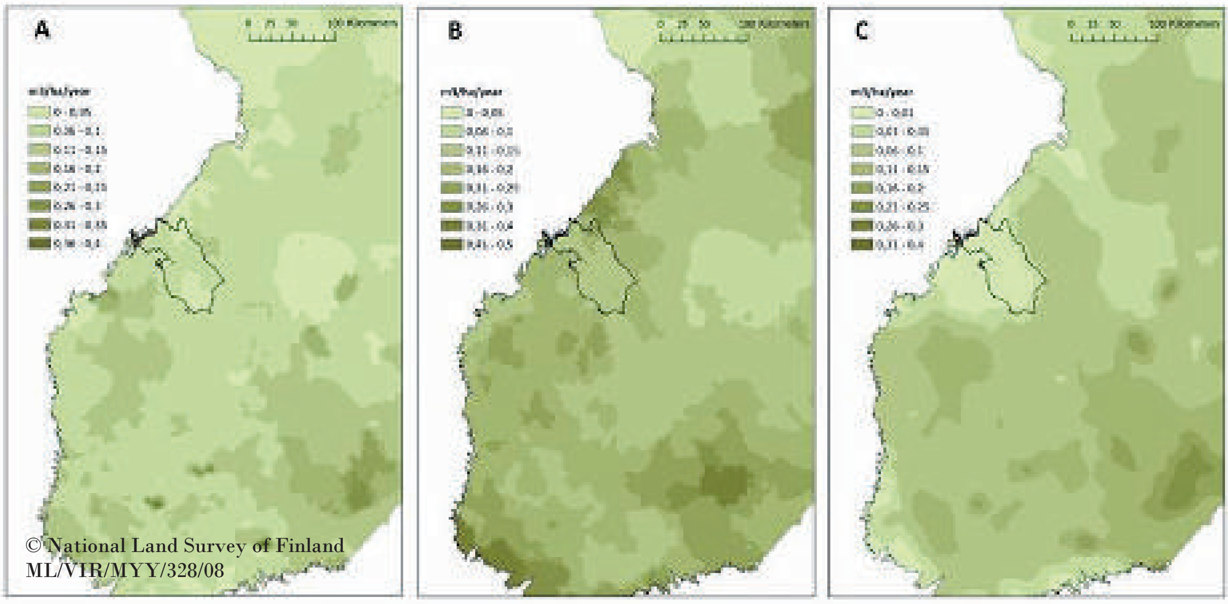


Figure 9. (A) Volumes (per hectare of forest land) of harvestable Scots pine logging residue based on the average harvesting level in 2002-2011. (B) Technically feasible potential harvesting volumes of pine logging residue estimated on the basis of data and recommendations in the 10th NFI. (C) Volumes of unexploited potentially harvestable pine logging residues, estimated by subtracting currently utilized volumes from the average harvestable volumes in (A). Total pine logging residue volumes in the province of Central Osthrobotnia (outlined in the maps): 29 900 m^3 in (A), 50 500 m^3 in (B) and 0 m^3 in (C). Harvesting statistics (A): Metla/MetINFO. The geographical distribution of logging residue utilization was estimated by Anttila et al. (2013).

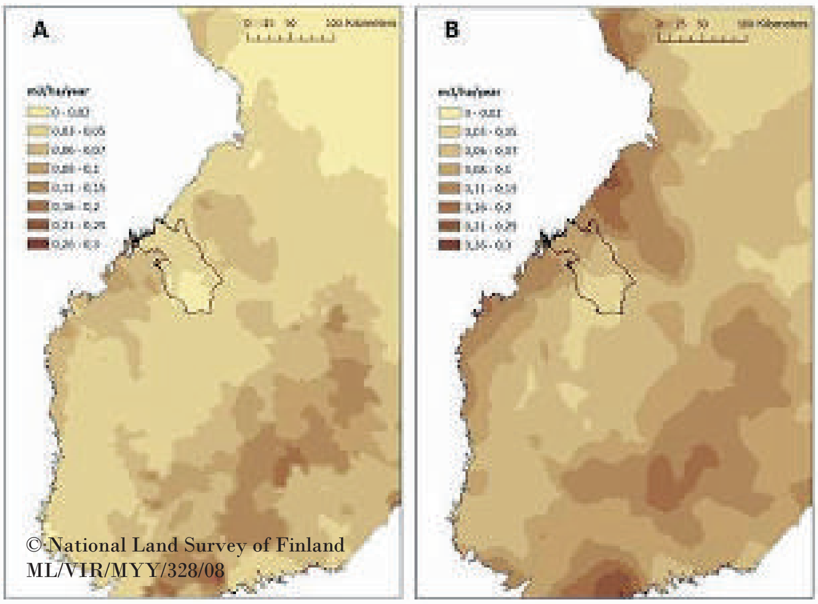


Figure 10. (A) Volumes (per hectare of forest land) of harvestable broadleaf (mainly birch) logging residues based on the average harvesting level in 2002-2011. (B) Technically feasible potential harvesting volumes of broadleaf logging residues estimated on the basis of data and recommendations in the 10th NFI. Total broadleaf logging residue volumes in the province of Central Osthrobotnia (outlined in the maps): 11 500 m^3 in (A) and 20 600 m^3 in (B). Harvesting statistics (A): Metla/MetINFO

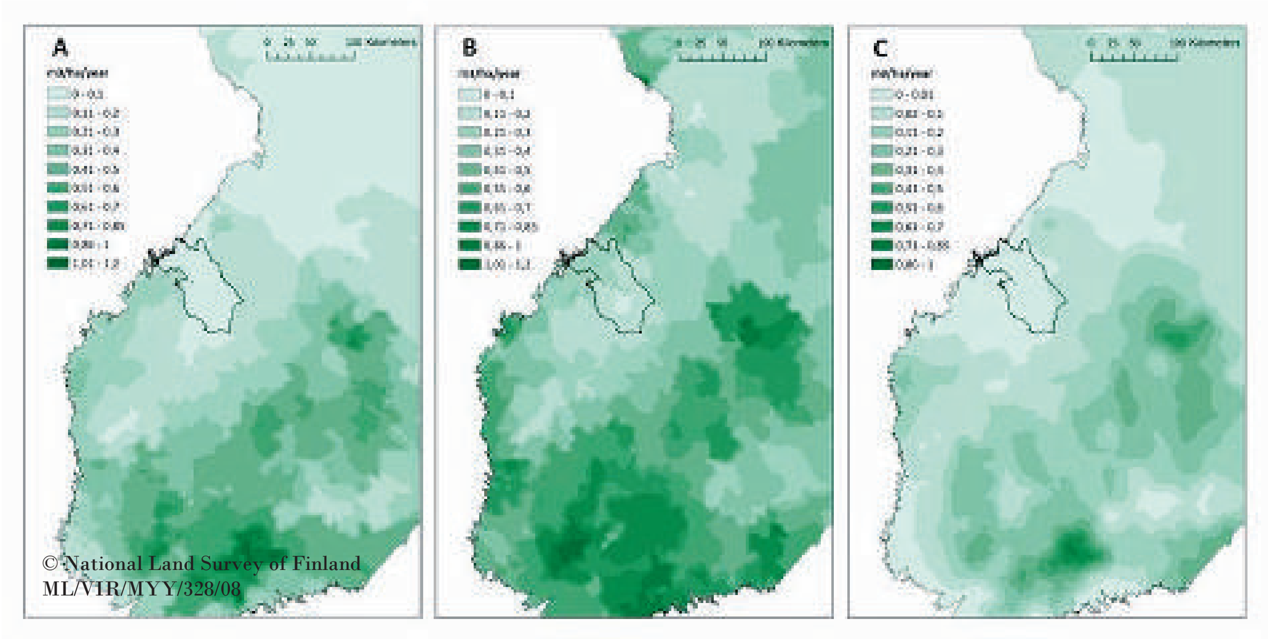


Figure 11. (A) Volumes (per hectare of forest land) of harvestable Norway spruce logging residue based on the average harvesting level in 2002-2011 (B) Technically feasible potential harvesting volumes of spruce logging residues estimated on the basis of data and recommendations in the 10th NFI. (C) Volumes of unexploited potentially harvestable spruce logging residues, estimated by subtracting currently utilized volumes from the average harvestable volumes in (A). Total spruce logging residue volumes in the province of Central Osthrobotnia (outlined in the maps): 31 200 m^3 in (A), 57 750 m^3 in (B) and 0 m^3 in (C). Harvesting statistics (A): Metla/MetINFO. The geographical distribution of logging residue utilization was estimated by Anttila et al. (2013).

Thinning of young stands

If the thinning wood is harvested as delimbed stem wood, the total potentially harvestable volume is reduced from 12.4 to 9.3 million m^3 per year. Using an integrated harvesting method requiring at least 20 m^3 per ha yield of roundwood in a thinning, the potentially available volume of small-diameter wood (without crowns) would be 10.2 million m^3 per year nationally. In 2011, 4.3 million m^3 of small-diameter thinning wood was used in energy production in Finland. Thus, regardless of the estimation basis, the utilized volume is clearly less than half of the full harvesting potential. The unutilized potential volume of whole-tree biomass from thinnings, taking into account the utilized volume in 2011, would be 8.1 million m^3 per year, while the unutilized potential volumes of delimbed stem wood and wood harvested using the integrated harvesting method would be 5.0 and 5.9 million m^3, respectively. The tree species with the highest thinning wood potential is Scots pine, closely followed by broadleaf species. The overall pine and broadleaved species' potentials are concentrated in the Northwestern part of Finland (Figs. 12, 13, 14). Similarly, the unutilized pine and broadleaf thinning wood potentials are concentrated in the Western and Northern parts of the country. The spruce thinning wood potential is concentrated in the Eastern and Southern parts of Finland, but most of the unutilized spruce potential lies in the East.

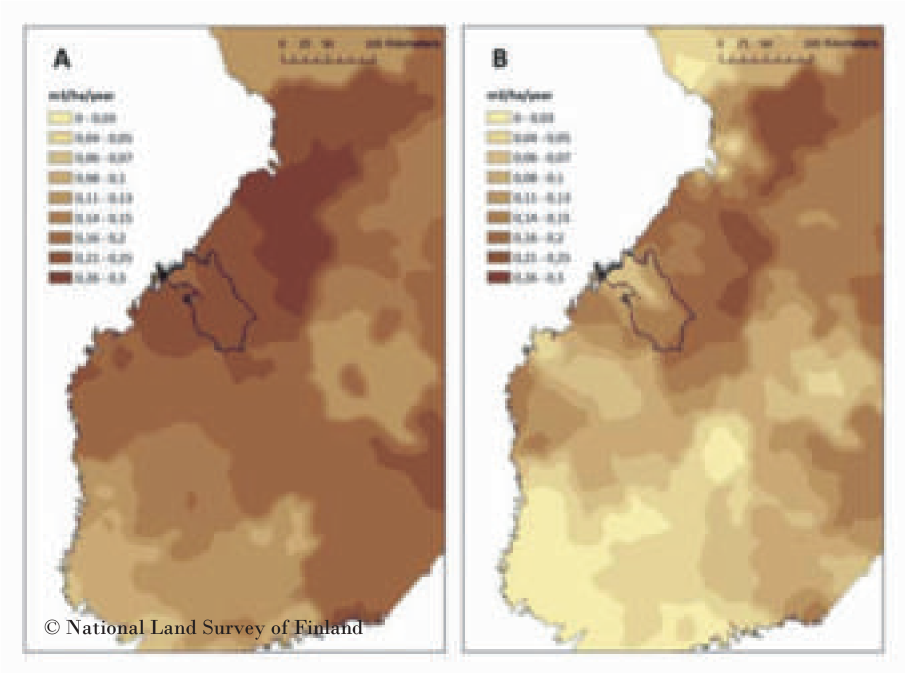


Figure 12. (A) Volumes (per hectare of forest land per year) of harvestable Scots pine small-diameter thinning wood (including crown biomass) estimated on the basis of data and harvesting recommendations in the 10th NFI. (B) Volumes of unexploited potentially harvestable pine small-diameter thinning wood, estimated by subtracting currently utilized volumes from the harvestable volumes in (A). Total pine small-diameter thinning wood volumes (including crowns) in the province of Central Ostrobothnia (outlined in the maps): 110 000 m^3 in (A) and 59 200 m^3 in (B). The geographical distribution of small wood utilization was estimated by Anttila et al. (2013).

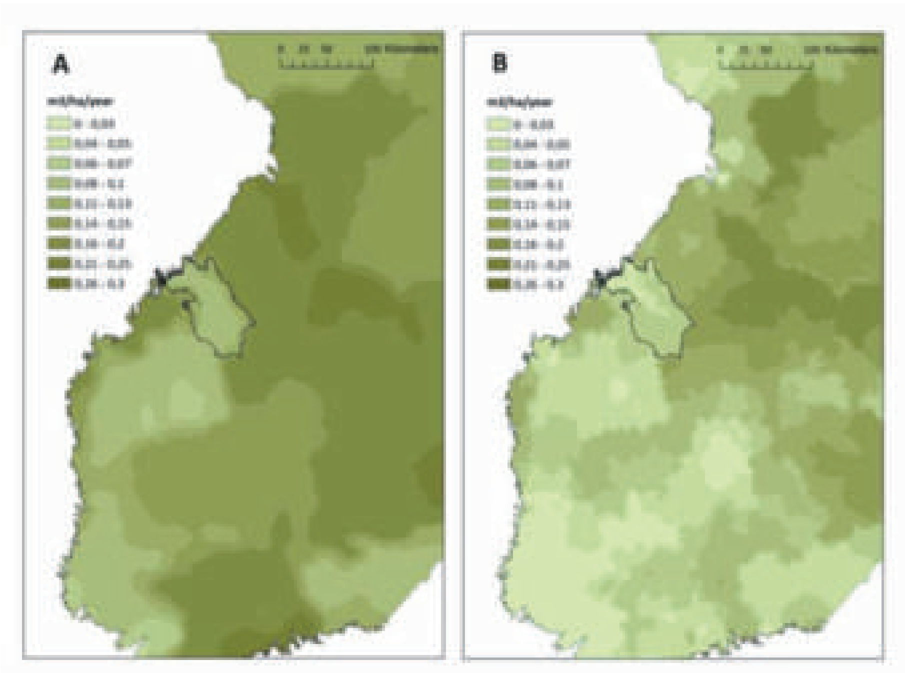


Figure 13. (A) Volumes (per hectare of forest land per year) of harvestable broadleaf small-diameter thinning wood (including crown biomass) estimated on the basis of data and harvesting recommendations in the 10th NFI. (B) Volumes of unexploited potentially harvestable broadleaf small-diameter thinning wood, estimated by subtracting currently utilized volumes from the harvestable volumes in (A). Total broadleaf small-diameter thinning wood volumes (including crowns) in the province of Central Ostrobothnia (outlined in the maps): 49 200 m^3 in (A) and 26 300 m^3 in (B). The geographical distribution of smallwood utilization was estimated by Anttila et al. (2013).

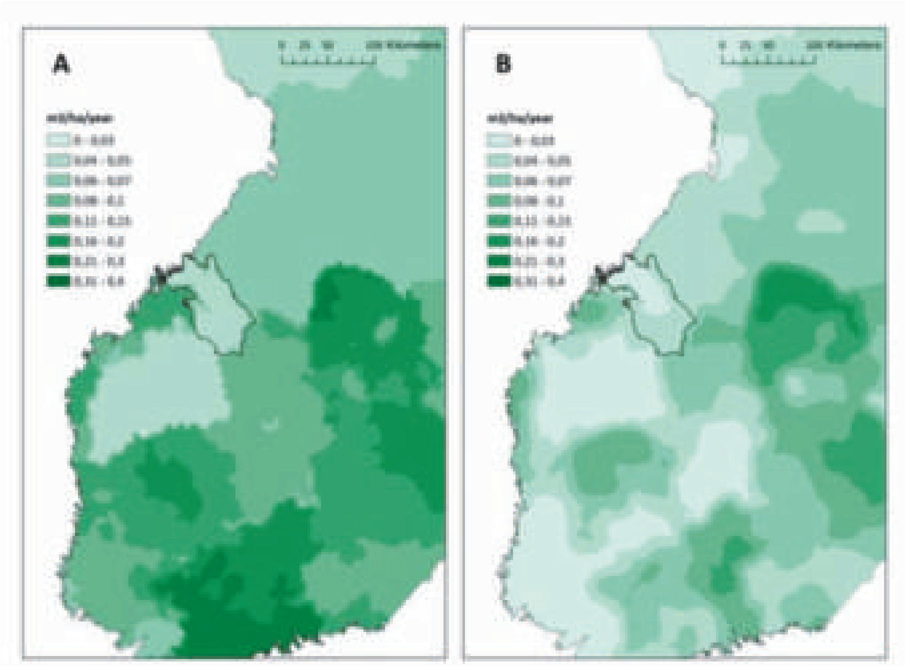


Figure 14. (A) Volumes (per hectare of forest land per year) of harvestable Norway spruce small-diameter thinning wood (including crown biomass) estimated on the basis of data and harvesting recommendations in the 10th NFI. (B) Volumes of unexploited potentially harvestable spruce small-diameter thinning wood, estimated by subtracting currently utilized volumes from the harvestable volumes in (A). Total spruce small-diameter thinning wood volumes (including crowns) in the province of Central Ostrobothnia (outlined in the maps): 22 700 m^3 in (A) and 12 100 m^3 in (B). The geographical distribution of smallwood utilization was estimated by Anttila et al. (2013).

Pulpwood

The volume of potentially harvestable pulpwood-sized stemwood in Finland (based on data and recommendations in the 10th NFI) is 37.6 million m^3 per year: consisting of 14.7, 11.9 and 10.9 million m^3 of pine, spruce and broadleaves (82% birches), respectively. The average pulpwood harvesting volume was 7.5 million m^3 below this full potential nationally. Most of this surplus consists of spruce and broadleaves, while pine pulpwood harvestings already appear to be close to the full potential. However, there are significant variations in harvested pulpwood volumes among years, so the surplus volume could be much larger or smaller in some years. Harvestings of Scots pine and broadleaf pulpwood are concentrated in the north-western and south-eastern parts of the country, while spruce pulpwood harvesting is more concentrated in south-eastern and southern parts (Figs. 15, 16, 17). According to the NFI data the harvesting potential of pine and broadleaves is focused in the West and South-east, while that of spruce is concentrated in the Southern and South-western parts of Finland. It should be noted that the regional variability in annual harvestings can be large, hence the harvested volumes in some regions may well exceed the estimated potential for the same areas.

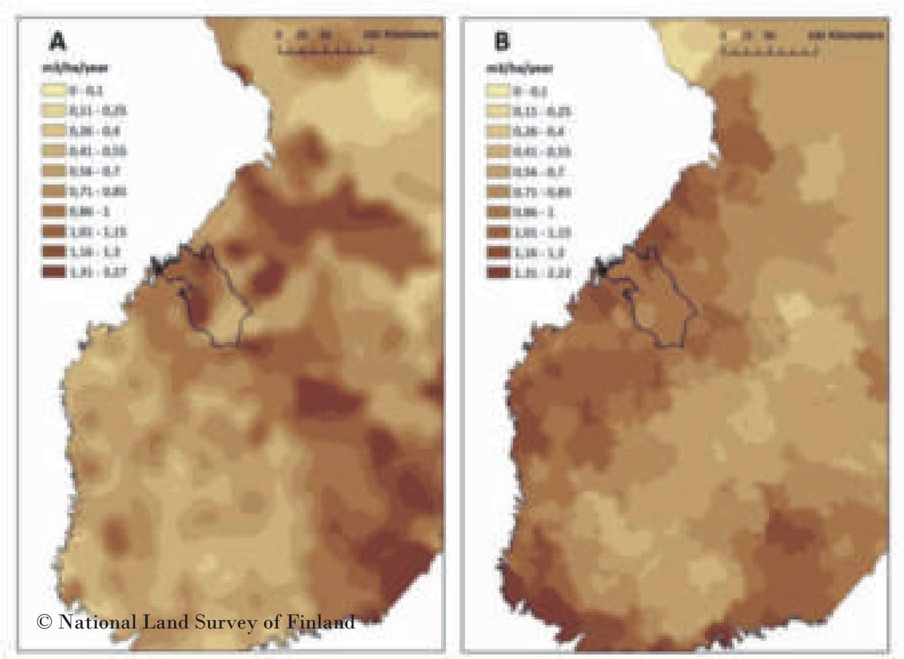


Figure 15. (A) Volumes (per hectare of forest land per year) of harvested Scots pine pulpwood from all felling types based on the average harvesting level in 2002-2011. (B) Volumes of potentially harvestable pine pulpwood estimated on the basis of data and harvesting recommendations in the 10th NFI. Total pine pulpwood volumes in the province of Central Ostrobothnia (outlined in the maps): 332 000 m^3 in (A) and 320 000 m^3 in (B). Harvesting statistics (A): Metla/MetINFO.

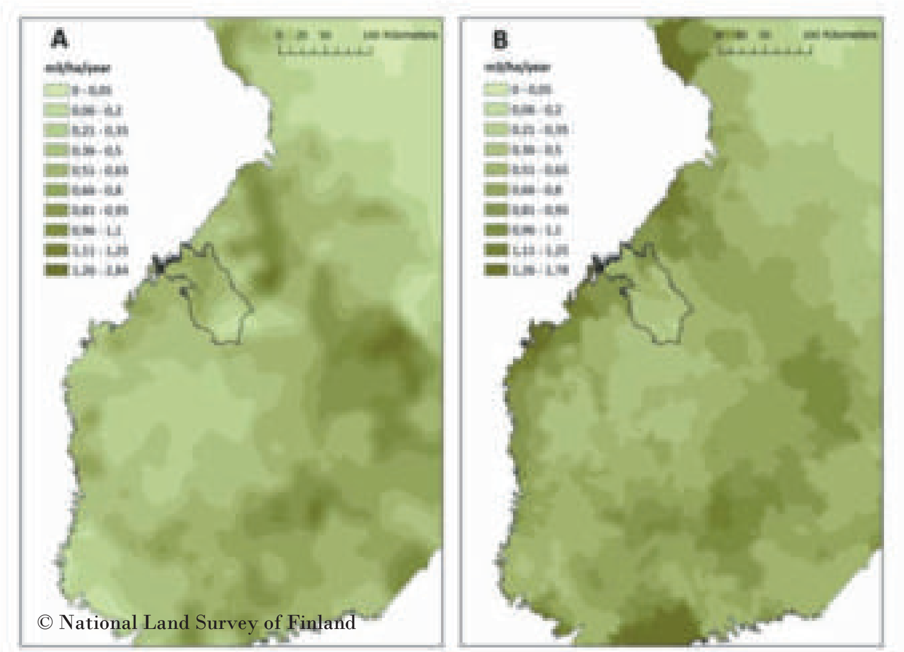


Figure 16. (A) Volumes (per hectare of forest land per year) of harvested broadleaf (mainly birches) pulpwood from all felling types based on the average harvesting level in 2002-2011. (B) Volumes of potentially harvestable broadleaf pulpwood estimated on the basis of data and harvesting recommendations in the 10th NFI. Total broadleaf pulpwood volumes in the province of Central Ostrobothnia (outlined in the maps): 176 000 m^3 in (A) and 181 000 m^3 in (B). Harvesting statistics (A): Metla/MetINFO.

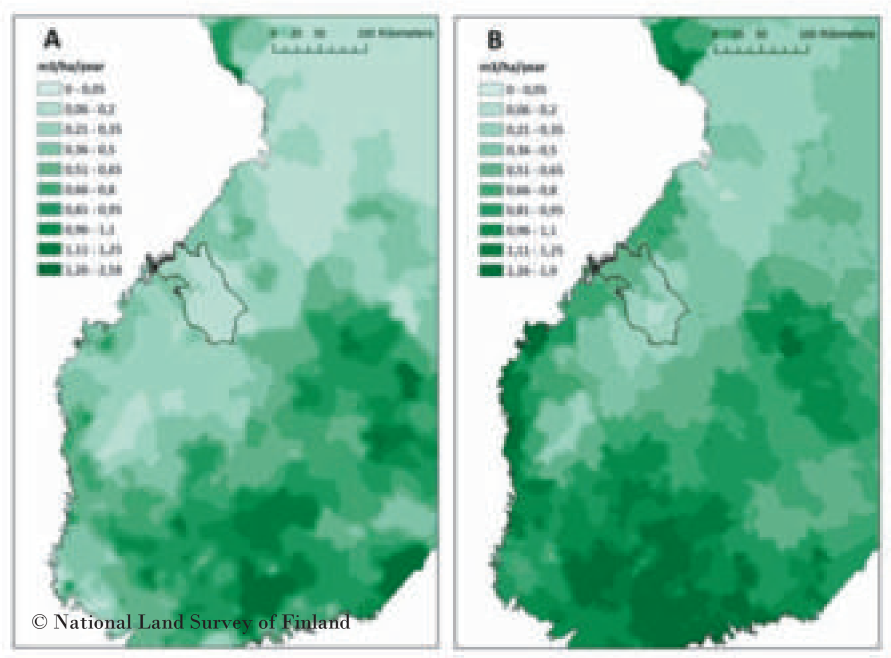


Figure 17. (A) Volumes (per hectare of forest land per year) of harvested Norway spruce pulpwood from all felling types based on the average harvesting level in 2002-2011. (B) Volumes of potentially harvestable spruce pulpwood estimated on the basis of data and harvesting recommendations in the 10th NFI. Total spruce pulpwood volumes in the province of Central Ostrobothnia (outlined in the maps): 48 000 m^3 in (A) and 123 000 m^3 in (B). Harvesting statistics (A): Metla/MetINFO.

GIS-analysis of potential biomasses from young forests in North Sweden

Objectives
The objective of this part of the project was to evaluate the distribution of young stands in the northern part of Sweden (Norrland).

Background & Materials and Methods
GIS-based spatial analysis was carried out to evaluate the distribution of young, un-thinned, dense forests in Sweden and subsequently calculate volumes of the following wood assortments (products) from these forests: delimbed logs, roughly delimbed logs, roughly delimbed tree sections and whole tree sections. The analysis utilized a dataset provided by the Swedish NFI, which includes geographical coordinates and data collected for all inventory plots from the period 2006-2010, *inter alia* their above-ground biomass density (OD t/ha), i.e. biomass of stem wood (including bark) and living branches (including needles). The average stem volume on bark, including the top (dm^3), was also calculated for each plot. In addition, the dataset provided information on the forest area (ha) "represented" by each plot, within each county of Sweden (i.e. the "extent" of the data concerning a single plot), the average tree height, average tree DBH, total volume per ha, density of trees per ha, and if the plot had been thinned or not.

In order to select the young dense stands from the total forest area of Sweden, the dataset was exported to the GIS, and the following selection criteria were applied: not-thinned stands, above-ground biomass density > 30 OD t/ha, average tree height 3 - 12 m, average DBH < 20 cm and average stem volume 10 - 120 dm^3. The harvesting volumes for each assortment were calculated by applying proportions found in seven inventoried sample stands to the above-ground biomass density of each of the selected plots, to obtain the extraction potential (OD t/ha).

Results & Conclusions

Across Sweden, young dense forests fulfilling the selection criteria cover a total area of 2.11 million ha (9 % of the total forest area of Sweden). The results showed the existence of large areas covered by young dense forests, especially in Norrland, in the counties of Västerbotten and Västernorrland (Fig. 18). In total these stands cover 1.38, 0.34 and 0.2 million ha in Norrland, Västerbotten and Västernorrland, respectively. The calculated annual extraction potentials for delimbed pulpwood logs, roughly delimbed pulpwood logs, roughly delimbed tree sections and whole tree sections in them were 8.8, 16.4, 26.5 and 29.2 million OD t, respectively. Further results from this early stage study will be implemented and discussed later.

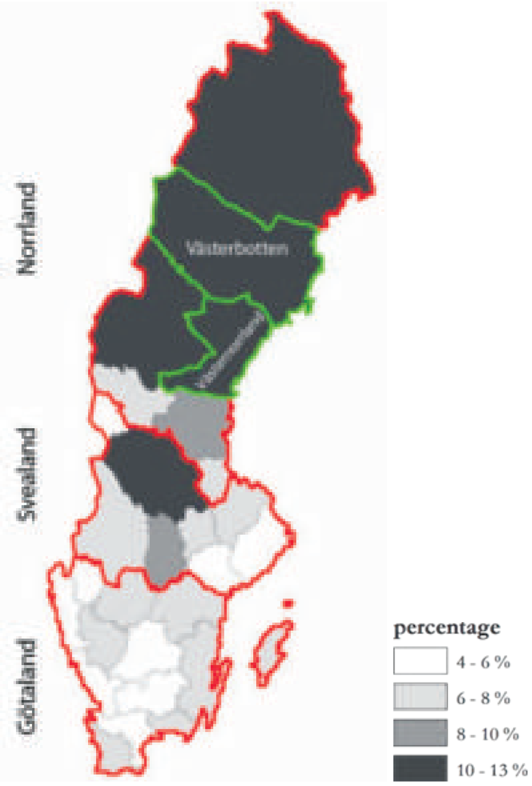


Figure 18. Percentage of the total forest area in each county represented by young-dense stands.

Potential pine, spruce and birch biomasses for three locations in the Swedish part of the Botnia-Atlantica region

Objectives

In this study the potentially available quantities of roundwood, bark, branches, leaves and needles as well as tops and stumps with attached root system were estimated for the period 2010-2059 for three localities in the North of Sweden.

Materials and methods

Two of the focal localities are situated on the coast, Umeå and Örnsköldsvik. Both have existing district heating plants that run on biomass as well as large pulp mills and potential sites for establishing new types of industries (Fig. 19). The third location, Storuman, is located inland and is a potential location for a new forest-based industry or an industrial-scale hub for feedstock handling and upgrading before further transport to remote industrial sites. A procurement area for each location with a 120 km radius was retrieved using the existing road network and the network analyst module in ArcGis 10.2. The calculations assumed there would be no competition for biomass from other industries. The estimations of the available quantities of forest biomass were based on data collected by the NFI from 2002 to 2006 (SFA 2008). This is a 100-year timber production forecast comparing a reference scenario with alternative scenarios, based on different forest management options. The estimations in the study take into account all the productive forest around the localities of Umeå, Storuman and Örnsköldsvik, including that within formally protected areas (national parks, nature reserves, etc.). The reference scenario assumes that Swedish silvicultural practices will not change and annual fellings will remain at a level that is regarded as sustainable, that environmental legislation will not change and that climate change will be light (SFA 2008). The predicted volumes of roundwood, bark, branches, needles, tops and stumps with attached root systems resulting from each harvesting operation within the study period (theoretical extraction potentials) are reported in OD t/ha for every considered tree species: spruce, pine and broadleaves (mostly birch). The biomass functions for estimating volumes of all the tree components except stumps with attached root systems are described in Pettersson (1999). The biomass functions are based on factors including the tree species, the DBH of the trees, tree height and the production capacity of the site. Biomass functions for estimating the volume of stumps with attached root systems were based on tree species and the breast height diameter of the trees, as described in Pettersson and Ståhl (2006). Roundwood is the main product of the harvesting operations, while branches, needles and tops (hereafter referred to as harvesting residues) and stumps with attached root systems (hereafter referred to as stumps) are regarded as by-products. The theoretical extraction potential expresses an upper limit of the availability of these components. In order to assess the ecological potential of harvesting residues and stumps a set of restrictions, developed in cooperation with the SFA (SFA 2008), can be applied to the theoretical potential (Athanassiadis et al. 2009). In this study, roundwood harvesting was not subjected to any ecological restrictions, i.e., the reported volume is the theoretical potential for the studied period. However, the output of harvesting residues and stumps from the harvesting operations was reduced by excluding plots in productive forest areas in the following locations. Firstly, sites within 25 meters of a lake, sea, water course or any ownership category other than forest (which minimizes damage to the water courses and takes into consideration social aspects, such as risks of damaging sites of cultural or recreational interest etc.). Secondly, very wet sites, with a water table less than 1 meter deep, and sites where peat covers more than half of the harvesting area (which have low bearing capacity), to avoid excessive soil compaction, rutting and rises of the water layer in both main and secondary strip roads. Thirdly, sites with a slope of more than 50% according to the Swedish terrain classification scheme (Berg, 1992), to avoid erosion. In addition, no hardwood stumps were considered for extraction due to their high biodiversity values. More information on guidelines and recommendations for harvesting stumps and logging residues is provided in SFA (2008).

Figure 19. Studied procurement areas of the facilities in Umeå, Storuman and Örnsköldsvik. The Botnia-Atlantica region is outlined with a yellow line.

Results

Theoretical potentials (1000 OD t) of assortments from commercial thinnings and final fellings for the period 2010-2059 are reported in Tables 2, 3 and 4.

Table 2. Potential availability of pine biomass assortments (1000 OD t/year) for facilities located in Umeå, Storuman and Örnsköldsvik

Locality	Period	Roundwood	Bark	Branches	Needles	Stumps	Tops
Umeå	2010-2019	702.4	48.3	112.7	37.9	291.8	13.8
	2020-2029	659.5	48.8	112.7	38.1	283.1	14.4
	2030-2039	616.5	44.0	96.9	31.1	264.6	12.2
	2040-2049	568.0	40.8	90.6	28.4	244.3	11.1
	2050-2059	688.8	49.3	108.8	33.6	293.9	13.5
	2060-2069	809.0	57.1	125.0	37.3	340.0	15.3
Storuman	2010-2019	454.9	34.9	79.4	34.9	203.0	10.6
	2020-2029	549.3	44.0	96.4	42.1	252.2	13.7
	2030-2039	446.2	32.5	68.3	26.8	199.3	8.9
	2040-2049	437.0	32.1	68.3	26.4	196.8	8.6
	2050-2059	436.2	31.5	66.9	25.4	196.1	8.0
	2060-2069	575.8	41.4	88.7	32.4	253.5	10.2
Örnsköldsvik	2010-2019	580.3	42.9	98.9	36.5	246.0	11.9
	2020-2029	674.9	50.6	113.4	40.6	289.9	14.1
	2030-2039	557.5	39.1	83.4	27.7	233.5	10.3
	2040-2049	593.5	42.4	90.3	30.0	252.8	11.5
	2050-2059	753.4	52.4	112.0	35.9	311.9	14.0
	2060-2069	799.6	56.1	119.2	37.8	332.6	15.2

Table 3. Potential availability of spruce biomass assortments (1000 OD t/year) for facilities located in Umeå, Storuman and Örnsköldsvik

Locality	Period	Roundwood	Bark	Branches	Needles	Stumps	Tops
Umeå	2010-2019	604.6	69.4	177.1	95.9	291.8	14.6
	2020-2029	440.8	50.9	131.6	71.7	283.1	10.9
	2030-2039	296.6	35.3	89.5	48.6	264.6	7.5
	2040-2049	326.6	38.4	94.9	50.3	244.3	7.9
	2050-2059	341.5	40.2	100.3	53.9	293.9	8.8
	2060-2069	357.8	41.1	100.2	52.9	340.0	8.1
Sroruman	2010-2019	338.3	43.4	108.1	58.2	212.4	9.3
	2020-2029	330.0	41.6	100.4	52.3	203.0	7.0
	2030-2039	477.9	62.4	142.8	72.1	296.2	10.5
	2040-2049	560.8	72.4	168.3	85.4	347.9	11.4
	2050-2059	408.5	51.2	122.4	63.3	250.1	8.2
	2060-2069	366.0	45.2	107.3	55.3	223.8	6.9
Örnsköldsvik	2010-2019	864.2	95.2	241.1	130.4	483.7	21.5
	2020-2029	715.8	80.1	204.0	110.5	405.5	17.2
	2030-2039	517.6	59.6	147.0	77.8	297.6	13.2
	2040-2049	569.5	65.1	158.5	82.3	326.1	13.1
	2050-2059	610.7	67.9	165.9	86.5	343.4	13.3
	2060-2069	556.4	61.1	147.3	76.0	310.7	11.2

Table 4. Potential availability of birch biomass assortments (1000 OD t/year) for facilities located in Umeå, Storuman and Örnsköldsvik

Locality	Period	Roundwood	Bark	Branches	Tops
Umeå	2010-2019	119.0	19.5	32.2	3.7
	2020-2029	138.9	22.8	37.1	4.3
	2030-2039	336.3	54.7	91.6	8.9
	2040-2049	276.9	44.2	74.8	8.1
	2050-2059	346.9	56.5	93.4	10.2
	2060-2069	420.2	65.4	115.4	10.2
Storuman	2010-2019	118.0	20.1	35.3	4.8
	2020-2029	119.4	20.6	34.6	4.8
	2030-2039	263.9	45.2	78.5	8.2
	2040-2049	373.9	64.6	101.4	10.1
	2050-2059	398.6	67.6	108.5	8.7
	2060-2069	330.9	56.0	96.5	8.0
Örnsköldsvik	2010-2019	166.7	26.9	45.0	5.0
	2020-2029	216.0	34.7	58.9	6.4
	2030-2039	458.6	72.5	128.7	12.1
	2040-2049	602.4	93.5	168.7	12.1
	2050-2059	586.2	93.6	154.8	13.2
	2060-2069	580.9	90.0	157.3	12.3

Potentially available forest biomasses for a biorefinery in Kokkola, Finland

Objectives

The objectives of this part of the project were to estimate the potentially available biomasses for a biorefinery in Kokkola, Finland, and their procurement costs as a function of distance and terminal location.

Materials and methods

The potentially available pulpwood, small-diameter thinning wood (delimbed and whole-tree), logging residues and stumps were estimated from the 10th NFI data and roundwood harvesting statistics. The full potentially harvestable volumes of the biomass assortments were estimated considering harvesting restrictions for each assortment. The current uses and regional distributions (in 2011) of small-diameter thinning wood, logging residues and stumps were estimated (Anttila et al. 2013). The used volumes of these assortments were subtracted from the full harvestable potentials to derive estimates of the volumes of unused forest biomass resources. The unused potentially harvestable volumes of pulpwood were estimated by subtracting harvested volumes (in 2011) from the total potentially harvestable volumes obtained from the NFI data. The potential volumes of the biomass assortments were divided into a point grid (5x5 km) and the existing road network was used to calculate the transport distance from each point to the facility (Fig. 20, left). The cumulative biomass potentials were calculated for 25 km intervals from the facility up to a maximum distance of 200 km (along the road network). Procurement costs (€/m^3) for each biomass assortment were estimated using harvesting, comminution and transport cost values from earlier studies. The facility type or production capacity of the biorefinery was not considered in the analysis. Potential terminal locations were selected from locations of existing wood fuel consuming facilities. It was assumed that each of these facility locations would be capable of storing and handling significant quantities of woody biomasses. Five terminal locations were chosen by weighing the surrounding volume of available forest biomasses for each location (Fig. 20, right). GIS analyses of the forest biomasses available to the terminal locations were performed using the Network Analyst tool in ArcGIS 10.1. The costs were calculated for the terminal locations independently, but the costs of transporting comminuted material from the terminals to the biorefinery in Kokkola were also considered.

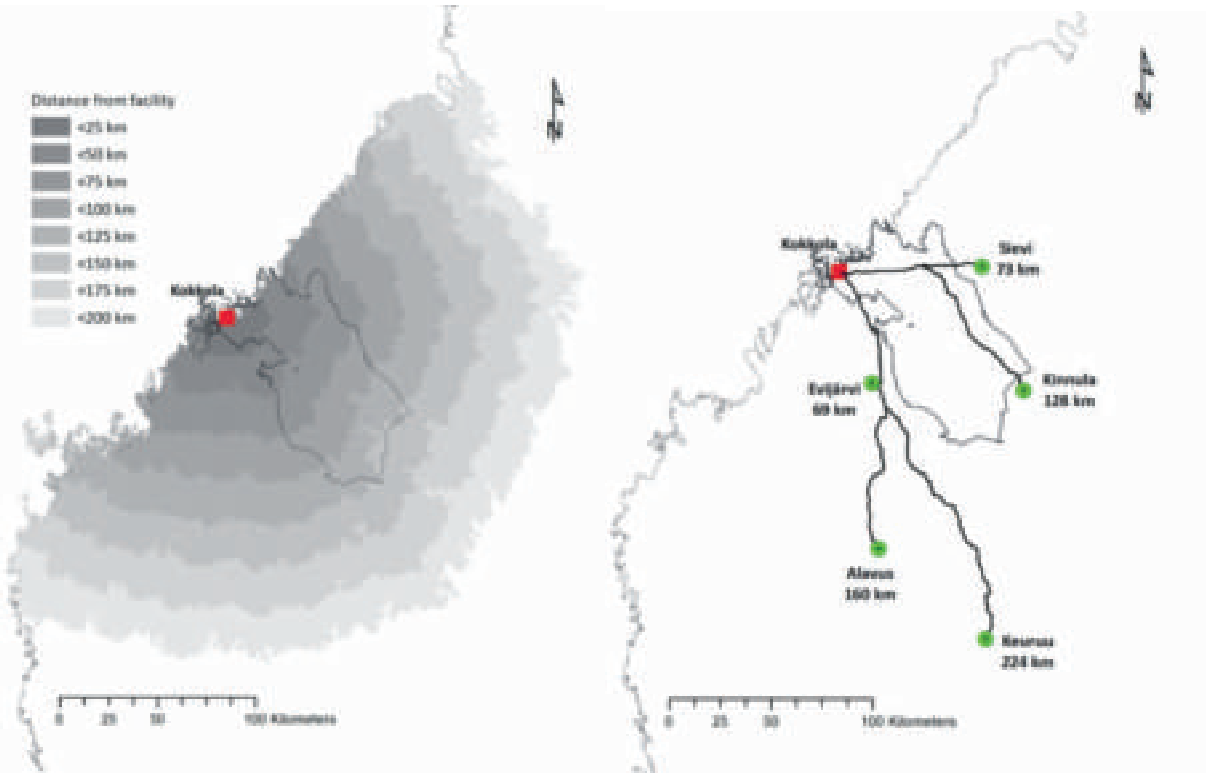


Figure 20. Left, studied procurement area of a facility in Kokkola. The province of Central Osthrobotnia is outlined with a black line. © National Land Survey of Finland MML/VIR/MYY/328/08. Right, alternative terminal locations and their distances from the facility via road. © National Land Survey of Finland MML/VIR/MYY/328/08.

Results & Conclusions

The assortment with by far the largest harvestable biomass potential in the studied procurement area is pulpwood (Table 5). The potential availability of small-diameter thinning wood is also high, especially if harvested as whole-tree biomass. Potentially harvestable volumes of stumps and logging residues from clear-cuts collectively exceed those of whole-tree thinning wood. However, the stumps and logging residues currently extracted are almost exclusively spruce, and their potential is much smaller than when all the tree species are considered. Furthermore, the unused potentials in the studied procurement area are much smaller for each assortment (Table 6). Particularly striking is the scarcity of spruce stumps and logging residues close to the facility. Small-diameter thinning wood becomes a more important raw material source when the unused potentials are considered. The procurement costs of each biomass assortment increase with increasing transport distance. The larger the volume of the raw material needed, the further away from the facility the procurement area must be extended. Therefore, the unit costs are also increased by increased procurement volumes (Figs. 21, 22, 23).

Table 5. Potentially available volumes (m^3/year) of forest biomass assortments for a facility located in Kokkola. The harvested pulpwood volume (including bark) was derived from harvesting statistics for 2011, while the total potentially harvestable volume was estimated on the basis of data in the 10th NFI.

Max. distance from facility	Harvested pulpwood	Pulpwood, potential	Delimbed thinning wood	Whole-tree thinning wood	Stumps, all species	Spruce stumps	Logging residues, all species	Spruce logging residues
25 km	102 117	127 116	23 358	31 223	12 787	4 291	18 731	10 248
50 km	355 751	478 924	98 005	130 291	55 309	18 096	81 937	45 395
75 km	818 724	1 036 865	224 753	299 268	130 933	39 688	177 298	94 922
100 km	1 304 011	1 728 925	385 421	513 043	240 650	71 025	310 975	161 107
125 km	1 980 040	2 624 978	605 144	804 435	388 561	114 137	495 586	259 686
150 km	2 911 087	3 838 973	890 646	1 183 094	572 252	171 323	720 183	382 547
175 km	4 056 563	5 337 707	1 259 088	1 672 372	815 086	255 748	1 022 698	548 090
200 km	5 079 671	6 702 670	1 593 426	2 118 859	1 055 429	351 824	1 327 459	730 030

Table 6. Unused potentially available volumes (m^3/year) of forest biomass assortments for a facility located in Kokkola. The unused pulpwood potential was calculated by subtracting the volume harvested in 2011 from the total potentially harvestable volume. The unused potentials of the other assortments were estimated by subtracting the currently used volumes from the potentially harvestable volumes presented in Table 5.

Max. distance from facility	Unused pulpwood	Delimbed thinning wood	Whole-tree thinning wood	Stumps, all species	Spruce stumps	Logging residues, all species	Spruce logging residues
25 km	24 998	5 569	11 683	3 194	0	3 445	0
50 km	123 173	32 510	61 866	14 179	0	15 753	154
75 km	218 140	86 032	158 498	33 768	92	37 389	2 001
100 km	424 914	156 225	283 957	60 391	388	81 575	16 922
125 km	644 938	248 137	449 237	101 936	2 078	158 084	46 502
150 km	927 885	379 588	677 964	173 543	13 488	245 612	78 144
175 km	1 281 144	567 296	993 883	287 114	42 670	361 715	125 496
200 km	1 622 999	747 158	1 296 382	415 045	86 800	498 955	195 065

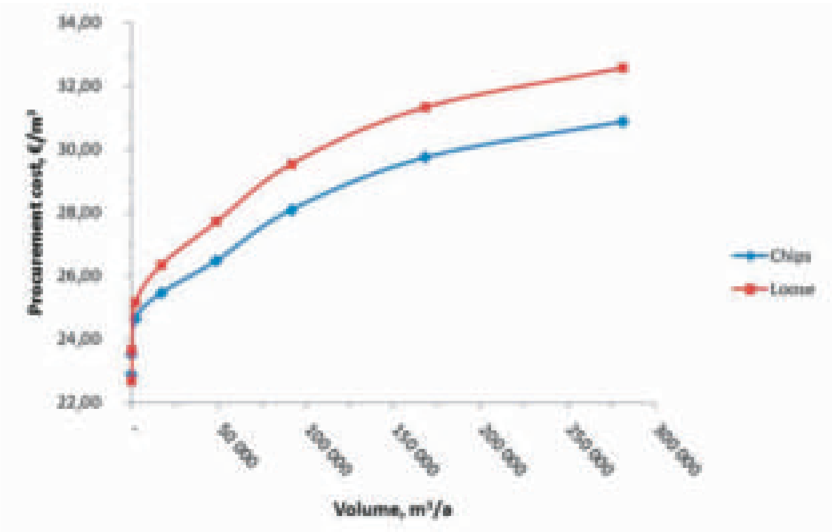


Figure 21. Procurement costs of stumps and logging residues in relation to the unused potential within the 200 km procurement area of a facility in Kokkola. Chips, logging residues chipped at roadside; Loose, logging residues transported uncomminuted and chipped at the facility. Stumps are transported as loose material and crushed at the facility.

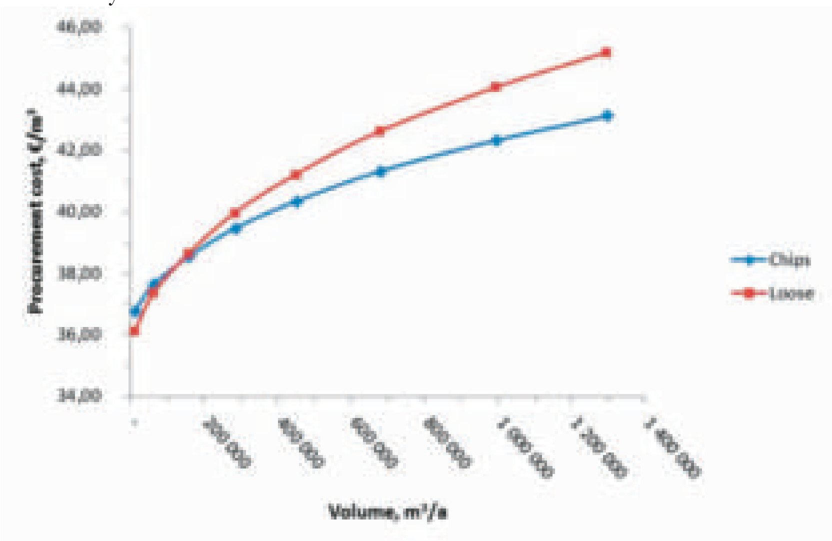


Figure 22. Procurement costs of whole-tree thinning wood in relation to the unused potential within the 200 km procurement area. Chips, thinning wood chipped at roadside and transported with a chip truck; Loose, wood transported as whole-trees and chipped at the facility.

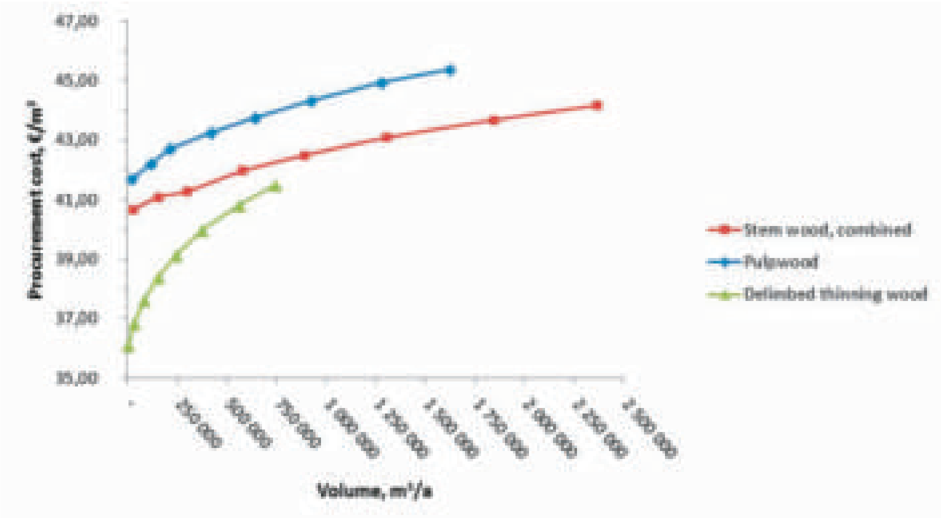


Figure 23. Procurement costs of stem wood in relation to the unused potential within the 200 km procurement area.

When the potentially harvestable biomasses were considered, some differences between the terminal locations were found (Tables 7, 8), due to the uneven geographical distribution of forest biomass reserves and regional differences in the rate of use of woody biomasses. Using the terminals was found to be more expensive in terms of unit cost than directly transporting raw material to the facility in Kokkola (Figs. 24, 25, 26). For instance, although there is a shortage of unused stumps in the areas surrounding Kokkola, it would still be more viable to transport them directly to Kokkola from longer distances than to use a terminal in Keuruu, where the stump potential is much larger. Transport costs of these biomass assortments form a significant share of the total procurement costs. Therefore, the overall costs of procurement tend to cumulate when the material has to be transported to the terminal and then transported again to the facility itself. From this perspective, using these terminal locations would only be a cost-effective option if direct transport to the facility was not possible for some reason.

Table 7. Harvested and potentially harvestable volumes (m^3) of forest biomass assortments for terminals at the considered locations.

Terminal location	Max. dist from terminal	Harvested pulpwood	Pulpwood, potential	Delimbed thinning wood	Whole-tree thinning wood	Stumps, all species	Spruce stumps	Logging residues, all species	Spruce logging Residues
ALAVUS	25 km	85 085	127 689	22 334	30 368	26 814	8 130	31 267	13 733
	50 km	439 032	686 189	119 882	163 095	143 399	47 780	157 707	83 240
	75 km	962 673	1 428 016	267 944	363 903	302 844	106 869	332 563	186 722
	100 km	1 870 357	2 704 799	546 904	741 623	591 419	218 590	652 394	382 047
EVIJÄRVI	25 km	118 282	140 890	30 370	40 581	35 624	9 478	37 165	18 657
	50 km	536 263	626 990	145 892	195 595	113 516	31 407	128 729	64 304
	75 km	1 103 728	1 420 847	300 233	402 380	229 687	66 298	267 875	134 835
	100 km	1 748 890	2 286 154	489 079	655 560	382 426	113 117	436 004	223 032
KEURUU	25 km	140 032	176 992	43 578	58 358	42 630	21 744	54 842	38 433
	50 km	622 995	756 312	176 192	236 855	206 118	103 481	258 011	184 544
	75 km	1 305 630	1 628 164	360 317	485 525	448 992	222 872	557 880	399 745
	100 km	2 305 882	2 875 826	612 000	826 083	759 110	368 997	940 371	657 072
KINNULA	25 km	62 189	116 266	32 668	43 637	21 362	6 042	20 009	10 731
	50 km	390 037	520 611	142 263	189 853	90 254	28 316	96 816	53 935
	75 km	1 090 419	1 253 203	341 509	455 377	212 433	69 260	243 170	135 349
	100 km	2 227 192	2 441 901	648 664	865 425	405 183	141 962	490 204	280 337
SIEVI	25 km	110 830	155 743	38 234	50 473	21 361	5 385	28 298	13 477
	50 km	583 782	721 644	198 014	261 557	108 714	30 733	150 304	79 603
	75 km	1 355 209	1 562 062	411 745	544 208	212 761	61 370	295 068	156 235
	100 km	2 135 942	2 514 460	692 493	915 673	341 934	101 478	471 970	249 035

Table 8. Unused potentially harvestable volumes (m^3) of forest biomass assortments for terminals at the considered locations.

Terminal location	Max. dist. from terminal	Unused pulpwood	Delimbed thinning wood	Whole-tree thinning wood	Stumps, all species	Spruce stumps	Logging residues, all species	Spruce logging residues
ALAVUS	25 km	42 605	3 196	11 734	3 151	951	792	290
	50 km	247 157	25 605	77 209	31 968	12 268	21 550	13 904
	75 km	465 343	70 948	192 798	86 901	35 913	76 576	50 203
	100 km	834 442	158 042	408 076	195 108	83 524	188 070	125 427
EVIJÄRVI	25 km	22 608	9 542	18 922	650	163	0	0
	50 km	90 727	59 489	110 935	1 570	385	87	27
	75 km	317 119	112 588	215 389	7 433	1 968	2 173	879
	100 km	537 264	188 363	357 152	37 933	11 807	28 434	15 847
KEURUU	25 km	36 960	11 874	30 204	20 203	10 308	27 081	18 971
	50 km	133 317	36 906	109 811	96 493	48 767	130 228	93 312
	75 km	322 534	67 279	210 457	202 291	102 394	274 893	199 496
	100 km	569 944	117 646	357 181	342 417	170 686	461 808	330 205
KINNULA	25 km	54 076	20 287	32 724	12 429	3 569	9 902	5 513
	50 km	130 574	87 743	140 872	46 644	15 647	51 229	30 203
	75 km	162 784	199 793	325 096	93 006	33 689	120 666	71 204
	100 km	214 709	358 713	592 969	163 895	67 778	238 252	145 705
SIEVI	25 km	44 913	17 209	30 014	0	0	7 934	3 877
	50 km	137 862	88 499	153 941	500	142	56 138	31 303
	75 km	206 853	190 079	324 898	3 958	1 330	108 261	60 587
	100 km	378 518	343 708	573 059	29 392	9 867	162 974	90 347

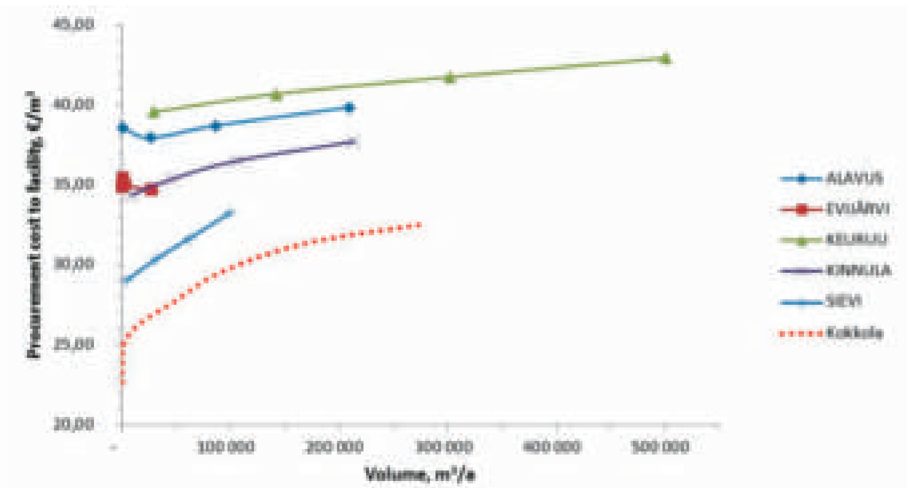


Figure 24. Procurement costs of transporting stumps and logging residues to the facility using terminals at the considered locations. The chipped (logging residues) and crushed (stumps) material is assumed to be transported from the terminal by a chip truck. Costs of direct transport to the facility in Kokkola are shown for reference.

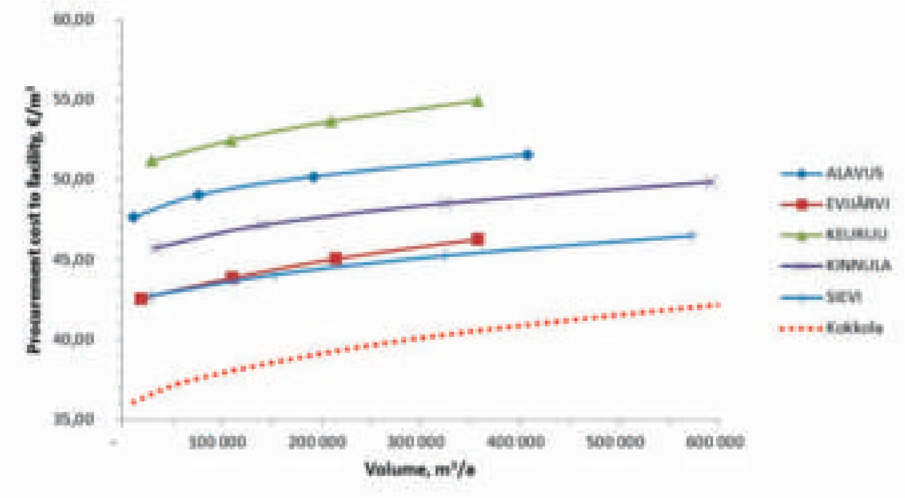


Figure 25. Procurement costs of transporting whole-tree thinning wood to the facility using terminals at the considered locations. The comminuted material is assumed to be transported from the terminal to the facility by a chip truck. Costs of direct transport to the facility in Kokkola are shown for reference.

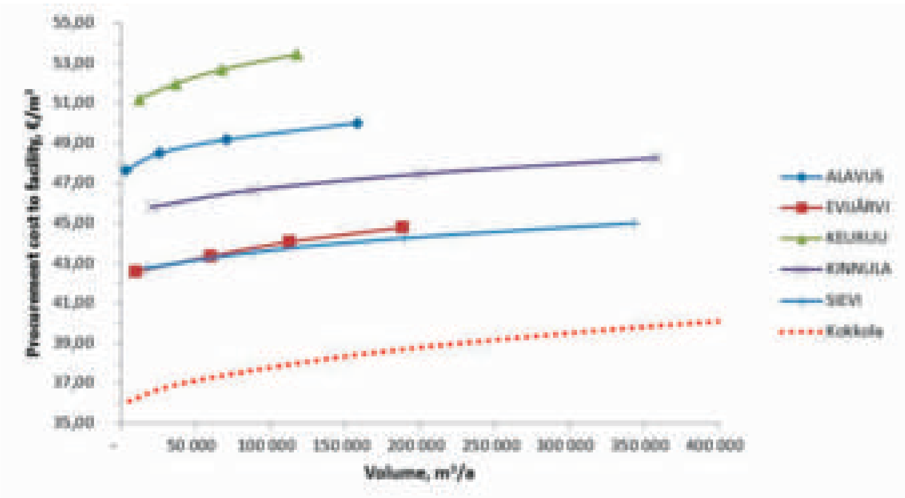


Figure 26. Procurement costs of transporting delimbed thinning wood to the facility using terminals at the considered locations. The comminuted material is assumed to be transported from the terminal to the facility by a chip truck. Costs of direct transport to the facility in Kokkola are shown for reference.

Effective raw material supply chain from the forest to biorefineries

Characteristics of Swedish forest biomass terminals

Objectives

The aim of this study was to characterize existing Swedish forest biomass terminals in terms of their location, size, assortment structure, infrastructure and basic management routines. Only terminals that handled biomass for energy production (either exclusively or in part) were examined (Kons et al. 2014).

Materials and methods

Data were gathered using a quantitative questionnaire that was sent out by the SDC. In total, 18 companies and forest owners' associations were asked to provide information on their forest terminals for 2010, and 16 responded. Two forest companies did not respond. Only terminals that had been in use for at least two years before the survey was conducted and which were expected to remain active throughout the year of the survey were included in the study. The total number of terminals surveyed was 270. Calculations were only performed using data for terminals whose areas had been estimated. In addition, certain analyses were only performed using data on those terminals for which specific information (on variables such as the volume of stored material, number of customers, or the equipment present at the site) was available. Therefore, the number of terminals considered when performing specific calculations ranged from 112 to 246 (Table 9). Terminals were divided into four classes based on their area: < 2 ha, 2 ≤ 5ha, 5 ≤ 10ha and ≥ 10ha.

Table 9. Number of terminals in Sweden considered when calculating various terminal properties that depend on the area of the terminal.

Terminal Properties	No. of terminals
Total area	246
Mass of yearly inventory turnover	208
Number of assortments	207
Measuring, loading and other equipment	203
Number of customers	203
Annual inventory frequency	180
Inventory method	170
Inventory maker	168
Terminal age from the year of establishment	149
Terminal geographical locations	112

Geographical information was available for 112 terminals. Unfortunately, the geographical data could only be related to the surface areas of the terminals and not to other variables. The locations of nearby heating and CHP plants were collected from the Swedish District Heating Association. Information on the locations of pulp mills and sawmills was gathered from the Swedish Forest Industries Federation. Road and rail road data were obtained from the Swedish Land Survey Authority. The shortest distances between terminals and nearby CHP plants, pulp mills, and sawmills were calculated based on the road network using ArcGIS network analyst. However, distances between a terminal and the nearest neighboring terminal or the nearest point on a railroad were calculated as the crow flies due to difficulties encountered when using ArcGIS network analyst.

Results & Conclusions

The yearly inventory turnover for 208 forest biomass terminals was 1.8 million OD t (Table 10). The largest terminal had an area of 20 ha and the smallest only 0.1 ha. 74 % of all terminals considered in the study had areas of less than 2 ha and only 8 % had areas exceeding 5 ha. There were similarly high level of variations between terminals with respect to the extent of asphalted/paved area, the number of assortments handled, and the number of customers. Comminution was performed on-site at 95 % of the studied terminals.

Table 10. Total annual mass handled (OD t) by terminals of indicated size classes in Sweden.

	Size Class, ha			
	< 2	**2 ≤ 5**	**5 ≤ 10**	**≥ 10**
	OD t	**OD t**	**OD t**	**OD t**
Number of Terminals	154	37	9	7
Energy Wood	605 267	268 041	156 800	96 000
Logging Residue Chips	139 156	42 677	7 123	30 000
Logging Residues	61 418	22 855	31 585	15 930
Bark	65 769	29 556	6 300	5 000
Saw Dust	30 800	3 696	10 400	12 400
Stem Wood Chips	19 076	10 200	23 600	
Tree Part Chips	17 660	3 471	176	1 371
Stumps	14 098	8 248	17 980	3 720
Tree Parts	14 065	16 494	1 445	264
Dry Sawmill Chips	5 000	-	-	-
Shavings	1 970	-	10 000	1 700
Cut-Offs	1 852	-	-	1 700
Recycled Wood	1 395	2 470	-	-
Peat	80	-	-	-
SUM	*977 605*	*407 709*	*265 410*	*168 085*

The average proportion of paved area at terminals of different sizes ranged from 28 % for those with areas of 5 ≤ 10 ha to 60 % for those covering 2 ≤ 5 ha. However, while the average proportion of paved area of terminals covering < 2 ha was 47 %, this size class also had the greatest proportion of terminals with no paving at all (36 %). In total, 13 % of 2 ≤ 5 ha terminals, 22 % of 5 ≤ 10 ha terminals, and 25 % of ≥ 10 ha terminals had no paved surfaces. In total, 14 different biomass assortments were handled at the 208 forest terminals, with a total volume of 1.8 million OD t. Energy wood accounted for 1.1 million OD t, or 63 % of the total biomass volume (Table 11). Aside from energy wood, the three most important assortments by mass were logging residue chips, loose logging residues and bark. All 14 assortments were handled by at least one terminal covering < 2 ha whereas terminals in other size classes only handled 10 different assortments. The average number of assortments handled at a given terminal tended to increase with the terminal's size class for terminals in the 2 ≤ 5 ha and 5 ≤ 10 ha size classes. However, the opposite trend was observed for terminals covering ≥10 ha. The same trend was also seen with respect to the average number of deliveries per customer. Terminals of < 2 ha had the fewest customers per terminal while all other terminal classes had 4 - 5 customers per terminal on average.

Table 11. Terminal characteristics in Sweden (area, mass, number of assortments handled, and number of customers) for each terminal size class.

	Size Class, ha									
	< 2		2 ≤ 5		5 ≤ 10		≥ 10		All Terminals	
	Value	sd	Value	sd	Value	sd	Value	sd	Value	sd
Area (ha)	0.9	0.48	3.0	0.81	6.3	1.31	14.3	4.02	1.9	2.74
Paved area (% of total area)	47	43	60	38	28	39	38	39	48	42
OD t/terminal	6307	10029	10454	8335	29490	40521	24012	21593	8661	14289
OD t/assortment	3039	5384	4155	2814	5596	4595	5949	3533	3446	4997
No. of assortments	2.4	1.14	2.7	1.11	4.0	2.26	3.4	1.84	2.5	1.3
No. of customers	3.0	2.1	4.5	4.0	4.1	2.6	5.0	2.1	3.4	2.7
Delivered mass per terminal and customer (OD t/year)	3004	8374	3333	3644	5223	4308	4020	2349	3198	7444

In total 27 % of the terminals were located within 30 km of the coast. Most of these terminals (21 %) covered less than 2 ha. There were no terminals larger than 10 ha closer than 30 km to the coast. The closest forest industry sites to the terminals were sawmills: on average, each terminal was 18 km away from the nearest sawmill by road (Table 12). The average distance between a terminal and the nearest railroad was 5 km as the crow flies, with larger (>5 ha) terminals being situated closer to railroads than smaller ones. The forest industry sites that were furthest from the terminals were pulp mills; the distance to the nearest pulp mill increased with terminal size.

Table 12. Distances from terminals in Sweden to the nearest forest industry sites and railroads.

	Terminal Size Class									
Distance to nearest:	< 2 ha		2 ≤ 5 ha		5 ≤ 10 ha		≥ 10 ha		All Terminals	
	km	sd	km	sd	km	sd	km	sd	km	sd
CHP with ≥ 100 GWh Annual output	43	31	43	30	56	42	42	32	44	32
Pulp mill	63	39	63	60	85	64	144	76	66	48
Sawmill	20	18	16	13	12	10	5	5	18	17
Rail road (straight line)	5	8	4	7	0	0	1	1	5	8
Other terminal (straight line)	21	14	22	20	38	14	7	7	22	16

The data presented herein provide a good overview of the state of forest biomass terminals in Sweden. Understanding the current properties of terminals in different size classes will facilitate the development of new terminal designs and machine systems that could improve operational capacities and economic performance while enabling stronger integration into the broader supply chain that provides forest biomass for CHPs and biorefineries.

Review of techniques and principles for forest biomass comminution and sorting

Objectives

This study had two main objectives. The first was to compile a list of the mechanical methods and principles that have been reported in the literature for comminuting woody biomass, sorting the main woody biomass fractions for different uses, and removing impurities such as minerals that may adhere to stumps (Eriksson et al. 2013). The second was to compare data from literature and manufacturers on machine performance data (such as work efficiency, productivity and fuel quality) for various forest biomass supply systems of solid fuels in order to identify aspects warranting further research. The review focused primarily on processes that were specifically designed for use in the field, at the roadside or at terminals, i.e. outside the gates of the forest industry sites.

Materials and methods

Study 1

The literature was searched for information on the comminution and sorting of woody biomass, using the ETDE, Web of Knowledge, Scopus and Google Scholar databases. Because the emphasis was on methods that are used outside the major wood-consuming industries (sawmills and pulp mills), an emphasis was placed on methods that were considered to be relevant to the use and sorting of assortments such as trees from early thinnings and logging residues. Methods involving sawing, abrading and finer comminution were therefore excluded in favor of those that produce chunked, chipped or hogged woody biomass. Comminution methods resulting in particle with approximate sizes below 100 mm were considered. Sorting methods that could potentially be used to separate the major components of the harvested trees were identified and selected for further classification according to their basic operating principles.

Study 2

The literature was searched for information on conventional chipping, chunking, crushing, grinding and shredding methods. Data on power, energy and torque requirements for these methods were compared with their productivities. In order to explain detected differences, factors including the location of operations (roadside, terrain, industrial site, geographical region), and raw material (tree species, type of material, e.g. stem wood, logging residues and stumps), on the resulting particle sizes and type of power source were used.

Results & Conclusions

Study 1

Three classes of machines are described in numerous literature reports: I) chippers, shredders, and grinders, which comminute the feedstock rather indiscriminately; II) drums for debarking and delimbing, which selectively tear off limbs and bark; and III) machines that sort comminuted material based on physical differences between the biocomponents (e.g. form, size, density, aerodynamic properties, or spectral characteristics). Depending on the particle size of the products and local conventions, machines belonging to Class I may be called hogs, shredders, grinders, crushers, chippers, chunkers, or flakers. Comminution techniques that rely on Class II machines can be said to involve some degree of sorting.

The efficiency and product quality of any comminution process is limited by its mechanical aspects (e.g. the precise combination of cutting, shearing, and impact applied, and also the cutting speed and direction relative to the fiber and particle size). Moreover, there are additional practical limitations to the efficiency that can be achieved under real-world conditions, so the theoretical maximum efficiency for any given process cannot generally be achieved. To better understand and classify these limitations, Gasslander et al. (1979) defined four levels at which efficiency can be affected: i) the physical level (which corresponds to the theoretical requirements of the process, e.g. in terms of energy input), ii)the machine level (which includes inefficiencies in the machines used for the primary process, but not the costs of operating auxiliary equipment), iii)the cycle level (which includes inefficiencies introduced by e.g. material-handling processes), and iv)the operational level (which includes inefficiencies due to idling and waiting).

Cutting studies have shown that the force required to cut wood decreases as its MC and/or temperature increases, but the cutting speed has relatively little effect on the force required (e.g. Franz 1958; Kivimaa 1949; McKenzie 1961). Several ways of estimating the energy required for comminution at the physical level have been suggested. These include methods based on the total surface area of the product or other variables related to the dimensions of the product particles (e.g. Nomura & Tanaka 2011).

Sorting is usually based on differences in the following physical properties (or some combination thereof): particle size; density; particle shape (aerodynamic drag and lift); optical or infrared reflectance or transmittance, or x-ray fluorescence. In general, sorting efficiencies are determined by complex interactions between the properties of the particles and the equipment used. For instance, the sorting efficiency of sieves is influenced by the particle size distribution, particle density distribution, inter-particle friction, pressure on the smaller particles from above, the amount and type of agitation, and the number, shapes, and sizes of the openings. Additional factors that have to be considered include surface moisture, electrostatic charges, the material's tendency to agglomerate, the angle of repose or bridging tendency, hygroscopicity, and the material's hardness and abrasiveness (Allen 1962). The flow arrangement also affects efficiency and depends on the particle size distribution. Particles that are much smaller than the holes fall through more rapidly than particles whose size is comparable to the hole diameter.

There are considerable differences between different comminution methods in terms of productivity and energy use. At the physical level, cutting along rather than across the fiber direction generally requires less force, and cleavage close to the surface requires less force because there is less pressure on the knife from the surrounding wood. Energy consumption can also be reduced by exploiting movement in the direction of the knife's edge, e.g. in augers, involuted chunkers, and disk chippers with a backsweep. For instance, compared to a hammer mill, the energy required by a wood planer is lower by a factor of 2.3 for the same increase in specific surface area when working with poplar and aspen (Holzapple et al. 1989). Some machines that employ perpendicular knives, such as the chipper used by Logan et al. (1960), also reportedly produce particles of more uniform sizes and shape, and may be useful if they are economically viable.

Impact-based machines such as hammer mills are mostly used for coarse comminution and are inherently less energy-efficient than machines that use sharp edges (Pottie & Guimier 1985). However, their mechanical robustness is advantageous when comminuting mineral-rich materials such as stumps. It is important to avoid comminuting the material more finely than is required. By using coarse comminution (chunking) rather than fine comminution (chipping), productivity can be increased and some energy saved; this is especially important at landings. For some comminution equipment, the particle size distribution can be adjusted by altering parameters such as speed of rotation, feeding rate, and sieve hole size, with production of particles of smaller average sizes requiring more time and energy. However, productivity and energy use are more likely to be determined by machine-level factors such as the speed of rotation, feeding rate, available power, and conversion efficiency. Using more efficient power sources and reducing the power required during interruptions may be at least as important as improving the performance of the physical comminution process. Comparisons of productivity and energy use for different types of comminution equipment should be interpreted with caution, because their conclusions may primarily reflect differences in downtime (Spinelli & Visser 2009). At the operational level, increasing knife sharpness increases productivity but requires more downtime, and there is an optimum time interval between knife replacements.

There is a substantial body of public data on the drums and cradles used for delimbing and debarking. However, their efficiencies are still difficult to compare, as they seem to be strongly influenced by the handled tree species and yield products with different qualities. Rolls and flails can be used to remove foliage and twigs, and can be deployed in the field in various ways (e.g. by fitting rolls on a forwarder grapple). Flail chain wear may be less of a problem in this context than in other applications. Mechanical devices such as swinging hammers and compression rolls can be used to decrease the adhesion between bark and wood in chips and to break up clusters of twigs, facilitating the separation of bark and needles.

Several sorting methods are available. Their efficiencies are limited by the magnitude of the differences between the biocomponents in terms of the parameters used for discrimination (e.g. size, density, or drag coefficient). These differences are often rather small and species-dependent, making efficient sorting difficult for woody biomass of mixed species. However, the differences exploited to remove contaminants are often bigger, making discrimination less problematic in this case. If necessary, it should be possible to overcome these problems using instruments that detect contaminants using other physical variables, such as optical sensors, which have not yet been fully exploited. Many publications have reported sorting efficiencies for various cases. However, because they are not generally provided together with data on productivity and costs, it is difficult to determine whether a particular method is useful.

Theoretically, chipping is preferable to grinding, but for materials such as logging residues and stumps, grinding and shredding may have practical advantages. In the case of logging residues, small branches may be randomly oriented, and they may not be cut at all if they happen to pass the drum in a drum chipper oriented parallel to the knives. Consequently, the long twigs still present in the processed material could cause practical problems in feeding systems at energy plants. Several methods have been suggested to overcome these difficulties (e.g. Novak 1986, Firus & Belter 1998), and it seems worthwhile to explore new solutions for this problem. Knives are not suitable for contaminated material, such as stumps. Low-speed shredders may be better suited to stumps, as stones may not be crushed and pressed into the wood to the same extent as with high-speed grinders.

Study 2

From the literature, 25 studies presenting relevant machine performance data were identified. A total of 117 combinations of equipment and woody raw material have been studied, with either the productivity (117 cases) or the energy efficiency (95 cases) reported, or both. The highest proportion of studies took place in the USA (41 of the cases), followed by Finland (31), Italy (19), Sweden (17), Japan (5), Spain (3) and Brazil (1). Of these cases, 70 concerned chippers, 24 horizontal grinders, 20 vertical grinders and three shredders. The equipment was frequently American (46%), Finnish (24%), Italian (15%) or Swedish (11%), with some German equipment in four cases, and Brazilian and Japanese in one case each. The materials processed were residues (RES) in 64 cases, small trees (SMALL) in seven cases, stem wood (SW) in 23 cases and stumps (STUMP) in five cases (Fig. 27). Grinders were mainly used for RES and STUMP, and shredders only for STUMP. Chippers were mostly used for "clean-wood" material (SW, SMALL), while the grinders and shredders were mostly used for potentially contaminated wood (RES, STUMP). The power of the examined chippers varied between 51.5 and 1 030 kW, the power of the grinders varied between 120 and 5800 kW, and the power of the shredders varied between 257 and 315 kW. From the websites of the manufacturers mentioned in the equipment reviews, 691 models were identified, with the following geographical distribution: the USA (26%), Germany (25%), Finland (12%), Italy (11%), Austria (11%), Sweden (6%) and Denmark (5 %). There have been few studies on German and Austrian chippers, compared to the number of manufacturers. Many German chippers are probably used in the sawmill industry, and many Austrian chippers are small-scale. No statistics are available on locations of customers of the equipment produced by the suppliers. However, the equipment surveys and models used in the retrieved studies clearly indicate that some suppliers are global, like the American companies CBI, Peterson and Morbark. Other manufacturers seem to focus on a more regional market, such as Sasmo, Finland, who supply cone-screw chippers that are not mentioned (for instance) in the Italian case studies.

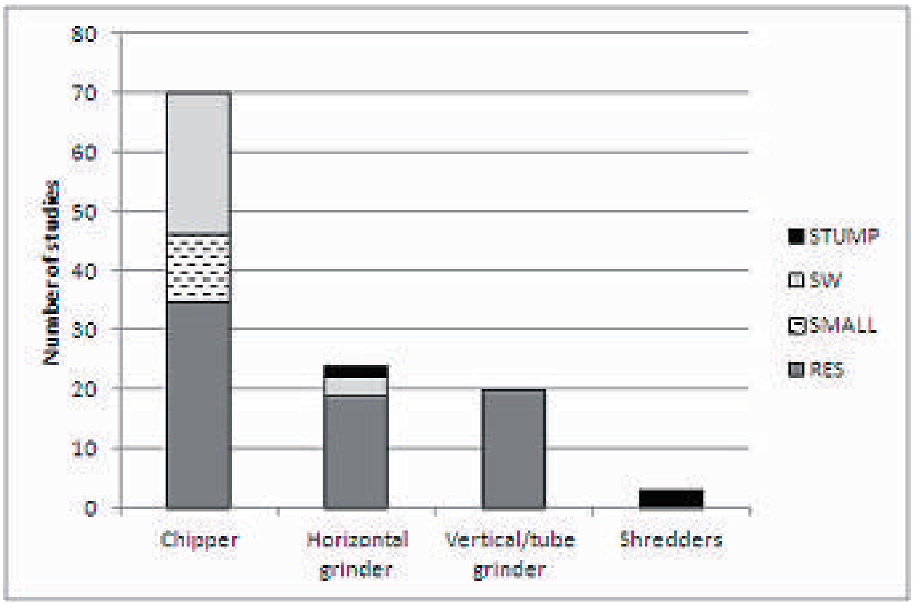


Figure 27. Total numbers of studies found providing data on commination of the indicated assortments (RES=logging residues, SMALL= small trees, SW= stem-wood, STUMP=stump-wood) by the studied categories of machines.

The nominal power of the equipment used for the reported studies has been compared to the power of the models available on the market, and there are clearly gaps, e.g. for chippers between 100 and 200 kW, for horizontal grinders below 400 kW and for vertical grinders below 200 kW and above 500 kW.

The reported productivities of the chippers, horizontal grinders, vertical grinders and shredders varied ranged from 1.5 to 137, 0.8 to 197, 5.6 to 64, and 8 to 49 m^3s/PMH_0, respectively. Small-scale grinders are generally less efficient than small-scale chippers, while for large-scale machines, the difference is considerably smaller, or non-existent. In chipping operations, the productivity increases by 0.114 m^3 for each kW increase in nominal power. For grinders with horizontal feeding, the productivity increases by 0.186 m^3 for each kW increase in nominal power. In one of the studies there was a considerable spread in productivity, as the hole size of the screen varied Arthur et al. (1982). The relationship between power and productivity is similar to that found by Spinelli and Hartsough (2001) in a time study on Italian chipper operations, but as their study included operational complications like waiting time, the results cannot be directly compared.

Much of the variation in reported productivities and findings in the surveyed studies may also be due to differences in the wood assortments used. In accordance with this hypothesis, Eliasson and Granlund (2010) found that a large horizontal grinder was respectively 29% and 51% less productive when crushing logging residues and stump wood than when crushing stem wood logs (with crushing time accounting for more than 95% of total time in all cases) and the machine power was not a limiting factor. Similarly, Eriksson (2008) found that productivities were 11% lower when crushing logging residues than when crushing stem wood logs using a similar grinder (but 32% higher if logging residues were bundled). One reason that the productivities measured in the studies are generally lower than the maximum productivities claimed by the manufacturers is that the feeding system is included in most studies. Limitations of the feeding systems clearly influenced the results, as shown by the differences in productivity between experiments where stem wood was used and where stumps, small trees and logging residues were used. On average, stems may be smaller than optimal in practice, which will reduce the maximum engine power required, but probably increase diesel consumption per m^3 processed as there will be more time when the diesel engine is running without full use of the chipping capacity. This conclusion is supported by findings presented by Spinelli and Hartsough (2001) that processing larger stems increases productivity (e.g. an increase in stem weight from 10 to 100 kg resulted in a ca. 2-3 fold increase in productivity, which also suggests that frequent feeding interruptions significantly reduce productivity). The feeding rate of the raw material may also contribute to the differences between claimed and observed productivities. Liss (1987) found that the productivity measured in practical tests was about two-thirds of the theoretical productivity (calculated from feed rate and maximum tree size), and suggested that in practice the feeding rate is lower than the set value, making the chips somewhat smaller. In the cited studies, efficient chipping time did not include time for setup, repositioning and similar interruptions. However, time when the crane feeding limited the chipping speed was included. Most time studies of chipping/grinding focus on the distribution among phases in the crane movement cycle, including the time when the crane operator is waiting for the chipper. Waiting times for the chipper/grinder when the crane loading limits the processing speed are seldom recorded.

Some, but not all, machines have some storage capacity for the raw material (such as a large feeding board or the tub of a vertically fed grinder), which can reduce this waiting time and increase the energy efficiency of the process. The influence of the feeding rate on energy efficiency suggests that the energy used when the machine is waiting is important, which is also confirmed by measurements (e.g. Spinelli & Hartsough 2001, Liss 1987). For any machine, the waiting time (due to feeding limitations) and the power of its engine during that time contribute to the energy consumed per m^3 of processed material. Thus, another strategy to increase the energy efficiency could be to reduce the maximum required power by providing some means for storing energy, such as a hybrid diesel-electric drive system, or a flywheel to store rotational energy to meet peak demands. Crane-loaded chippers are usually horizontally fed, or fed at some angle to the horizontal direction, while a considerable number of grinders and shredders are vertically fed (notably tub grinders). The distinction between horizontal and vertical feeding is mainly important for crane-loaded machines. When the chipping/grinding is part of an industrial production process, either type of feeding can probably be used efficiently. For terrain and roadside chipping/grinding, where space is limited, vertical feeding is advantageous because the tub provides a buffer without increasing the length and width of the machine, but lifting the material into the tub probably hampers the crane loading. Furthermore, vertically feeding high-speed rotors (such as tub grinders) raises safety risks, as even large chunks of material may be thrown out of the tub when hit by a hammer (Arthur 1982). A practical disadvantage is that the diameter of the tub is often too small for convenient feeding of logging residues (Asikainen & Pulkkinen 1998).

Clearly, particle size affects productivity and specific energy consumption. For chippers, changing the knife settings affects the productivity (Liss 1991). The screen size affects the specific energy consumption and capacity of grinders (Hoque et al. 2007) and the productivity of stump shredding (Tolosana 2013). Hoque et al. (2007) found that reducing the screen hole size by a factor of two doubled the power consumption and halved both the grinding rate and specific capacity. Similarly, (Tolosana 2013) found that using a screen caused a nearly 25% reduction in productivity when stump shredding with a Hammel machine. Finally, it should be noted that for large-scale combustion, some increase in particle size may be advantageous as too small particles cause operational difficulties.

Effects of wood properties and chipping length on the operational efficiency of a 30 kW electrically powered disc chipper

Objectives

The objectives of this study were to evaluate effects of properties (size and density) of pine, spruce and birch wood on the power and energy demands, and time consumption, of a 30 kW electric chipper when producing chips of two sizes, in order to create models that can be used when designing efficient hybrid systems based on similar chippers (Di Fulvio et al. 2014).

Materials and methods

Delimbed logs from pine, spruce and birch stems were sampled from a thinning site in the coastal area of Västerbotten, northern Sweden. The sampled stand had a density of 3200 trees/ha, an average tree diameter of 8.1 cm at DBH and an average height of 8.3 m. In total, about 30 m^3 of round-wood was harvested by thinning from below and transported to the experimental site (Biofuel Technology Centre in Umeå) a few days after cutting. The chipping trials were carried out during five days in October 2012. A total of 185 logs (63 pine, 61 spruce, 52 birch) were randomly sampled from the piles. Their lengths fell in the range 2.6 – 5.1 m, their diameters at butt-end (d_{butt}) ranged from 5.6 to 14.4 cm and their mass (fresh weight) ranged from 3.5 to 43.5 kg. The total mass was 4 189 kg. The logs were sorted by species and butt diameter (d_{butt}, Ø) into five classes: Ø < 9 cm, 9 ≤Ø<11 cm, 11 ≤ Ø <12 cm, 12 ≤ Ø <13 cm and 13 ≤ Ø ≤ 14 cm. Each combination of species and diameter class (15 treatment combinations) was repeated three times. Each treatment combination was carried out using two different disc chipper knife settings, with nominal lengths of 8 mm ("short") and 12 mm ("long").

The chipper used was an Edsbyhuggen 250H (Edsbyhuggen AB, Sweden, year of manufacture 2011) with a 30 kW electric motor (Busck T1C 200L-4) which had an efficiency of 91.2 – 93.5% at full load (Swedish Energy Agency 2010). The chipper was equipped with a steel disc 825 mm in diameter and 38 mm thick, with four knives, giving a total mass of 205 kg. The disc formed an angle of 45° with the feed direction and rotated at 540 rpm. The four knives were adjustable to produce chips from 5 to 12 mm in target length. The chips produced were blown 2.0 m into an expulsion tube by means of a fan and then collected in 1.5 m^3 plastic bags. The chipper's electricity supply was connected to a Fluke Power Log data logger during the experiment, giving instantaneous measurements of the electricity used by the engine, at a sampling frequency of 2 Hz (1 observation every 0.5 seconds). The chipping output was defined as the scaled mass of each log and its solid volume, which was calculated using the butt and top diameters with the length in the formula for the volume of a truncated cone. The absolute maximum power (kW) demand reached over the chipping time for each run represented the "maximum power demand". The "energy demand" (kWh/OD t; kWh/m^3) was obtained by integrating the total power demand over the chipping time for each run divided by the mass/volume of each log.

Results & Conclusions

The power required for chipping consisted of two parts: one proportional to the mass flow through the chipper (for a given chip size), and the other constant, regardless of chip production (including friction and powering of the hydraulic pump for the feed-rolls). The maximum power required for chipping (P max) was roughly proportional to the butt cross-sectional area of the stems, which explained most of the variability. It was almost independent of the chip length, which accounted for only slight variation (1 %), however significantly higher peak power was required for producing the longer spruce chips than the shorter spruce chips. When processing birch, the maximum power absorbed was also directly correlated to the density, which accounted for a minor portion of variability (2%). The higher mass flow through the chipper when processing thicker logs meant that the chipping energy per m^3 increased linearly with the reciprocal cross-sectional area; the relationship was statistically significant in all cases. Thus, the chipping energy per m^3 of processed material decreased with increasing stem diameter. When the energy required for running the chipper whilst not chipping was subtracted (E net), the dependence on stem diameter became less evident. The chip size also had a significant effect for all species, since producing longer chips reduced the energy requirements, due to the minor refinement. The chipping energy per m^3 of processed material was about 20% less for a nominal chip size of 12 mm, compared to 8 mm. At the same time, an increase of OD density significantly increased the energy demand per m^3, while the density was inversely proportional to the energy per OD t, since density and output (OD t) are directly related. Wood density generally had weaker effects than either stem size or chipping length and was only significant in some of the cases.

The productivities (m^3/PMH_0) based on effective chipping work time (excluding all waiting times) were strongly correlated to the stem diameter. The productivities were roughly proportional to the cross-sectional area of the logs fed into the chipper, while the difference in feeding speed was minor (0.04 m/s) with a slight reduction in feeding rate seen for thicker logs. As the chip length was increased from 8 to 12 mm, the productivity increased, and the difference between the two sizes was 22% at a cross-sectional area of 80 cm^2.

In conclusion, the power requirements and productivity when chipping small logs from thinning operations were found to be significantly affected by chip length, butt area and density, as follows:

- The maximum power required for chipping was roughly proportional to the butt cross-sectional area of the stems, which explained most of the variability, but it was almost independent of the chip length.
- The energy needed per m^3 of processed material decreased by 4% for each centimeter increase in stem butt diameter. The chip size also had a significant effect, and the chipping energy per m^3 was about 20% less for a nominal chip size of 12 mm, compared to 8 mm, and increases in OD density increased the energy demand per m^3.
- The productivities were roughly proportional to the cross-sectional area of the logs fed into the chipper. As the chip length was increased from 8 to 12 mm the productivity increased, and the difference between the two sizes was 22% at a cross-sectional area of 80 cm^2.
- Energy demands per m^3 of processed material were slightly higher (3-4%) for chipping hardwood (birch) than softwood (pine and spruce).

Comparison of ground disturbance caused by the Ellettari stump drill and a stump rake harvesting head on frozen peatland

Objectives

The objectives of this study were: to compare the ground disturbance after stump harvesting with a stump drill and a conventional stump rake; to investigate changes in the ground disturbance over a winter period with ground frost, to estimate the yield and carbon emissions after stump harvesting with the two heads; and to investigate the productivity of the stump drill on peat land in winter conditions (Berg et al. 2014).

Materials and methods

The study was conducted on ditched peatland in Lappajärvi municipality in Southern Ostrobothnia, Finland. The tree species recorded at the site were Scots pine, Norway spruce and birch (*Betula pendula* and *Betula publescens*, for which data were pooled) in stem number proportions of 85:6:9. The average arithmetic and basal area weighed diameters at stump height (DSH) were 241 mm (sd 57) and 266 mm, respectively. Before the harvest 448 stumps were measured on five plots, each of which covered 16×75 m (1200 m^2). The ground disturbance caused by the conventional rake head and an Ellettari stump drill (di Ellettari Luca & C., Italy) with a 45 cm inner diameter (Fig. 28) was compared. The stump drill was mounted on a New Holland Kobelco E200SR excavator and the stump rake was mounted on an another excavator (brand not known). Most of the snow had thawed when the harvest was conducted, but ground frost was still present.

Figure 28. The Ellettari stump drill.

The ground disturbance after the stump harvests was measured by placing a net with a 0.024 m^2 mesh size (which set the precision of the measurements) over the disturbed area and counting all the squares in which more than 50% of the ground was disturbed (Fig. 29). The depths of the holes created by the stump drill and stump rake (up to the estimated edge of the soil before harvest) were measured with a folding ruler to the nearest cm. Measurements were taken on two occasions: six months and 18 months after the harvests (in the harvest year and following year, respectively).

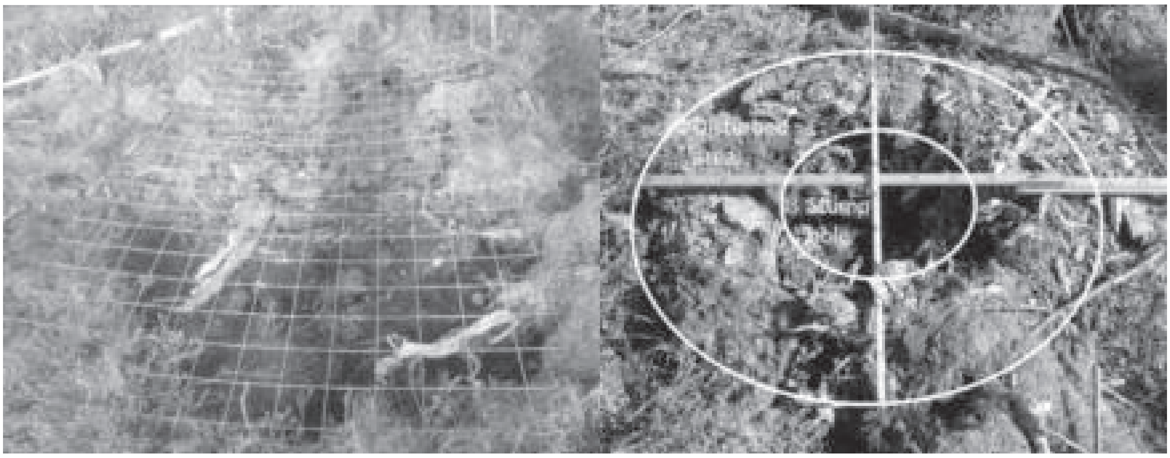


Figure 29. To the left a net for estimating the ground disturbance placed over a hole from the stump rake. To the right folding roles used to measure the a hole and disturbed area after the stump drill.

Results and Conclusions

A shown in Table 13, substantial differences in the ground disturbance (but not hole depths) caused by the stump drill and stump rake were found on both measurement occasions. On average the stump rake disturbed ca. 10-fold and 8-fold larger areas of ground than the stump drill in the harvest year and following year, respectively. In addition, the area disturbed and depth of the holes created by the stump rake significantly differed between the two occasions. The size and depth of the holes created by the stump drill also differed between the two occasions, but not the area of ground it had disturbed. This difference is probably due to effects of ground frost and frost heaving. The holes created by the machines were less deep, and both the area of disturbed ground and the holes created by the stump rake were smaller in the year after harvest.

Table 13. Area of disturbed ground and depth of the holes created by the stump rake and stump drill, and sizes of holes created by the stump drill, in the harvest year (year 1) and the following year (year 2). Standard deviations are shown in parenthesis.

Harvesting head	Ground disturbance (m^2)	Hole size (m^2)	Hole depth (cm)
Stump rake, year 1	9.04 (4.01)	-	36.4 (7.57)
Stump drill, year 1	0.90 (0.17)	0.31 (0.03)	39.3 (7.09)
Stump rake, year 2	7.60 (2.62)	-	29.3 (5.54)
Stump drill, year 2	0.93 (0.20)	0.27 (0.04)	31.9 (6.0)

In conclusion, the ground disturbance was significantly smaller when harvesting stumps on peat land with the stump drill than with the stump rake. Therefore, only stump drills should probably be used on peatlands to avoid excessive reduction in bearing capacity. Reductions in ground disturbance should also reduce increases in competing vegetation as well as risks of both erosion (and hence possible releases of nutrients and heavy metals) and soil compaction. The ground disturbance could be reduced by up to 90% if the harvested volume is reduced by 47-68%, depending on the tree species.

Stump crushing productivity at terminal and analysis of fuel qualities

Objectives

The objective of this study was to evaluate the productivity of a terminal crushing system and the fuel quality when comminuting stump wood.

Materials and Methods

Three stump assortments were crushed at a terminal owned by Skellefteå Kraft AB at Hedensbyn in Skellefteå municipality (Fig. 30). Assortment 1 was extracted from stands growing on mineral soil in autumn 2009 and spring 2010 then forwarded to roadside in 2012. Assortment 2 was extracted from stands growing on mineral soil in 2010 and forwarded to roadside in 2011. Assortment 3 was extracted from stands growing on peatland (date not known) and forwarded to roadside in 2011. All three stump assortments were crushed in early February 2013, using a CBI Magnum Force Series 8400 Hz, 1000 HP Hog, fed with a wheel-based crane loader (CAT M322C) equipped with a timber log grapple. The system's productivity when handling each assortment was recorded in a frequency time study, with 10 sec intervals, covering about 90 min of productive working time (PM) per assortment. The mass of each assortment was scaled after crushing. Samples of crushed material were taken for determinations of MC and ash content, heating values and the crushed particles' size distribution, following relevant Swedish standards: for sieving SS-EN 14918, heating value SS-EN 14918, moisture content SIS-CEN/TS 14774-3:2004 and ash content SS-EN 14775. Additionally the fuel consumption of the crusher per assortment was measured. A heating value for the diesel fuel of 35.3 MJ/L was assumed.

Figure 30. Stump crushing at a terminal.

Results & Conclusions

There were large variations in crushing productivity (33-68%) between assortments (Table 14), partly because efficiently loading relatively small stump parts with the timber grapple was problematic. This problem could be eliminated by using a front end loader with a bucket for loading stumps mounted on the crusher's loading deck. The measured heating values of stumps varied between 18.79 – 19.47 MJ/OD kg, while the heating values as delivered ranged from 3.96 MWh/t (fresh) for assortment 3 to 4.96 MWh/t (fresh) for assortment 2. There was also high variation in ash content, ranging from 2.3% for assortment 2 to 6.1% for assortment 3 (Table 14).

Table 14. Productivity of the crusher and wood fuel properties of the indicated assortments.

	Assortment 1	Assortment 2	Assortment 3
Total mass (OD t)	48.9	62.4	28.6
MC (%)	41	33	68
Ash content (%)	3.7	2.3	6.1
Effective heating value (MJ/OD kg)	18.79	19.06	19.47
Energy content, as delivered (MWh/OD t)	4.75	4.96	3.96
Crusher's productivity (OD t/PMH_0)	32.3	41.1	18.9
Fuel consumption (l/OD t)	3.6	2.9	4.2
Energy return on energy invested	135	173	97

The distribution of the crusher's work time elements was similar for all three assortments (Fig. 31). For 82% of the total work time the work element *"grip/crushing"* was performed simultaneously with other work elements (mostly crane-related) when processing assortments 1 and 2. The corresponding value for assortment 3 was 66%, and the average value for the whole study was 77%. Most of the crusher's work time was spent on the work element *"grip"*, which was mostly affected by the size of the handled stump parts and limitations imposed by the design of the grapple used for loading.

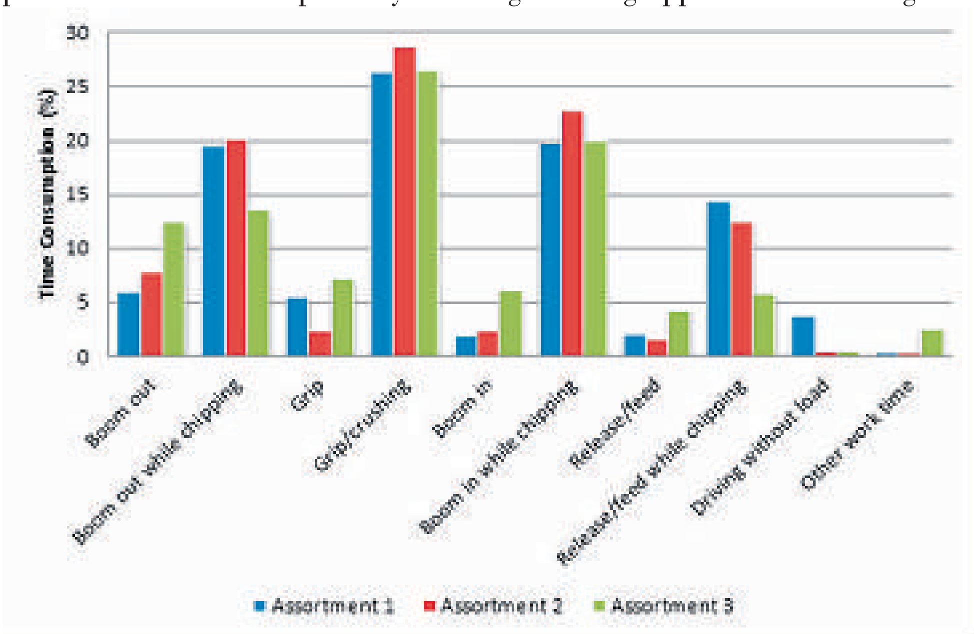


Figure 31. Distribution of stump crushing work time elements.

The size distributions of particles produced from assortments 1 and 2 were very similar, while higher proportions of fine (< 16 mm) particles, 56%, were produced from assortment 3 (Fig. 32), probably because assortment 3 consisted of partly decomposed stumps from peatland. On average, sizes of 43.6% of the particles produced from all three assortments ranged from 16 to 31.5 mm.

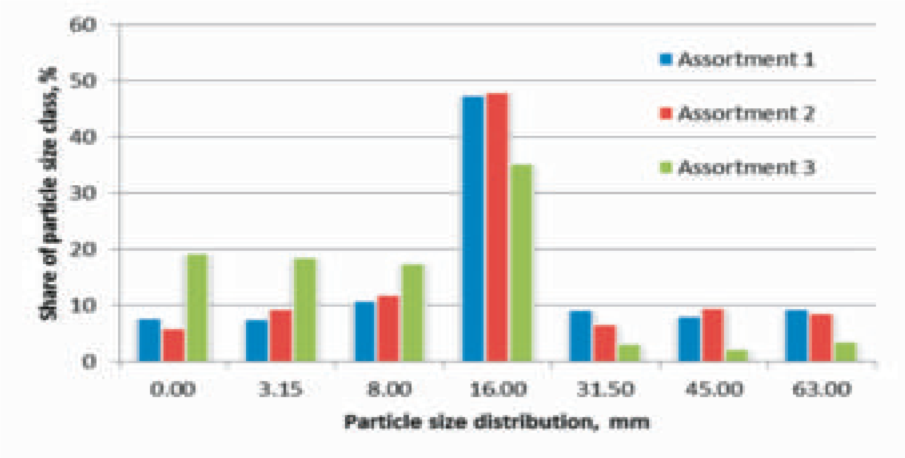


Figure 32. Particle size distributions of the crushed stump assortments.

Although assortment 3 had the highest energy content, its high MC and ash content dramatically lowered its fuel quality for combustion, indicating that (in some cases at least) material should be pre-dried and sieved to reduce the MC, amount of fine particles and contamination in the crushed material.

Evaluation of a novel prototype harvester head in early fuel wood thinnings

Objectives

The objectives of this investigation were to measure and compare the stand-to-roadside productivity and operating costs of two harvesting systems for fuel wood production in dense early thinnings. System 1 consisted of a harvester equipped with the prototype MAMA head featuring a feed-roller system for compression-processing and a standard forwarder. System 2 was used as a reference and consisted of a harvester equipped with **a** commercial C16 head together with a forwarder fitted with a grapple-saw for bucking. Because the MAMA head is a prototype, an additional objective was to identify factors that significantly influence the effectiveness of systems using this head (Bergström & Di Fulvio 2014).

Materials and methods

The study area was forested with Scots pine, Norway spruce and birch. Twelve study units were marked out; half were randomly designated for harvesting with System 1 (six units) and the remainder were assigned to System 2 (six units). In order to obtain statistically significant data for each head in isolation, an additional four units were harvested with System 2 (10 units in total) and one more unit was harvested with System 2 (seven units in total).

The harvester used was an Ecolog 560 D (Ecolog AB, Sweden) with a mass of 18.6 t, equipped with an 11 m Ecolog 250 crane attached to the cabin capable of rotating through 280 degrees. The same base machine was used for tests with both heads (the prototype MAMA head and the commercial C16 unit shown in Fig. 33, both manufactured by Bracke Forest AB, Sweden) and the same harvester operator performed all of the harvesting operations in the study. The MAMA head had a mass of 950 kg and was equipped with a circular saw-disc with a saw-chain for cutting with a maximum cutting capacity of 300 mm. It also had three feed-rollers (a cylindrical roller on the head-plate and two conical rollers at staggered heights on either side of the head) and a pair of accumulating arms on the top of the head. The C16 head had a mass of 700 kg with a maximum cutting capacity of 270 mm and was equipped with four-jawed cutting arms and four-jawed accumulating arms.

Figure 33. Left: the C16 head. Center and right: the MAMA prototype head. Both heads were developed by Bracke Forest AB, Sweden (www.brackeforest.com), and cut trees using a circular disc with a 3/4" saw-chain.

The thinning was performed from below and the operator selected which trees to fell, aiming to leave 1200-1500 future crop trees/ha. During the thinning work with the MAMA head, the trees that were felled and accumulated in each crane cycle were pulled over the strip-road and then processed and cross-cut into sections of ca. 5 m. The branches that were partially cut off during compression-processing fell down on the strip-road area, while the cut-off/scraped-off tree-parts fell down in piles into the stand perpendicular to the strip-road. The forwarder used was a Ponsse Buffalo (Ponsse Plc, Finland) with a mass of 20 t. Biomass was loaded and forwarded on a per study-unit basis and each load was scaled with a crane scale (Indexator AB) during unloading. The biomass was unloaded in two separate piles, one for compression-processed tree-parts (System 1) and another for whole tree-parts (System 2). The machines' work times, including delays of less than 15 minutes, were recorded using an Allegro Field PC® running SDI software (Haglöf Sweden AB). Work times in productive machine hours (PMH_0) were determined by excluding all delays. The harvester was studied for 19.0 hours, including 12.3 PMH_0 of operation with the MAMA head and 6.3 PMH_0 with the C16 head. Forwarding work was studied for 10.6 hours, consisting of 6.0 PMH_0 for hauling compression-processed whole tree-parts (System 1) and 4.2 PMH_0 for hauling unprocessed whole tree-parts.

Results & Conclusions

There were no significant differences between Systems 1 and 2 with respect to the properties of the harvested trees or other measured properties of the stands. The strip roads had similar widths and spacing distances in all cases, and the level of tree damage after forwarding was low for both systems. The MAMA head used in System 1 caused a slightly higher degree of damage to the remaining trees than the C16 head of System 2. The biomass removal per tree was 14% lower for System 1 but this difference was not significant. The mean harvested surfaces and amount of harvested biomass for Systems 1 and 2 were 1.36 ha and 130 m^3, and 0.72 ha and 74 m^3, respectively. Compression processing reduced the OD mass of the harvested material by 10.4-22.8%. The effects of compression-processing were substantial, particularly for larger trees, but did not differ appreciably between species.

On average, 3.2 (sd 0.6) trees per crane cycle were handled with the MAMA head, while 2.3 (sd 0.8) trees/cycle were handled with the C16 head. This difference was significant ($p=0.024$). There was no significant difference in total time consumption between the MAMA and C16 heads (Table 15). The number of crane cycles per PMH_{15} was 82 (sd 6) for the MAMA head and 104 (sd 14) for the C16 head, and this difference was significant ($p<0.001$). The numbers of harvested trees per PMH_{15} for the MAMA and C16 heads were 259 (sd 48) and 237 (sd 84), respectively. The time required for the boom to reach the first tree to be felled in each crane cycle (i.e. boom out) was significantly shorter for the MAMA head because when using the C16 head the operator must select trees carefully to enable the bunching of whole trees from the remaining stand.

Table 15. Mean harvester work efficiency values per work element. System 1 comprised a harvester fitted with the MAMA head and a standard forwarder; System 2 comprised a harvester fitted with the C16 head and a forwarder equipped with a grapple-saw. Standard deviations are quoted in parentheses

	Treatment				
	System 1 (n=10)		**System 2 (n=7)**		
Work element	**(s/tree)**	**(%)**	**(s/tree)**	**(%)**	***p-value***
Boom out	1.3 (0.3)	9	1.9 (0.8)	11	*0.031*
Felling	8.8 (2.0)	61	13.8 (6.0)	79	*0.025*
Boom in	0.5 (0.1)	3	0.7 (0.3)	4	*0.093*
Processing	3.0 (0.7)	21	0.1 (0.1)	0	*0.000*
Moving	0.8 (0.3)	6	0.9 (0.5)	5	*0.809*
Miscellaneous	0.1 (0.0)	0	0.1 (0.1)	1	*0.571*
Total Time	*14.4 (3.0)*	*100*	*17.4 (7.4)*	*100*	*0.270*

Overall, 26 loads were forwarded to roadside. There were 20 full loads, 12 of which contained compression-processed whole tree-parts (System 1) and eight contained unprocessed whole tree-parts (System 2). The average mass of the full loads was 10.3 t (sd 1.5; 4.6 OD t) for compression-processed whole tree-parts and 8.5 t (sd 1.0; 3.8 OD t) for unprocessed whole tree-parts. These values correspond to 74% and 61% of the two forwarders' respective load capacities. The average bulk volume of a full load was 28.1 m^3 for compression-processed whole tree-parts and 34.2 m^3 for unprocessed whole tree-parts, corresponding to 10.3 (sd 1.1) and 8.4 (sd 1.2) m^3s, respectively. The compression-processed biomass thus yielded a 22.6% higher solid volume and a 46% higher bulk density per load than unprocessed whole tree-parts. The studied systems had similar total costs for cutting and forwarding to roadside in an average stand (Table 16), with System 1 becoming more favorable as the size of the harvested trees and the extraction distance increased.

Table 16. Productivities and costs for the two systems in the "average" stand for an extraction distance of 300 m, and differences between systems at 200 m intervals, using the values for System 2 as references. System 1 comprised a harvester fitted with the MAMA head and a standard forwarder; System 2 comprised a harvester fitted with the C16 head and a forwarder equipped with a grapple-saw.

	300 m extraction distance		**Difference between systems (%)**		
Operational properties	**System 2**	**System 1**	**100 m**	**300 m**	**500 m**
Harvester productivity (m^3/PMH_{15})	9.5	8.2	-13	-13	-13
Forwarder productivity (m^3/PMH_{15})	13.2	19.2	+55	+46	+41
Harvester cost (USD/m^3)	17.0	20.6	+21	+21	+21
Forwarder cost (USD/m^3)	9.8	6.5	-37	-33	-31
Total system cost (USD/m^3)	*26.8*	*27.1*	*+3*	*+1*	*-1*

This study was the first field evaluation of the prototype MAMA head (Bracke Forest AB, Sweden); its performance was compared to that of the conventional C16 head. Although the MAMA head is a prototype that has yet to be optimized in terms of mass and functionality, its overall operating costs are already comparable to those for conventional systems if both cutting and forwarding are taken into account. With further development, it can be expected to reduce harvesting costs by up to 6% under the studied conditions. The concept should therefore be evaluated under other stand conditions and in the integrated harvesting of fuel wood and pulpwood (and possibly small timber). This head and the principle on which it operates have great potential for use under diverse stand conditions and in the production of various assortments, and could therefore significantly increase the efficiency and effectiveness of supply chains based on dense young thinnings in Fennoscandia.

Biomass compressing-processing using an innovative harvesting head

Objectives

The objective of this study was to investigate the compression effect of the MAMA prototype head (Fig. 33 & 34) on tree bunches in early thinnings.

Figure 34. The "MAMA" head used in field trials for processing a bunch of trees on a blanket to collect the scraped-off biomass.

Materials and methods

In field trials executed in November 2013 in a forest near Umeå, 20 bunches of pine trees were produced, divided into two size classes: one containing "small trees" (10 bunches, five trees per bunch, including trees with DBH from 4 to 8 cm) and another containing "big trees" (10 bunches, three trees per bunch, including trees with DBH from 8 to 13 cm). Half of the bunches in each class were felled and bucked (unprocessed bunches), and the other half were processed, i.e. fed into the head feed-rollers (processed bunches). A blanket was laid under the head to collect the branches, needles and small fractions falling while processing the bunches. The collected biomass was then scaled. For each of the bunches, the length, the circumference at butt, middle and top, and the weight were measured. Three bunches from each treatment were subsequently randomly selected and transported to the Biofuel Technology Center (BTC) in Umeå. Then, each of the bunches was individually chipped and sampled to assess the fuel quality in terms of MC, particle size distribution, ash content and energy content.

Results & Conclusions

The compression had stronger effects on the bunches of big trees, for which bulk density increased by 76% compared to 35% for bunches of small trees (Table 17). On average, 2 OD kg of branches, twigs, needles and bark per bunch were collected from the bunches of small trees and 4 OD kg per bunch from the bunches of big trees. Thus, 5% of the biomass was scraped off during compression of the former and 7% of the latter. Although a reduction in harvested mass reduces harvesting productivity and income, this is expected to have a positive effect on the nutrient balance and fuel quality (e.g. decreasing the ash content). These results are consistent with previous studies on the prototype MAMA head, in which a 17-24% increase in forwarder payloads was found, resulting in a 47-70% increase in bulk density when biomass was stacked in a pile at roadside.

Table 17. Characteristics of the studied tree bunches: average values and differences (Δ) between non-processed and processed bunches. The average moisture content was 56%.

	Small trees			Δ	Big trees			Δ
	Unprocessed	Processed		(%)	Unprocessed	Processed		(%)
DBH trees (cm)	5.7	5.9			9.8	9.8		
Height trees (m)	7.0	7.1			9.3	9.4		
Mass bunch (OD kg)	36	*Before*	*After*		70	*Before*	*After*	
		38	36	-5		62	58	-7
Bunch volume (m^3loose)	0.6	0.4		-32	1.1	0.6		-41
Bulk density (OD kg/m^3)	65	88		+35	67	117		+76

Effects of harvested tree size and undergrowth density on the operational efficiency of a bundle-harvester system in early fuel wood thinnings

Objectives

The objectives of this study were: to assess effects of harvested tree size and undergrowth density on the operational efficiency of a bundle-harvester in early fuel wood thinnings, and to analyze the supply cost and break-even properties when including both terrain and road transportation costs (Bergström et al 2014).

Materials and methods

A Fixteri FX15a bundler system developed for handling small diameter trees, mounted on an 8-wheel Logman 811FC harwarder, equipped with a Nisula 280E accumulating felling head, was used in the study (Fig. 35). The machine integrates felling/bundling of small trees at the harvesting stage to produce tree section bundles of ca. 500 kg. A field time study of the system was carried out in Holmsund (63°43' N; 20°25'E) in the coastal area of Västerbotten county, Sweden.

Figure 35. The Fixteri bundle-harvester system.

The study was performed in dense early thinning stands, where the removal stem volume varied between 10-30 dm^3 and the removal density varied between 2000 and 5000 trees/ha. Twenty-six time study units with a surface of 1000 m^2/unit (50 x 20 m) were laid out and separately harvested in areas dominated by pine (10 units), birch (13 units) and spruce (three units), covering a total area of ca. 2.6 ha. Half of the units were pre-cleaned of trees with DBH<3 cm using a cleaning saw. Each unit was inventoried before and after harvesting to determine dendrometrical features using 2×100 m^2 transects. The harvesting was carried out between May 5th and 14th 2014. In total 176 t (fresh) of biomass was harvested. The output of the whole-tree bundler was recorded through the machine's on-board production statistics (time and weight of each bundle as reported by the on-board computer) as the number of bundles per time study unit and fresh t. Biomass samples were taken for determining the MC of each tree species. The weight of each bundle was transformed into volume (m^3) values using local conversion coefficients from dry-density to volume (855 kg fresh mass/m^3 for pine and spruce; 900 kg fresh/m^3 for birch). A separate time and motion study of cutting and bundling the trees was performed with both a hand-held field computer and filming followed by time-recording at office. The PM_0 working time per plot was recorded by applying the continuous timing method and the times for different work elements were separated from each other by numeric codes.

Results & Conclusions

The harvested biomass per hectare varied between 46 and 112 m^3/ha and the number of trees harvested between 1640 and 6450 trees/ha. The productivity of the Fixteri bundle-harvester appeared to be strongly correlated with the harvested whole tree volume (see Fig. 36), varying between 5.3 and 9.9 m^3s/PMH_0 when the harvested whole tree volume increased from 14 to 41 dm^3. The results are consistent with a study conducted recently in pine-dominated first thinning stands in Finland, where the productivity varied between 9.7 and 13.8 m^3s/PMH_0 when removing whole tree volumes between 27 and 84 dm^3 (Björheden & Nuutinen 2014). Undergrowth seemed to have limited effects on productivity in the present study (preliminary results), compared to the effect of harvested tree volume.

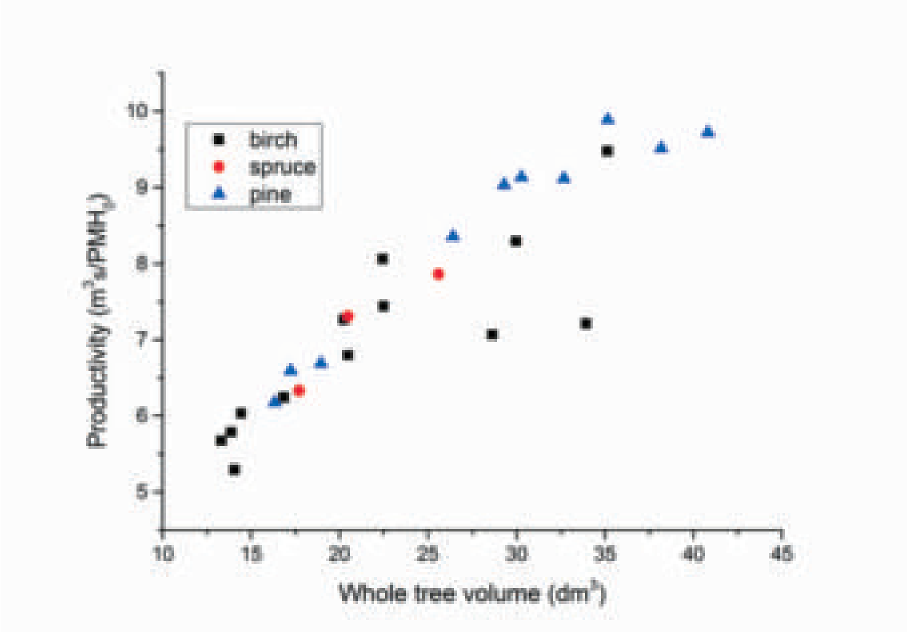


Figure 36. Fixteri FX15a productivity (felling and bundling) as a function of harvested whole tree volume in birch-, pine- and spruce-dominated harvested units (n=26).

Operational studies of a chain-flail debarker

Objectives

The objectives of this study were to evaluate the productivity of a chain-flail debarking system and its debarking quality.

Materials and Methods

Whole pine trees from first thinning stands were debarked at a terminal owned by UPM Kymmene in Ostrobothnia, Finland, at the beginning of April 2013. The debarked logs and bark within the terminal were moved away from the debarker by a Volvo L120E front-end loader equipped with both a bucket and log grapple (Fig. 37, left).The trees were debarked with a mobile chain-flail debarker manufactured by Hooli (Fig. 37, right).

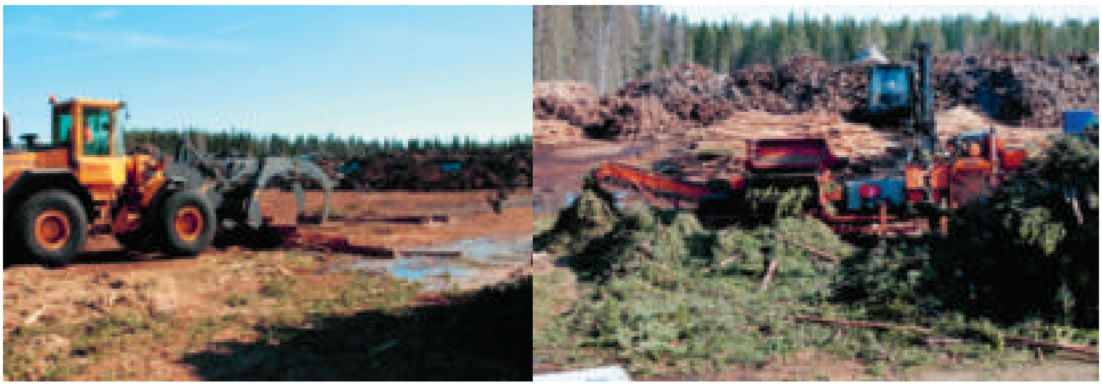


Figure 37. Left, a front-end loader and, right, a chain-flail debarking system.

The chain flail debarker had two drums, upper and lower, equipped with chains. Two different RPM settings of these drums were used. On one day the settings were 520 and 480 RPM, respectively. On the following day the setting for both drums was 280 RPM, due to problems with the hydraulic system. Both debarked logs and bark were separated during each day and then scaled at a UPM pulp mill. A frequency time study was performed, with 10 seconds intervals for registering current work elements on both occasions, and the fuel consumption was measured separately for each day. The quality of the logs debarked during both days was evaluated by sampling discs from the middle of logs, removing the bark from the discs, then scaling the mass of the wood and bark. In total 72 logs were sampled to measure their bark content and 22 logs for characterizing log properties during the trial.

Results & Conclusions

The average length, diameter and weight of the logs were 5 m, 9.8 cm and 42.2 dm^3, respectively. The minimum area required for the debarking process was 0.8 ha. Most of this area was used for storing the debarked logs and for the front-end loader to operate. The productivity of the debarker was 13.6 OD t of debarked logs/PMH_0 when it was run at 520/480 RPM and 9.3 OD t/PMH_0 when run at 280 RPM (Table 18). The corresponding productivity of produced residual bark and branches was 1.1 OD t/PMH_0 at 520/480 RPM and 5.0 OD t/PMH_0 at 280 RPM. The average time per crane cycle was 20.6 s, and on average, 3.7 logs were handled per crane cycle.

Table 18. Properties of the chain flail debarker and the biomass during the trials.

Properties	Day 1	Day 2
Rotation speed of chain flail debarker drum, upper/lower (RPM)	520/480	280/280
Total mass of debarked logs (OD t)	62.2	61.7
Total mass of bark (OD t)	5.0	14.5
Total energy content of debarked logs (MWh)	343.1	324.8
Total energy content of bark (MWh)	27.7	77.0
MC (%)	58	56
Productivity of debarked logs (OD t/PMH_0)	13.6	9.3
Productivity of bark (OD t/PMH_0)	1.1	5.0
Fuel consumption (L/OD t)	1.9	2.0
EROEI	233.1	300.6

In 43% of the total work time crane movements and debarking were performed simultaneously (Fig. 38). Most of the waiting times occurred when the debarked logs had to be removed from the side of the debarker and transported by the front-end loader to the landing area in the terminal. The bark content still attached to the debarked logs varied widely from 0.3 % to 14.7 %, averaging 2.8 %.

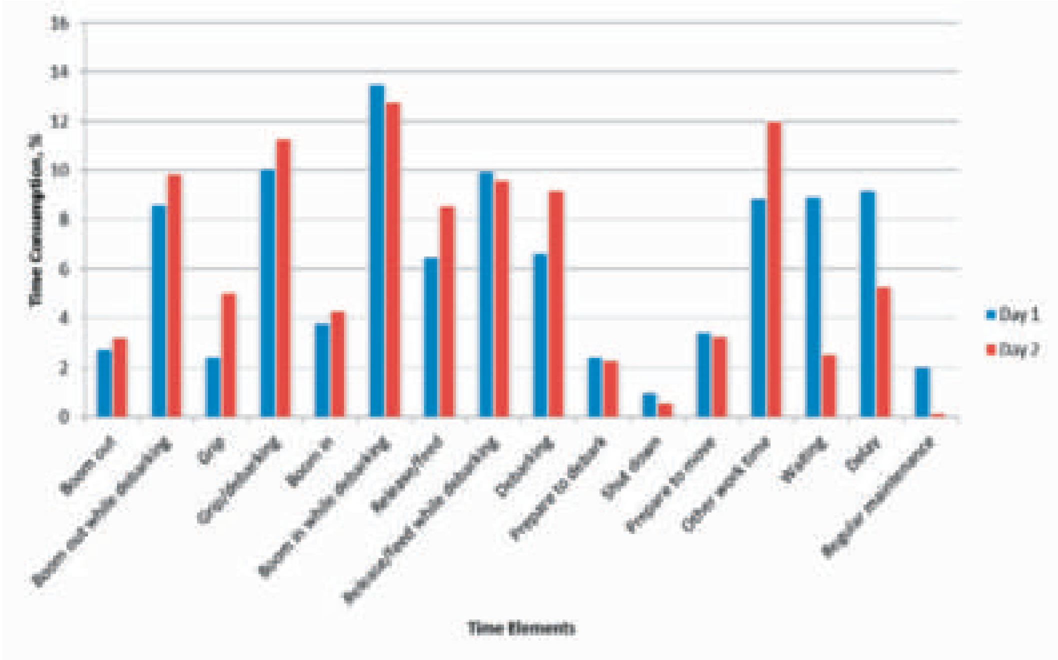


Figure 38. Distribution of work time elements in the chain flail debarking operation, including delay time.

Reductions in extractives during storage of chain-flail residues from small-diameter pine and comminuted pine stumps

Objectives
The objectives of this study were to evaluate changes in the chemical composition of chain-flailing residues and comminuted stumps during storage.

Materials and methods
Whole pine trees were chain-flailed at a UPM terminal in Pietarsaari, Finland, and a 150 m^3 storage pile of residue (composed of branches and small diameter stem tops, bark and needles was made and sampled at the time of consrtuction and after 1, 2, 4, and 24 weeks of storage. The stump material consisted of two types of Scots pine stumps: fresh stumps and stumps that had been left for a year in the ground after clear cutting a mature stand. The stumps were lifted and crushed then a 150 m^3 storage pile was made, at the same terminal, for each type of stump material and sampled after the same storage times (and at initiation) as in the previous experiment. Four samples were taken from each pile at each sampling time, representing different parts of the pile. The extractives contents of the samples were subsequently analyzed by Soxhlet extraction with two solvents (hexane followed by a 95:5, v/v, acetone:water mixture), weighed and chromatographically determined (by GC/FID) according to the method presented by Örså and Holmbom (1994).

Results & Conclusions

<u>Chain-flail residues</u>
The gravimetric amount of extractives decreased significantly during storage (Fig. 39), roughly halving during the first four weeks. The biggest losses were in amounts of hydrophilic (acetone:water soluble) extractives, but amounts of lipophilic (hexane soluble) extractives also decreased.

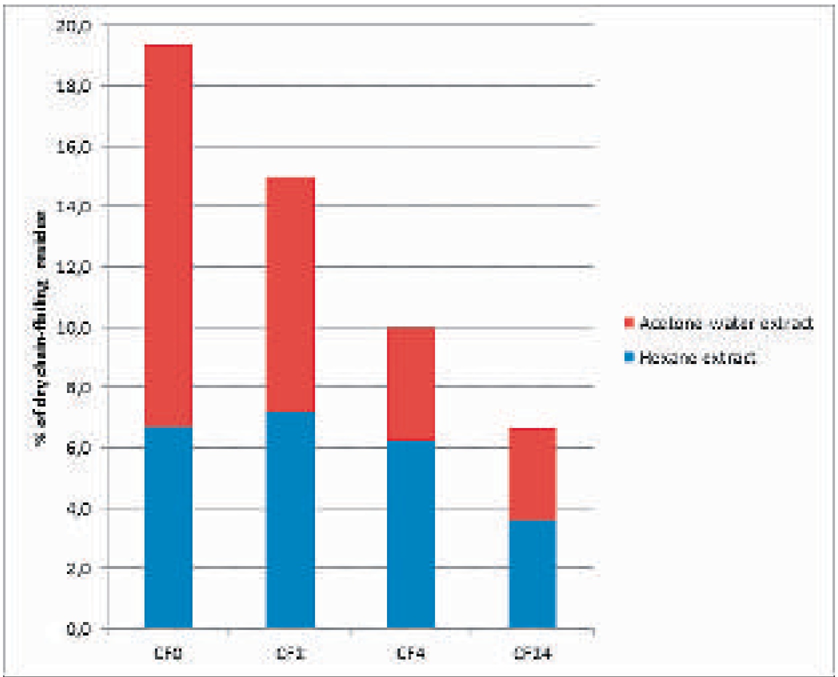


Figure 39. Gravimetrically determined amounts of extractives in uncompacted chain-flailing residue. CF0 = Chain-flailing residue sample taken before storage, CF1 = after 1 week, CF2 = after 2 weeks, CF4 = after 4 weeks, and CF24 = after 24 weeks.

In the chain-flailing residue the amount of triglycerides decreased remarkably, and amounts of free fatty acids also decreased significantly (Fig. 40), but the resin acid contents seemed to be fairly constant during six months storage. It should be noted that after 24 weeks of storage no detectable lignans were left in this material.

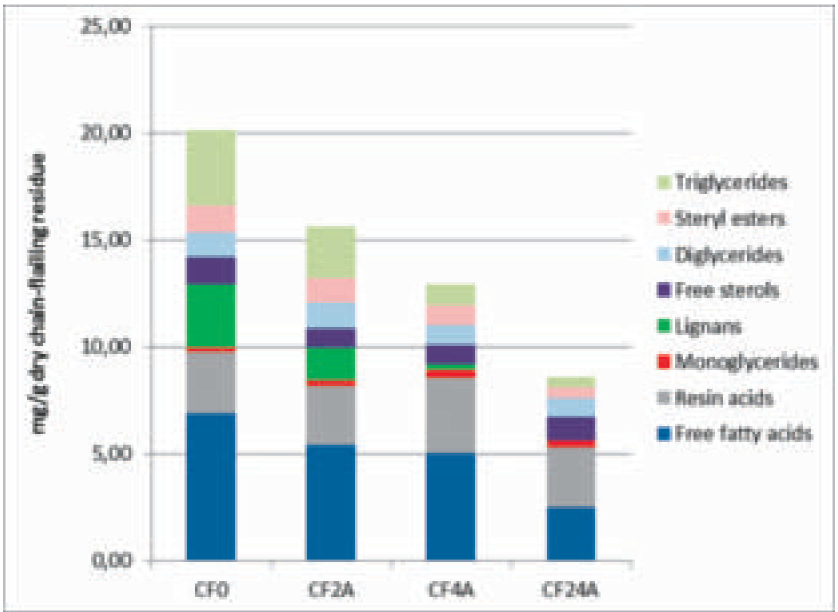


Figure 40. Amounts of indicated extractives detected in softwood bark. CF0 = Chain-flailing residue sample taken before storage, CF2 = after 2 weeks, CF4 = after 4 weeks, and CF24 = after 24 weeks. A = one of the four sample positions, at the bottom of the pile.

This storage study shows that the extractives content decreased notably during storage, even during the first four weeks. The composition of this fraction also changed during storage and valuable bioactive compounds were lost, amongst others. Thus, the freshness of the feedstock and recovery logistics are major factors to consider when designing and implementing processes intended to recover extractives.

Comminuted stumps
The total amount of stumps-derived extractives decreased slightly during storage, from 4.1% of dry solids to 3.6% of dry solids in fresh stumps, and from 4.3% to 3.7% in one-year-old stumps. In this study only two solvents were used, consecutively, for extraction. The changes in the chemical composition of the extractives fraction were more pronounced than the changes in the gravimetrically determined amounts. The extractives composition of stumps differs from that of (for example) stemwood, which partly explains the differences in their behavior during storage.

The strongest reductions in stumps' specific extractive contents during storage were in the free fatty acid content, although contents of triglycerides and steryl esters also decreased. As shown in Figures 41 and 42, reductions in contents of the measured extractives started and proceeded more quickly in fresh stumps than in the one-year-old stumps. Some changes had probably already occurred in the latter, during their storage underground, but to a lesser degree than in the freshly comminuted material. From the yield perspective this indicates that it may be advantageous to store stumps underground rather than comminuting and storing them fresh.

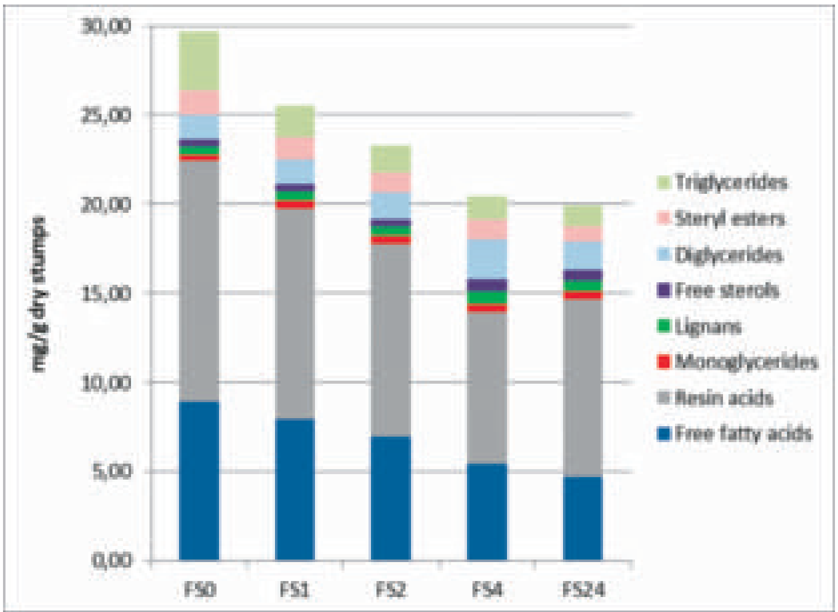


Figure 41. Amounts of indicated extractives detected in fresh stumps. FS0 = fresh stump sample taken before storage, FS1 = after 1 week, FS2 = after 2 weeks, FS4 = after 4 weeks, and FS24 = after 24 weeks.

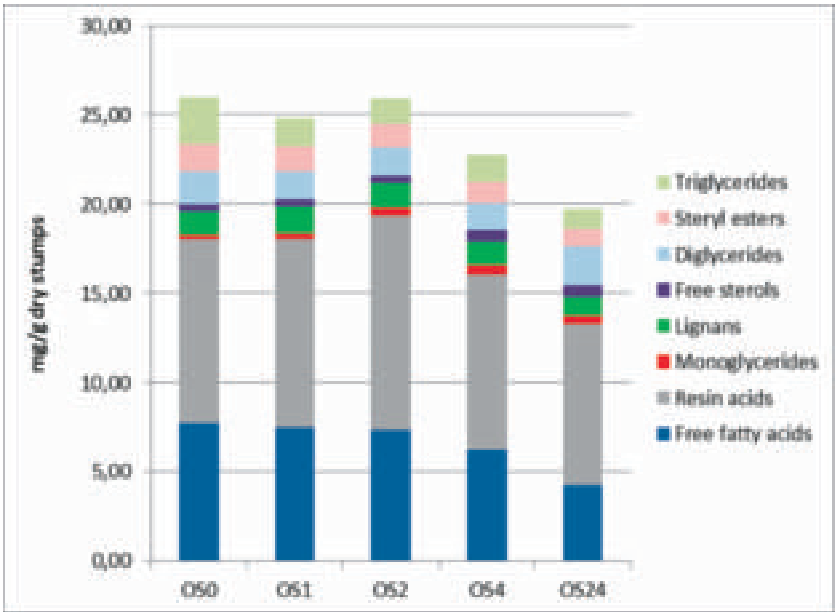


Figure 42. Amounts of indicated extractives detected in one-year-old stumps.OS0 = old stump sample taken before storage, OS1 = after 1 week, OS2 = after 2 weeks, OS4 = after 4 weeks, and OS24 = after 24 weeks.

Storage of logging residues with a TopTex cover sheet

Objectives

The objective of this study was to compare the MC, biomass losses and temperature changes in TopTex covered and uncovered stacks of stored comminuted logging residues during winter time.

Materials and methods

The trials were performed in the region of Kramfors and Sollefteå, in Västernorrland, Sweden, using materials, owned by the forest owner association Norrskog, delivered during October 2012 to the Utansjö industrial site and divided into four stacks. Two of the stacks were covered with a TopTex ventilating cover sheet, fastened by placing logs on it (Fig. 43). Net-sacks, tubes and temperature sensors were placed in eight positions in each stack (P1-P8) (Fig. 44). At each point, and in "mirror-points", i.e. points at corresponding locations on the opposite side (Fig. 44), samples were taken for MC determination (M9-M16), giving in total 16 samples per stack, which were subsequently analyzed at VMF in Örnsköldsvik.

Figure 43. A stack with logging residues covered with a TopTex fiber-sheet.

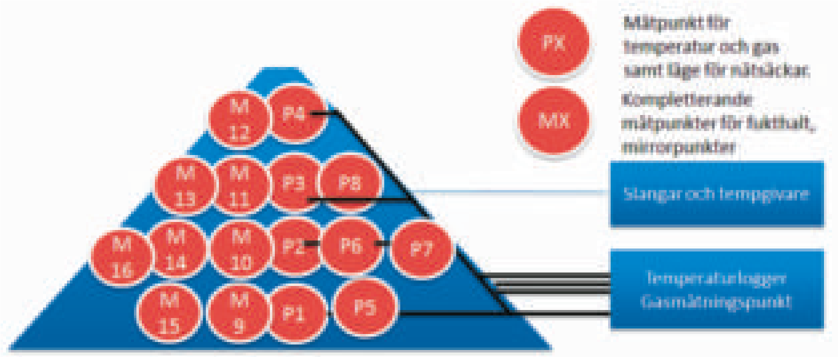


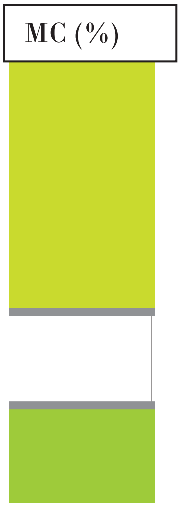
Figure 44. Schematic illustration of the sensor placement and biomass sampling points. M indicates corresponding measuring points for MC determination, P indicates points for temperature and gas measurements, and placement of net-sacks.

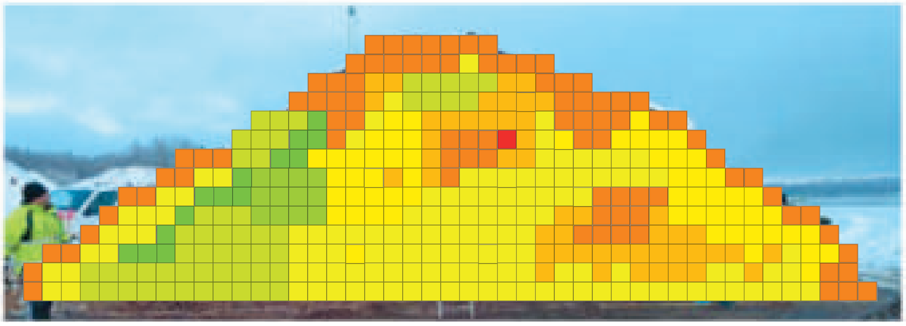
On December 10th 2012 trials with two of the stacks ended. The ambient temperature was then ca - 20 °C. The uncovered stack was taken apart first: a sample-cut was created in which temperature sensors, gas tubes and net-sacks were uncovered (Fig. 45). In the sample-cut MC, temperature and gas were measured. The sample-cut was photographed to determine the relative area of MC-zones.


Figure 45. Sample-cut at the time of taking apart the uncovered stack.

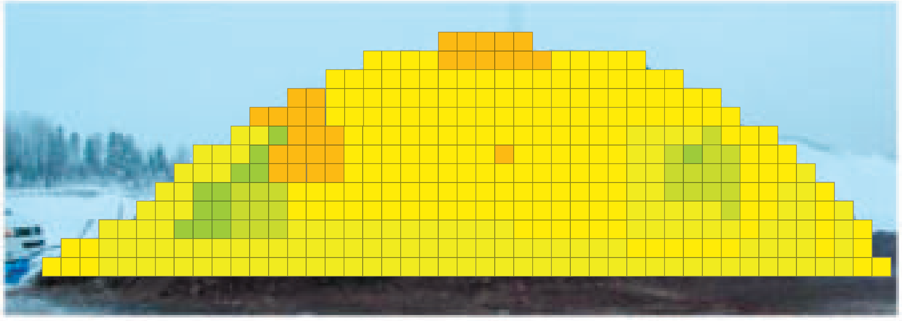
On March 12-13th 2013 the trials with the two other stacks ended. The uncovered stack was taken apart first. At this time the wind was strong, it was snowing and the temperature was 0 °C.

Results & Conclusions
The trials with the uncovered stack were stopped in December (short-term storage). At this time its MC had increased by 4.9% units, while the MC of the covered stack remained unchanged (Fig. 46). A visual observation was that the uncovered stack was substantially wetter on the side oriented towards the sea, but not the covered stack.





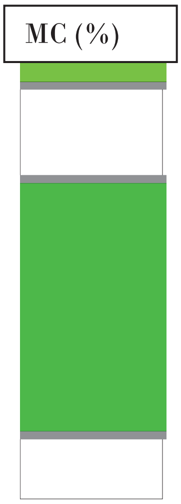
Uncovered stack, short term storage: MC at breakage=51.6% (initial MC =46.7%)

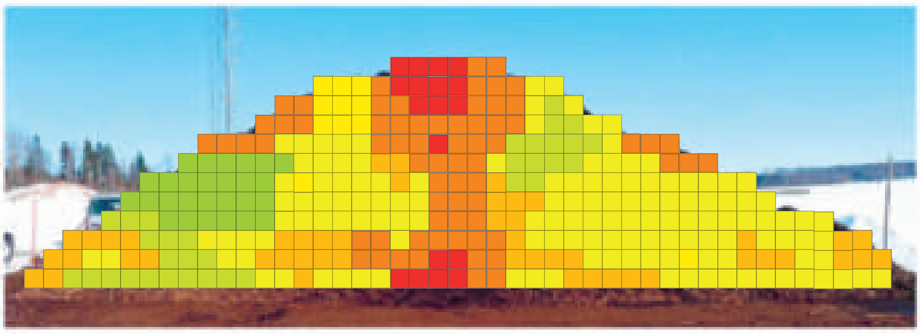


Covered stack, short term storage: MC at breakage=50.3% (initial MC = 50.2%)

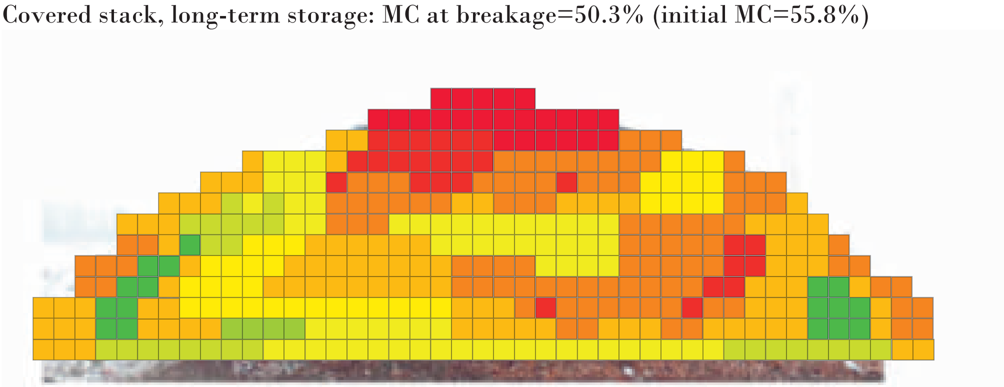
Figure 46. MC distribution in sample-cuts at breakage of uncovered and covered logging residue stacks stored short-term.

The MC (volume-weighted) of the uncovered and covered stacks stored long-term increased by 3.5% and decreased by 5.5% units, respectively (Fig. 47), resulting in a difference of 9% units.





Covered stack, long-term storage: MC at breakage=50.3% (initial MC=55.8%)



Uncovered stack, long-term storage: MC at breakage=53.0% (initial MC=49.5)

Figure 47. MC distribution in sample-cuts at breakage of uncovered and covered logging residue stacks stored long-term.

In the stacks the temperature initially rose rapidly then levelled out at ca 70 °C after ca. four weeks. Thus, covering comminuted logging residues by a TopTex fibre-cover results in a lower MC during storage in the winter time.

Comparison of cost and energy efficiencies of present and future biomass supply systems for young dense forests

Objectives

The objectives of this study were to assess simulated effects of implementing new harvesting and handling technologies on the cost and energy efficiencies of alternative supply chains for delivering material harvested in early thinning of stands under Nordic conditions to forest terminals or industrial sites, in comparison to present conventional systems. Only systems for delivering uncomminuted assortments were considered (Bergström & Di Fulvio 2014).

Materials and methods

All the input data for modeling machine and system time, as well as the cost and energy requirements to carry out the work needed to deliver the biomass from the stand to a terminal or industrial site, were based on published data. The supply systems' operational cost efficiency (SEK/OD t) using a currency conversion rate of 1 SEK=0.15 USD=0.12 EUR, energy efficiency (MJ/OD t) and the EROEI (cf. Everett et al. 2012) were considered. Effects of variations in stand type, products delivered and transport distances on these variables were addressed in the models. The effects of 10%, 20% and 30% increases in off-road and road transport payload capacities, simulating implementation of load-integrated compression methods for tree parts, were also analyzed. The performance of machines in each system were deterministically calculated. Data obtained from measurements of seven early thinning stands, five located in Central Sweden (Bredberg 1972, Gustavsson 1974) and two located in Northern Sweden (Di Fulvio et al. 2011a) were used. The stands contained Scots pine, Norway spruce and birch trees. Trees with DBH $\geq$ 3 cm were considered, and six different products: delimbed pulpwood logs (PW), rough delimbed pulpwood logs (PW_{rough}), whole tree parts (WT), rough delimbed WT (WT_{rough}), bundled WT_{rough} ($WT_{rough}B$) and bundled WT (WTB). The OD masses for stem wood, branches and foliage were calculated using functions presented by Marklund (1987). Calculations were carried out for individual trees to identify the variation of tree part mass due to the tree size distribution. The thinning was carried out selectively from below or geometrically by boom-corridor thinning in 1 m wide and fan-shaped corridors, as described by Bergström et al. (2007) and Sängstuvall et al. (2011), in strip-road systems with 20 m spacing between strip-roads. The following harvesting systems were modeled. Firstly, a thinning harvester fitted with a harvester head with feed-rollers and multiple tree handling capacity (MTH) and a standard forwarder. Secondly, a thinning harvester equipped with an accumulating felling head (with no feed-rollers) (AFH) and a standard forwarder. Thirdly, a base machine equipped with a felling crane with an AFH, a bundling unit (bundle-harvester) capable of producing 1 m^3 (bulk volume) bundles, and a standard forwarder. Fourthly, a base machine equipped with a felling crane with an MTH, a bundling unit capable of producing 1 m^3 (bulk volume) bundles, and a standard forwarder. Two area-based boom-corridor felling machines described in Bergström et al. (2007) were also considered: a thinning harvester equipped with a head capable of felling trees in a 2 m^2 area in one movement (AFH-2m^2) and a thinning harvester equipped with a head capable of continuous felling in boom-corridors (CF). Four optimized bundle-harvester systems (OPT) based on the third to sixth of these sytems, which produce bundles at the same rate as the biomass is felled and fed to the bundler were modeled, i.e. no time delay between felling and collecting and bundling was considered. Two different truck systems were modeled: a timber truck and trailer system for pulpwood and bundles, and a truck and trailer with side blades for transportation of WT and WT_{rough}. All truck systems were self-loading, i.e. worked independently of other machines. In total, 14 supply systems were modeled (Table 19).

Table 19. Description of harvesting and supply systems analyzed. PW=pulpwood, PW_{rough}=rough delimbed PW, WT=whole tree parts, WT_{rough}=rough delimbed WT, MTH=multi-tree handling harvester head with feed-rollers, AFH=accumulating felling head, **2 m²**=AFH able to fell trees in 2 m^2 areas in one movement, CF=AFH able to fell trees continuously in a corridor, BC=boom-corridor thinning.

Harvesting and supply systems notation	Type of system	General description of system
MTH-PW	Conventional	Pulpwood system
MTH-PW_{rough}	Conventional	Rough delimbed pulpwood system
MTH-WT_{rough}	Conventional	Rough delimbed whole tree-part system
AFH-WT	Conventional	Whole tree part system
AFH-WT-BC	Conventional	Whole tree part system combined with boom-corridor thinning
AFH-2m²-WT-BC	Future	Whole tree part system with a head that fells trees in 2 m^2 areas in one movement in combination with boom-corridor thinning
AFH-CF-WT-BC	Future	Whole tree part system with a new innovative head, especially developed for continuously felling trees in boom-corridors
AFH-WTB	Conventional	Bundle system for whole tree parts
MTH-WT_{rough}B	Conventional	Bundle system for rough delimbed whole tree parts
AFH-WTB-OPT	Future	Bundle system for whole tree parts with a conventional felling head in combination with a bundling unit where no delays occur from waiting times between the felling and bundling work
AFH-WTB-BC-OPT	Future	Bundle system for whole tree parts with a conventional felling head in combination with boom-corridor thinning and a bundling unit where no delays occur from waiting times between the felling and bundling work
MTH-WT_{rough}B-OPT	Future	Bundle system for rough delimbed whole tree parts with a conventional harvester head in combination with a bundling unit where no delays occur from waiting times between the felling and bundling work
AFH-2m²-WTB-BC-OPT	Future	Bundle system for whole tree parts with a head that fells trees in 2 m^2 areas in one movement in combination with a bundling unit where no delays occur from waiting times between the felling and bundling work
AFH-CF-WTB-BC-OPT	Future	Bundle system for whole tree parts with a new innovative head, especially developed for continuously felling trees in boom-corridors in combination with a bundling unit where no delays occur from waiting times between the felling and bundling work

The time consumption for production of WTB was modeled using data acquired by Nuutinen et al. (2011) in a study of the "Fixteri" bundler-harvester. Forwarder models were based on values for medium-sized 12 – 16 t forwarders with carrying capacities of 10 – 12 t. For road transportation, a standard 24 m truck and trailer system weighing 22 – 32 t (unloaded) with a crane for self-loading was used for all products. The hourly cost (SEK/PMH_{15}, excluding VAT) for forest machines was calculated as described by Harstela (1993). The harvester's operational cost was modeled as functions dependent on the specific characteristics of the different stand types. The cost of each supply system for different transport distances was calculated as the sum of the cost for delivering products to the roadside and road transportation costs. Energy consumption calculations were based on the consumption of diesel fuel for corresponding operations, i.e. consumption of lubricants during the operations was neglected. The heating value of diesel fuel was set to 35.3 MJ/L (Athanassiadis 2000). The energy efficiency (MJ/OD t) was calculated using the specific operational fuel consumption and the heating value of diesel fuel. A 10%, 20% and 30% increase in load capacity (due to load compaction) in forwarding and road transport was used for WT and WT_{rough} systems.

Results & Conclusions

Of all harvesting systems, costs were lowest for the conventional AFH-WT in combination with boom-corridor thinning for a harvested tree size of 8 dm^3, and cost 37% less than carrying out the work as thinning from below (Fig. 48, left). This difference decreased as the stem volume increased and was only 7% and 4% for 17 and 22 dm^3 trees, respectively. The cost difference for $MTH\text{-}WT_{rough}$ was small compared to AFH-WT for all stand types, being only 2 – 7% higher. The harvesting cost for the AFH bundle-harvester system was 110% higher than AFH-WT for 8 dm^3 trees and 40% more for 22 dm^3 trees. The corresponding cost for the optimized AFH bundle-harvester system was 8% to 40% higher than AFH-WT. The cost for the conventional AFH bundle-harvester system in combination with boom-corridor thinning was 10% higher than AFH-WT for 8 dm^3 trees and 5% more for 22 dm^3 trees. Compared to AFH-WT, the MTH-PW cost around 500% more for 8 dm^3 trees, 120% more for 22 dm^3 trees and 30% more for 50 dm^3 trees, but cost 13% less for 70 dm^3 trees. Compared to AFH-WT, the $MTH\text{-}PW_{rough}$ cost around 70% more for 8 dm^3 trees, 30% more for 22 dm^3 trees and 2% more for 70 dm^3 trees. The most energy efficient harvesting system for stands 1 – 4 was AFH-CF-WT, which required 17 – 46% less energy input than AFH-WT (Fig. 2, right). The energy demand for stands 1 – 4 was 10 – 14% higher for the optimized AFH-2m^2 bundle-harvester system than for AFH-WT. In stands 5 and 6, the most energy efficient harvesting system was AFH-WT, which required 11 – 17% less energy than $MTH\text{-}PW_{rough}$. In stand 7, MTH-PW was the most energy efficient system, requiring 14% less energy than AFH-WT.

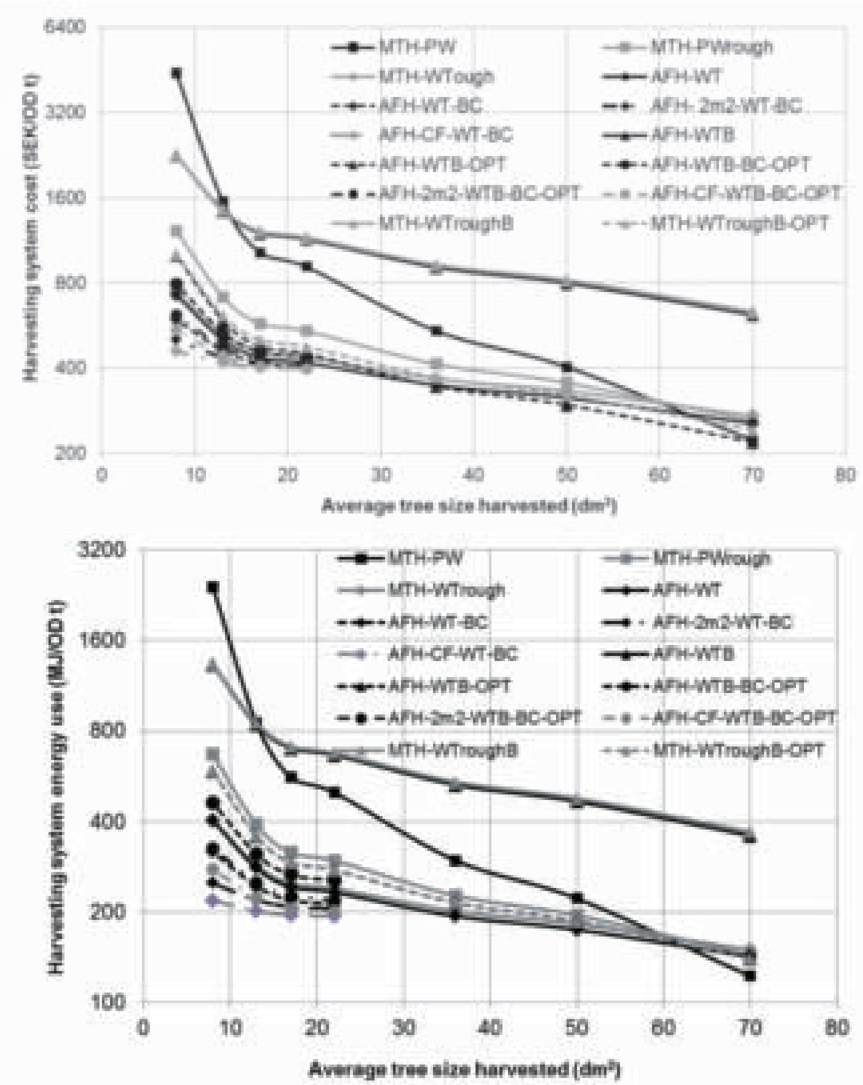


Figure 48. Upper panel, harvesting systems' costs. Lower panel, harvesting systems' energy use, at roadside (including harvester and forwarder work; forwarding distance 300 m), as a function of the average tree size harvested. Polygons along the lines represent the seven sample stands. See Table 2 for detailed description of the systems. NOTE: the y axis is shown as a Log_2 scale and starts at 200 in the upper figure and 100 in the lower figure.

At a road transportation distance of 75 km, the most cost efficient supply system for harvesting tree sizes of 8 dm^3 was AFH-CF-WT-BC, which cost 28% less than the conventional AFH-WT system (Fig. 48). AFH-2m^2-WTB-BC-OPT was the most cost efficient when harvesting trees of sizes from 13 to 22 dm^3. For harvesting trees of sizes from 36 to 50 dm^3, the AFH-WTB-OPT system was most cost-efficient. For harvesting 70 dm^3 trees, MTH-PW was the most cost efficient system in all cases. The effects of load compaction were only considered for systems that included the road transportation of loose WT. The effect increased with tree size. With a load compaction of 30% for stands 6 and 7, the costs for MTH-WT_{rough} and AFH-WT were reduced by 9 and 11%, respectively. There was a 10% reduction in the energy demand for MTH-WT_{rough} and AFH-WT with a 20% load compaction, corresponding to a 10% increase in their EROEIs. The highest increase in EROEI was 22% and occurred for AFH-WT at an average harvested tree size of 70 dm^3 with a 30% load compaction.

In conclusion, the effects of developing techniques and systems for boom-corridor thinning operations (cf. Bergström 2009, Forsberg & Wennberg 2011) on the supply system's cost and energy efficiency are especially significant for stands where the average size of trees removed is less than ca. 30 dm^3. These types of stands represent a significant proportion of the potential area that could be harvested annually from Swedish forests (cf. Nordfjell et al. 2008). Thus, further research and development to design and realize new harvesting and handling technologies for young dense thinning forests is warranted. Specifically, developing and integrating felling technologies (heads and cranes) for boom-corridor thinning and bundling units in single-machine units for operational use in strip-road systems should be prioritized.

Chemical and physical requirements of the forest biomass for biorefineries, fractionation of biomass, and preparation of bio-chemicals

Current development of forest biorefineries in Finland and Sweden

Objectives
The objective of this study was to review the history and current development of biorefining in Finland and Sweden in order to provide a broad overview of stakeholders and ongoing activities.

Materials and methods
The literature and websites were searched for information. Activities were grouped by the main technology applied: 1) cellulose hydrolysis and ethanol production, 2) gasification, 3) pyrolysis and torrefaction and 4) pulp-mill based biorefining.

Results & Conclusions
Diverse efforts are being made to examine and enhance relevant processes. In particular, biorefinery-related research is being undertaken at virtually all universities and various research institutes in Finland and Sweden. However, there have been few commercial-scale demonstration projects for new technologies and ongoing EU investment programs may be important to overcome barriers. There are also clusters and centres for coordination of research, development and innovation, such as: (in Sweden) the Biorefinery of the Future, NumberOne forest industry network, Energy Technology Centre, Swedish Gasification Centre, Wallenberg Wood Science Center; and (in Finland) the Finnish Bioeconomy Cluster FIBIC Oy, CLEEN Ltd (Cluster for Energy and Environment) the Forest Industry Future and the Energy Technology clusters.

A selection of ongoing and planned biorefinery projects in Sweden and Finland is presented in Table 20. The projects are applying different technologies to separate wood components. Cellulose hydrolysis and ethanol technology has been demonstrated and is considered ready for larger-scale applications, but no such projects have been announced as yet. Several large-scale gasification projects are planned and participants have applied for NER300 investment grants (EU financing instruments funded by emission allowances set aside in the “New Entrants’ Reserve”). A number of pyrolysis projects are underway, in which the aim is to develop technology to generate oil pyrolitically that will primarily replace fuel oil but could also eventually be upgraded to motor fuel. There are also projects for demonstration of biomass torrefaction - a pre-treatment of biomass to simplify long distance transport and processing. The pulp industry is actively involved in the development of new biorefinery processes, and is for example developing technologies for producing new types of materials and products from pulp fibres, upgrading residue streams to generate marketable products and implementing processes for co-production of process steam and marketable products. Tall oil from pulp mills is being increasingly used as feedstock for motor fuels and various chemicals. There is also a growing interest in the chemicals industry to develop large-volume chemicals from forest biomass.

Table 20. A selection of Swedish and Finnish biorefinery activities

Project	1	2	Description
Hydrolysis & Ethanol			
EPAB	D	S	Pilot plant for cellulosic ethanol production in Örnsköldsvik (~200 m^3/yr). Owned by Umeå University, Luleå University, SEKAB.
NBE Sweden	D	S	Development plant for cellulosic ethanol production in Sveg (3000 t/yr). Owned by NBE Co. Ltd., HMAB, Härjedalen municipality.
ST1	P	F	St1 biofuels are currently producing ethanol from sugar- and starch-containing waste in several plants and are researching technology for ethanol production from cellulose.
Chempolis	D	F	Chempolis Ltd is an R&D company developing biorefinery technologies, specialised in non-food, non-wood raw materials. Has a biorefinery park in Oulu.
Gasification			
BLG DME DP1	D	S	Black liquor gasification demonstration plant. Pressurised (30 bar), oxygen-blown entrained flow gasifier (3 MWth) with a DME demo plant. Developed by Chemrec AB.
IVAB	D	S	Pressurised entrained flow wood powder gasification pilot plant (1 MW, 15 bar) in Piteå.
MIUN	D	S	Circulating fluidized bed, indirect gasification (150 kW) with fuel synthesis, Härnösand.
WoodRoll	D	S	Indirect gasification technology demo (500 kW) in Köping. Developed by Cortus.
Chalmers	D	S	A 2-4 MWth indirectly heated gasifier integrated on the return leg of a 12 MWth CFB boiler
Värnamo IGCC	D	S	IGCC demo plant (18 MWth). Planned rebuild for syngas production was cancelled. Mothballed.
NSE Biofuels	D	F	Neste Oil and Stora Enso built a wood gasification demo (12 MWth) in Varkaus. Syngas combusted in lime kiln. The aim was to establish a commercial BTL plant, but it has not been prioritised for NER300 support.
Vaskiluodon Voima	P	F	140 MW gasification plant for CHP under construction in Vaasa
Vallvik biofuel	P	S	Planned black liquor gasification plant with methanol production at the Rottneros mill in Vallvik. Applied for NER300 support but has not been prioritised.
Rottneros biorefinery	P	S	Planned gasification plant for methanol production at the Rottneros mill in Rottneros. Applied for NER300 support but has not been prioritised.
WoodRoll Köping	P	S	Cortus is planning a 5 MW gasifier with upscaling to 25 MW in a second step.
Hagfors	P	S	Planned fluidized bed gasifier for methanol production (1000000 t/yr) by Värmlandsmetanol. Uhde selected as technology supplier.
Norrtorp	P	S	Pre-study for 250 MW methanol and SNG plant by Vämlandsmetanol, EON, SAKAB and others.
GoBiGas	P	S	20 MW plant for SNG under construction by Göteborg Energi. An 80-100 MW unit is planned for a second phase. Has been prioritised for NER300 support.
E.ON Bio2G	P	S	SNG plant planned by EON, up to 200 MW. On the reserve list for NER300 support.
UPM Rauma	P	F	Planned gasification/FT plant in either Rauma (Finland) or Strasbourg (France). Strasbourg plant prioritised for NER300 support and Rauma plant on the reserve list.
Ajos BTL	P	F	Planned gasification/FT-plant. Metsä group recently withdrew from the project. Vapo Oy are pursuing the project and are seeking new partners. Prioritised for NER300 support.
Pyrolysis & Torrefaction			
Metso	D	F	2 MW pyrolysis R&D plant in Tampere.
Pyrogrot	P	S	Planned pyrolysis oil plant at the Billerud pulp mill in Skärblacka. Prioritised for NER300 support.
Fortum	P	F	Plant for pyrolysis oil production (50000 t/yr) in Joensuu.
Green Fuel Nordic	P	F	Three facilities for pyrolysis oil production to be built. Expected output 270000 t/yr.
BioEndev	D	S	Torrefaction demonstration plant planned in Umeå.
Torkapparater	D	S	Torrefaction demonstration project located on Gotland.
Preseco	D	F	Bio-char demonstration plant in Lempäälä.
Pulp-mill based			
Domsjö	P	S	Production of specialty cellulose, ethanol and lignin at industrial biorefinery site in Örnsköldsvik.
Södra Cell	P	S	Development of new materials such as specialty cellulose and composite materials. Lignin extraction from black liquor.
SunPine/Preem	P	S	Production of diesel (Evolution Diesel) from tall oil.
Arizona Chemicals	P	S	Production of a range of chemicals from tall oil.
UPM BioVerno	P	F	Planned tall oil based diesel (BioVerno) production facility in Lappenranta.

(1) Demonstration/development (D) or production (P) plant. (2) Geographic location: Finland (F) or Sweden (S)

Raw material requirements of biorefinery processes

Objectives
The objective of this study was to describe the key characteristics of forest biomasses that are relevant for different biorefinery processes.

Materials and methods
Knowledge about raw material quality requirements for biorefineries was surveyed through a review of technical and scientific publications. In addition, a questionnaire has been produced and used to acquire information from stakeholders. A number of stakeholders have also been contacted and interviewed – in physical meetings or by telephone - and the questionnaire has further been emailed to a number of stakeholders. However, none of the stakeholders who only received the questionnaire by email responded. It can be concluded that direct contact with the stakeholders is needed to acquire this kind of information.

Results & Conclusions
Some general observations can be made. Firstly, since many of the biorefinery technologies are still in a developmental stage, there is no complete picture of their respective raw material requirements in industrial-scale applications. Some of the ongoing developmental work specifically aims at adapting the processes so that they can accept a wider range of feedstock qualities. Thus, there are no definite, fixed, raw material quality criteria that have to be met. Instead, there are tradeoffs between strict feedstock specifications and laxer requirements for specific single or multiple processes, the feedstocks available, and the most efficient locations (at the industrial sites or appropriate points along the supply chain) for feedstock preparation. A general observation is that a given process can often be adapted to handle specific feedstock-related problems, but variations in the feedstock properties may be more difficult to handle. Hence, cost-efficient supply of a homogenous, well-characterized feedstock would be highly valuable from the industry's point of view. Cost per unit energy content would be a key parameter for biorefineries that produce energy products (such as solid and liquid fuels, heat and electricity). The cost per unit mass of sugar molecules, and the composition of the sugars, would be important for biorefineries based on sugar chemistry (for example cellulosic ethanol production by biochemical processes). Forest feedstock contains highly diverse small-volume substances which could, potentially, be utilized for high-value chemical products. Certain parts of the tree (such as the knots) are richer in these substances. However, commercial developments within this area are scarce, and the present study has, so far, not been able to draw any general conclusions regarding feedstock requirements for these high-value chemical applications. The requirements will probably be highly specific to the individual applications. The influence of key raw material properties on important biorefinery processes are summarized in Table 21. The information in Table 21 draws on a report by Väisänen (2010), in addition to the stakeholder interviews. The main biorefinery processes are briefly described in the following paragraphs.

<u>Pelletizing:</u> Small particles are pressed through a die with holes to form pellets of desired dimensions. The process requires a relatively dry feedstock with suitable particle sizes. The energy requirements of the pelletizing process and the physical durability of the pellets are affected by the raw material properties. The intended end-use of the pellets determines the quality requirements.

<u>Thermochemical processes</u>
In thermochemical processes, the feedstock is chemically converted through the application of heat and, potentially, an oxidizing medium such as air, oxygen or steam. Thermochemical processes can be characterized by the reaction temperature, time and availability of the oxidizing medium. *Torrefaction* is a pre-treatment performed at relatively low temperature over a long time, in the absence of an oxidizing medium, to obtain a compact and brittle solid material. *Pyrolysis* is performed at higher temperature in the absence of an oxidizing medium, often with a liquid as the main product, which can replace fuel oil or be upgraded to other fuels or chemicals. *Gasification* is typically performed at even higher

temperature, with a limited supply of oxidizing medium to produce a gas consisting mainly of carbon monoxide, carbon dioxide, hydrogen, methane and nitrogen, the exact composition depending on the process conditions. The gas can be converted into fuels and chemicals or combusted for heat and power production. *Combustion* generates heat by the full conversion of the feedstock into, mainly, carbon dioxide and water, through complete oxidation. The heating value, moisture content, ash content and ash properties are generally relevant for thermochemical processes. The particle size governs the reaction rate, which is a key parameter.

Biochemical processes

In biochemical processes enzymes are used to chemically convert the feedstock. An example is the hydrolysis of polymeric sugars (cellulose and hemicelluloses) to produce monomeric sugars through enzymatic treatment and subsequent fermentation of the sugars into ethanol by microorganisms. Important raw material properties include the molecular composition (especially the sugars' abundance and profile), properties affecting the accessibility of the enzymes or microorganisms to the substrate and the tendency of the feedstock to produce unwanted substances in the process, which inhibit the biochemical reactions.

Table 21. Summary of key raw material properties' influence on important biorefinery processes.

	Feedstock composition	Physical properties	Other
Pelletizing	Lignin is beneficial for pellet production while high concentrations of extractives may be unfavourable. The acceptable ash content varies with the end use. Household pellet boilers and stoves generally require low ash content, and thus low bark content in the feedstock. Impurities such as sand and rocks can be very detrimental to the pelletizing equipment.	Ideal moisture content for the pelletizer is around 10%. The material may have to be dried or wetted. Particle sizes should not exceed 60% of the pellet diameter (typically 6-10 mm). For the drying process, a small particle size is beneficial. The desired particle sizes may also vary with the end use. Smaller particle sizes are preferred when the pellets are crushed into dust before end use.	Variations in particle size and moisture content cause severe problems in drying and pelletizing. Uneven moisture content of the dried material and plugged die holes in the pelletizer may be the result. The desired properties are to a large extent governed by the intended end-use of the pellets.
Combustion	A high heating value is desired, but the ash content and ash characteristics are also important. Relatively insensitive to impurities, although both ash and non-wood components are undesirable. Metals, salts and large rocks may cause major problems. The sensitivity to impurities and ash properties varies with the combustion technology. Grate boilers tolerate impurities well in comparison to other combustion equipment.	Higher moisture content reduces the heating value of the raw material, which is generally unfavorable, but large-scale combustion technologies are relatively insensitive to moisture content. Particle size is not crucial for large-scale combustion technologies, but should preferably be known, so the process can be adapted. Very small particles – fines – may cause problems.	Fluctuations in the raw material feed may lead to high levels of unwanted emissions from the combustion. Some raw material variability can be accepted but abrupt changes are difficult to handle. Variations may also cause feeding problems. In general, grate boilers are more sensitive to particle size variations than BFB boilers.
Gasification	The ratio between oxygen, hydrogen and carbon in the feedstock affects the gasification process and should preferably be known. Catalytic conversion of the gas into fuels or chemicals is negatively affected by sulphur, phosphor and alkali metals. Gas turbines are less sensitive but corrosion and erosion may be problems. For indirect gasification, more volatile substances and less coke is desirable. Ash content and properties are important. Low ash melting point is a problem in FB gasification. Impurities may cause jams in feeding equipment. Metals are detrimental as they cause corrosion and sintering of bed material in FB gasifiers. The content of, for example, active silicon, phosphor and calcium affects the ash melting behaviour. Clay minerals may reduce potassium-related problems.	Moisture levels should be below 10-20% for syngas production (depending on gasification technology). EF gasifiers require lower moisture content than FB gasifiers. Drying is often needed and could preferably be integrated with the gasification process. Desired particle size depends on the gasification process, but generally the size must not vary much. EF gasifiers require a powder-like feed (particle size typically lower than 0.5 mm) but large fractions of too fine material may also cause problems. FB gasifiers are more tolerant of feed quality changes and larger particle sizes (up to 50 mm for BFB gasifiers). Too fine materials may cause problems, especially in BFB gasifiers, while circulating FB gasifiers are less sensitive.	Raw material homogeneity is very important for gasification processes. The moisture level affects the consumption of gasification agent which must be carefully controlled. EF gasification is particularly sensitive to particle size variations. Feeding, especially to pressurized reactors, may be problematic. Bulk density is one important parameter. For the EF process, grinding of the feed into a suitable powder is crucial. Factors that affect the grindability, such as moisture content, are important. Also, less fibrous material, such as bark and torrefied materials may be easier to use.
Pyrolysis	Impurities are detrimental to the pyrolysis process. Rocks and metal parts must be removed. High levels of extractive substances in the raw material reduce the yield. The effect of impurities in large-scale applications is not yet totally clarified.	Pyrolysis processes require moisture content to be below 10%. Variations in moisture are also generally problematic. In fast pyrolysis, particle sizes should be small (<3 mm).	A homogenous feed is desired. Variations in the feed properties cause undesirable variations in the end products' properties.
Torrefaction	All organic matter is of interest. High share of easily volatilized substances lowers the yield. Relatively insensitive to impurities. However, the amount of impurities and ash etc. affects the end product quality. The quality requirements depend on the intended end use.	The material needs to be pre-dried before entering the torrefaction process (to ~10%). The particle size is not so critical. Chips (10x20x40 mm) are good. High share of fine particles may cause dusting problems. Oversized material may cause feeding problems.	Homogeneity in particle size and other properties is beneficial for process optimization – facilitating a homogeneous degree of torrefaction.
Hydrolysis	The content and composition of sugars are important. For fermentation to ethanol, glucose is preferred, followed by other hexoses. Pentoses are more difficult to ferment. There are three main groups of fermentation inhibitors: Furans (sugar degradation product); acids, especially acetic acid (mainly from hemicelluloses); and phenols (probably from lignin). Lignin is generally undesirable as it lowers sugar yields and inhibits enzymatic hydrolysis. Extractives may also cause some problems in the process. Hydrolysis is relatively insensitive to impurities. Sand and rocks cause wear on equipment.	Moisture is not a major problem in ethanol production, but the feedstock should not be too dry. Small particle size is generally desirable, but particles of various sizes, such as chips and sawdust, can be used. Fine materials may cause problems in filtering operations.	The particle size should be homogenous to control process conditions. Moisture variations are tolerable, but process optimization is easier with stable moisture content. Bark may cause problems according to some sources. Some sources say that bark and logging residues can be handled.

Nomenclature: EF: entrained flow, FB: Fluidized bed, BFB: Bubbling fluidized bed

Birch bark suberin – a potential source of valuable compounds

Objectives
The objectives of this study were to extract and analyse suberin from wet birch bark obtained from debarking at a pulp mill.

Materials and methods
Suberin was extracted from wet birch bark (both inner and outer fractions) immediately after debarking in UPM's pulp mill at Pietarsaari, Finland (Fig. 49), and analysed following Ekman and Eckerman (1985). Briefly, alkali hydrolysis was applied to extractives-free bark samples to liberate the suberin monomers, then samples for qualitative gas chromatographic analysis of the monomers were prepared from the hydrolyzate. Cholesterol was added to the samples prior to the hydrolysis as an internal standard. Peak areas in Fig. 50 show estimated relative amounts of the monomers formed in the hydrolysis.

Figure 49. Pile of birch bark at UPM Pietarsaari mill. The sample taken for analysing suberin was taken immediately after the wet debarking. The pile in this photo was constructed for the storage experiment in which changes in chemical and physical properties of the bark were monitored (see above).

Results & Conclusions
As shown in Fig. 50, the main monomers liberated by the alkaline hydrolysis of suberin were various ω-hydroxy fatty acids, α,ω-dicarboxylic acids and 9,10-epoxy-18-hydroxyoctadecanoic acid (an epoxy derivative).

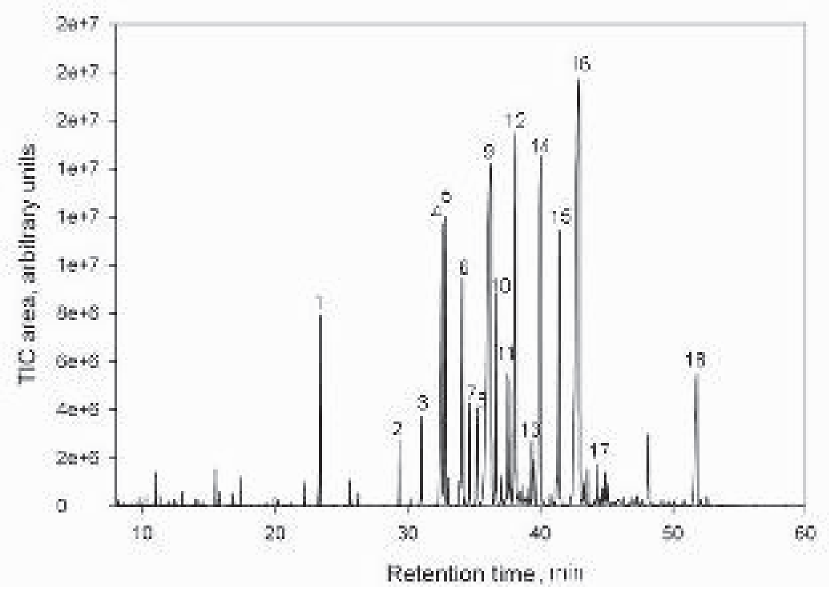


Figure 50. Gas chromatogram of the silylated compounds (suberin monomers and betulinol) from alkaline hydrolysis of wet debarked pulpmill birch bark. Main compounds identified with numbers: 1 = ferulic acid, 2 = 16-hydroxyhexadecanoic acid, 3 = hexadecane-1,16-dioic acid, 4 = 18-hydroxyoctadec-9-enoic acid, 5 = dihydroxyhexadecanoic acid, 6 = octadec-9-ene-1,18-dioic acid, 7 = octadecane-1,18-dioic acid, 8 = 9,18-dihydroxyoctadec-9-enoic acid, 9 = 9,10-epoxy-18-hydroxyoctadecanoic acid, 10 = 20-hydroxyeicosanoic acid, 11 = eicosene-1,20-dioic acid, 12 = eicosane-1,20-dioic acid, 13 = 22-hydroxydocosenoic acid, 14 = 22-hydroxydocosanoic acid, 15 = docosane-1,22-dioic acid, 16 = internal standard, cholesterol, 17 = tetracosane-1, 24-dioic acid, 18 = betulinol.

Commercial utilization of suberin requires more research. The literature records many highly attractive potential applications of suberin monomers, e.g., in pharmaceuticals, cosmeceuticals and nutraceuticals. Results of this study indicate that suberin is a cheap renewable resource, and that large amounts can be potentially extracted from birch bark. Furthermore, previous findings indicate that industrial wet debarking does not cause pronounced changes in the suberin (Ekman 1983). This suggests that the birch bark produced at pulp mills would be good material for the production of suberin-derived components.

Biomass quality improvements by sieving and fractioning

Objectives
The objective of this study was to characterize the physical and chemical properties of fractions from pine and spruce stumps and thinning materials from young stands (birch, pine and spruce). Characterized parameters were moisture content, ash content, extractive content, cellulose, hemi-celluloses, lignin, bulk density and particle size distribution.

Material and methods

Biomass samples used in this study
The stumps used were of spruce and pine trees, lifted shortly after clear cutting. All stumps were transported to the BTC plant in Umeå, where they were crushed in a hammer crusher (Petersson 4700 B). After crushing the biomass it was dried to about 15% MC in low-temperature (30°C) air. The sample mass after drying was about 500 kg. Before sieving and fractionation sub-samples were comminuted in a shredder (Micromat 2000) with a sieve size of Ø 15 mm.

The thinning materials used were small delimbed spruce, pine and birch trees, collected from a stand in the coastland of Västerbotten, Sweden. A sample (10 m^3) of each assortment of the delimbed pine, spruce and birch trees was transported to the BTC plant in Umeå shortly after harvest. All assortments were then chipped in a stationary chipper (Edsbyhuggen 250H Electric power 65A) with two chipping lengths

(8.0 mm and 12.0 mm). After chipping all assortments were dried to about 15 % MC in low-temperature (30°C) air, then mechanically sieved using a Mogensen Sizer Type E0 554 separator (10-1000 kg/h), with various sieve combinations.

<u>Studied factors</u>

Stumps

The stump analysis examined effects of two treatments on ca. 250 g samples of the crushed material. Firstly, sieving in the sizer with one sieve (Ø 1.0 mm), which separated 12.5% and 7.3% of fine materials from the starting weight of crushed pine and spruce stumps, respectively. Secondly, gravimetric fractionation, which separated 11.5% of the lightest and 0.7% of the heaviest fraction (mostly rocks) from the spruce material, and 9.9% of the lightest and 0.7% of the heaviest fraction (mostly rocks) from the pine material. Combined effects of the treatments were also evaluated.

Small trees

The small tree analysis examined effects of three treatments on ca. 250 kg samples of pine and spruce material. Firstly, chipping to two particle sizes. Secondly, sieving in the screener with one sieve (Ø 1.9 mm and 14 mm for 8 mm chips, Ø 1.9 mm and 16 mm for 12 mm chips), which sorted 12.5% and 7.3 %of the fine materials from the starting weights of the pine and spruce material, respectively. Thirdly, gravimetric fractionation, which sorted 7.3% of the fine materials from the starting weights.

<u>Gravimetric fractionation</u>

Gravimetric fractionation exploits differences in the density of different types of particles in treated biomass. After the biomass has been dried and comminuted to an appropriate particle size by chipping or shredding it is fed into the gravimetric separator in an even flow (Fig. 51), via an air-tight rotary valve or screw. The biomass is then transported in a thin layer by a vibrating table.

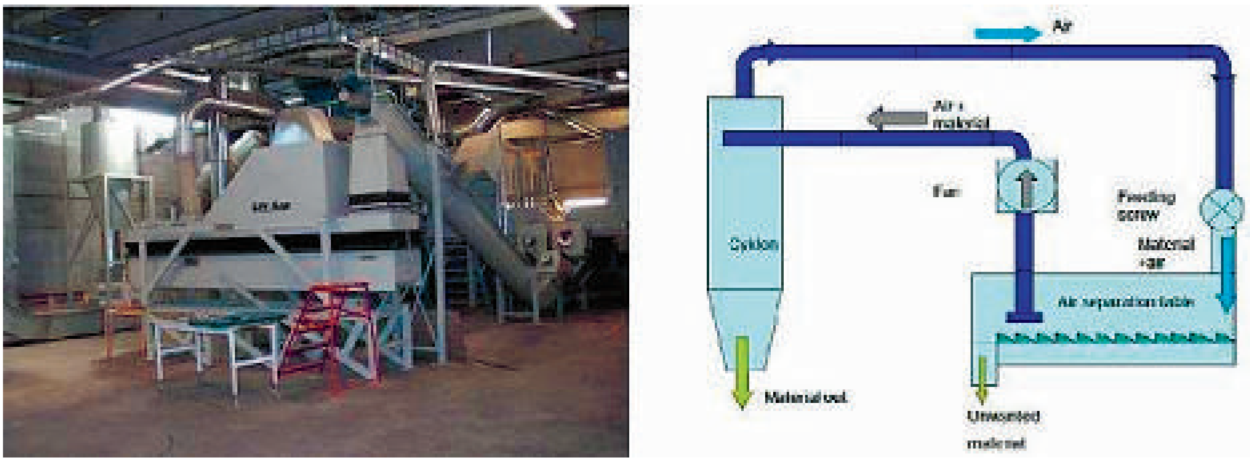


Figure 51. Left, gravimetric separator for commercial use. Right, schematic diagram of a gravimetric separator. An adjustable nozzle is placed at the end of the table and lifts relatively light fractions by an air stream, allowing heavier fractions like rocks, gravel and metal pieces pass by. Conversely, the equipment can be used to reduce amounts of very light and unwanted fractions.

In this study the biomass was treated twice in order to separate and exclude both the finest material (light fraction) and heavy fractions. For spruce and pines stumps, 5.6% and 6.1% of the light fractions, respectively, were sorted out from the starting weights. Corresponding percentages of the heavy fractions were 1.0% and 0.8%, respectively.

<u>Fractionation by sieving</u>

Fractionation in industries is commonly done by sieving (Fig. 52), using sieves with various designs and active screening surfaces, varying in area from 2 to 5 m³. Sieve hole diameters vary from 0.1 to 30 mm. The screener is driven by a vibrator, which generates a typical elliptical motion pattern that counteracts blinding, and both loosens and stratifies the feed material. Screens are manufactured with up to five decks, suiting the screening duty. Screening biomass is usually used to reject two main fractions: excessively large particles that might cause problems in downstream operations and excessively small particles, which are usually more ash-rich than others. In the reported study sieving to remove < 1.0 mm particles (dust) resulted in a 10-12% mass reduction, while two-step gravimetric fractionation to remove light and heavy particles (mostly gravel) resulted in 8-10% and 0.8-1.0 % mass reductions, respectively (Fig. 53).

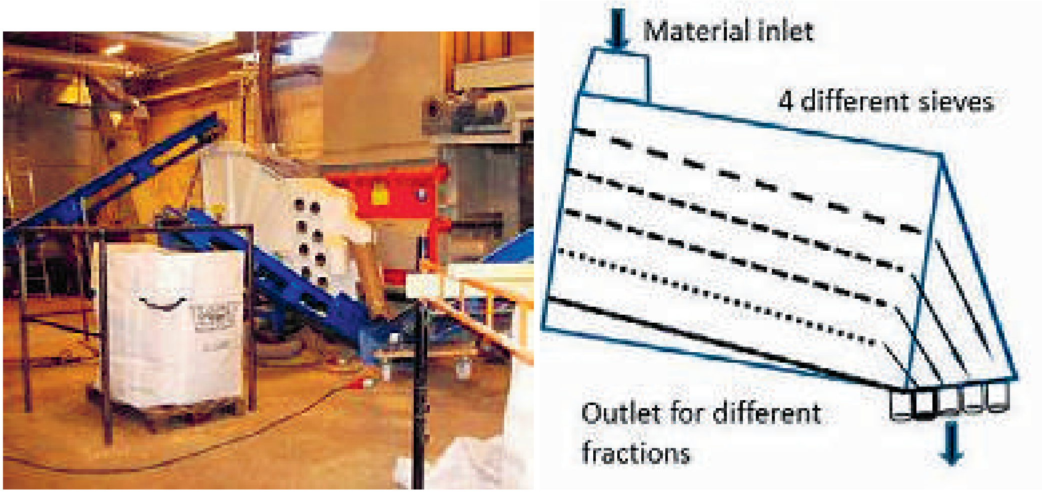


Figure 52. Left, experimental sieving set-up, and right, schematic diagram of a screen separator for sieving.

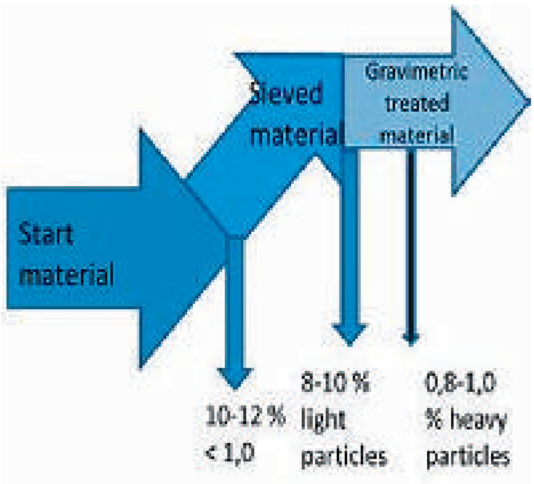


Figure 53. Combined treatment for both sieving and gravimetric fractionation

<u>Sample size reduction</u>

In order to create a representative sample for an inhomogeneous biomaterial like chipped small trees, crushed stumps or logging residues, the methods used for taking and handling samples are crucial. For evaluating samples' chemical composition the size of samples must be reduced appropriately. It is also extremely important to use appropriate methods for chemical analysis for the final sample size. This is because of the importance of reducing the standard deviation in the results. In this study a model for sample preparation and sample size reduction was developed. The study included two types of biomass assortments: pine and spruce stumps with starting weights of 500 kg per sample; and small pine, spruce and birch trees from thinning also with starting weights of 500 kg per sample. After initial particle size reduction by chipping (small trees) or crushing (stumps) samples were dried in low temperature air to ca. 12% MC. During the chipping and crushing, samples (ca. 1.0 kg) were continuously taken from the flowing stream for chemical analysis. Samples (1 kg) of all the material were also taken after gravimetric fractionation and sieving. These samples were reduced and milled to Ø 1 mm particles with a sample size of just 100 g per sample, and for the chemical analysis they were further reduced in size to 1 g per sample. All sample size reductions were done after thorough mixing of the sample.

Responses

Following standard extraction and analytical practices, carbohydrate and lignin contents of triplicate samples were examined using pyrolysis combined with GS/MS, while total amounts of sugars in celluloses and hemicelluloses were analyzed by GC/FID (references). The lignin measured by the stated technique is called "Klason lignin" and is the amount of biomass that is not dissolved in conc. sulfuric acid (72%, H_2SO_4, 30 ± 1°C, 2 hours). To determine the content of lipophilic extractives like fatty acids, resins, turpentine and alcohols the samples were extracted in ether (ethoxyethane) and analyzed.

Experimental design

For the stump analysis the experimental design was quadratic, since effects of sieving and gravimetric fractionation were evaluated (Fig. 54, left). For the small trees analysis the design was cubic, since effects of chipping to two particle sizes, sieving and gravimetric fractionation were evaluated (Fig. 54, right).

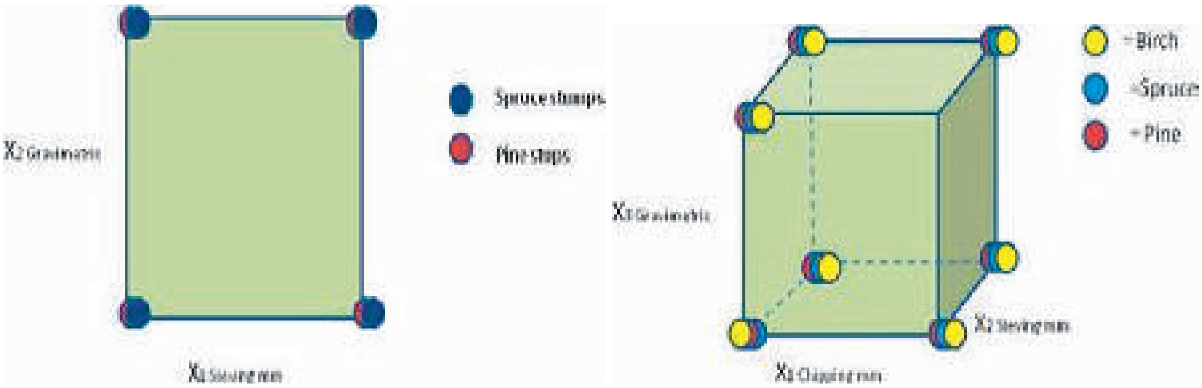


Figure 54. Schematic diagrams of the experimental designs for stump analysis (left), and small tree analysis (right).

Results & Conclusions

Ash content

Small particle size fractions of pine and spruce stumps are rich in ash, providing possibilities to reduce ash contents by sieving and reducing the finer fractions (Fig. 55). However, a major complication is that variations in ash contents are high, especially for stump material, which makes drawing general conclusions difficult and can cause downstream processing problems.

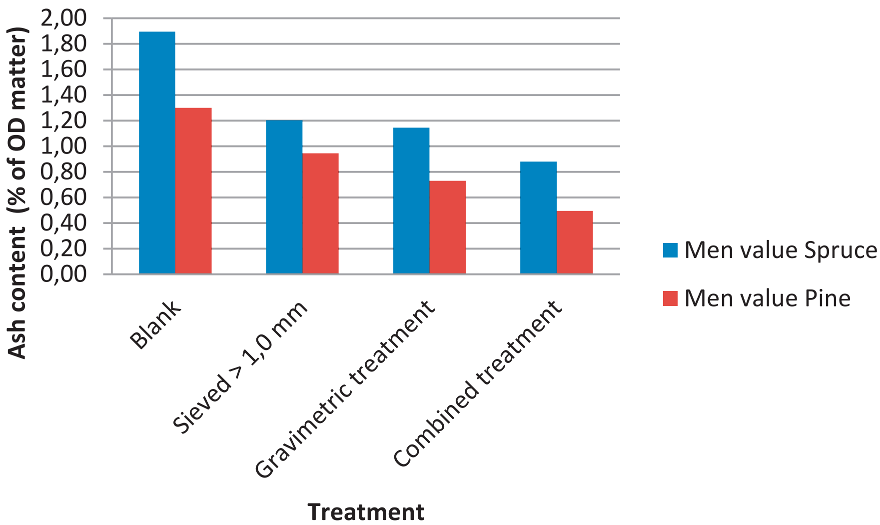


Figure 55. Ash contents in spruce and pine stumps after indicated fractionation treatments.

Extractives

The standard deviations of extractive contents in stumps are much lower than those of the ash contents (Fig. 56).

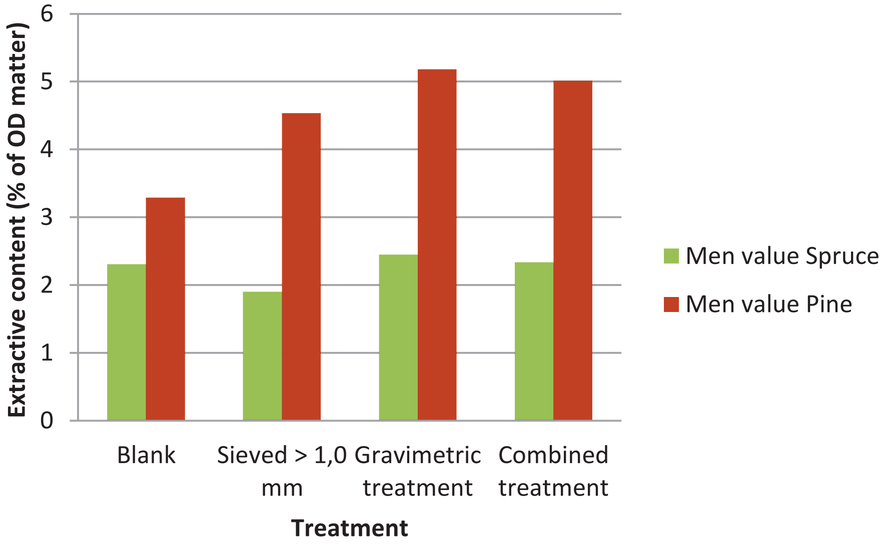


Figure 56. Extractive contents in spruce and pine stumps after indicated fractionation treatments

The ash contents of the samples of small spruce, pine and birch trees were low, but as in the case of stumps, the small particles (< 1.9 mm) were relatively ash-rich, indicating potential possibilities to reduce ash contents of harvested small trees by sieving and reducing the finer fractions in the same manner as for stumps. As shown in Figure 57, bark components of the small trees (especially spruce) were also much richer in ash than the stem wood.

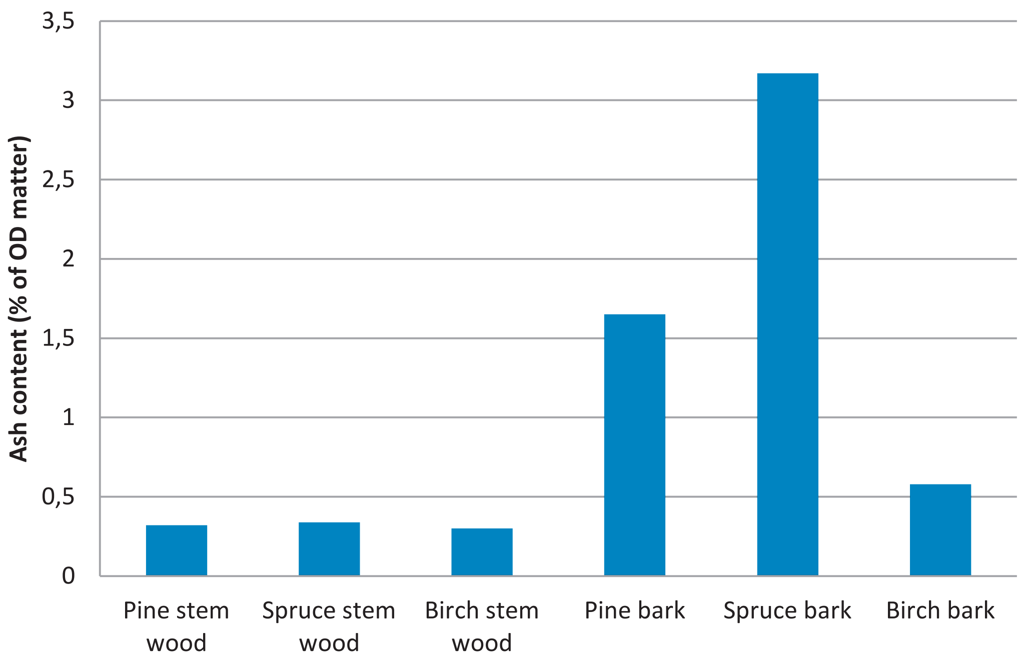


Figure 57. Ash contents of birch, pine and spruce stem wood and bark.

The bark fraction of spruce and pine trees also generally has much higher contents of extractives than their stem wood. As shown in Figures 58 and 59, extractives accounted for 5-6% and ca. 20% of the pine and birch bark DM, respectively. In control pine and spruce samples (chipped samples of small tree logs including bark), the extractive content was found to be 2-3%, and pure stem wood has even lower values.

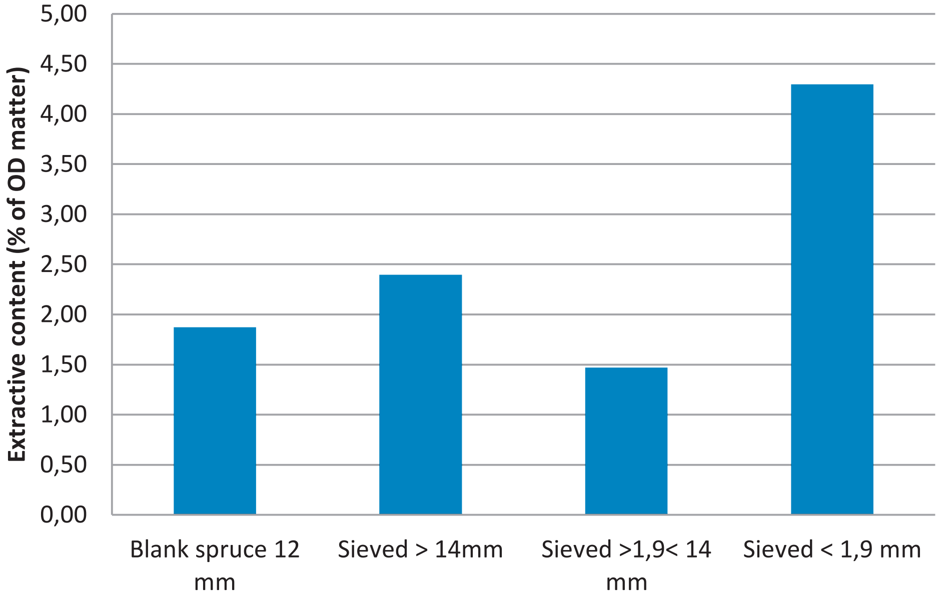


Figure 58. Extractive contents in small spruce trees after sieving.

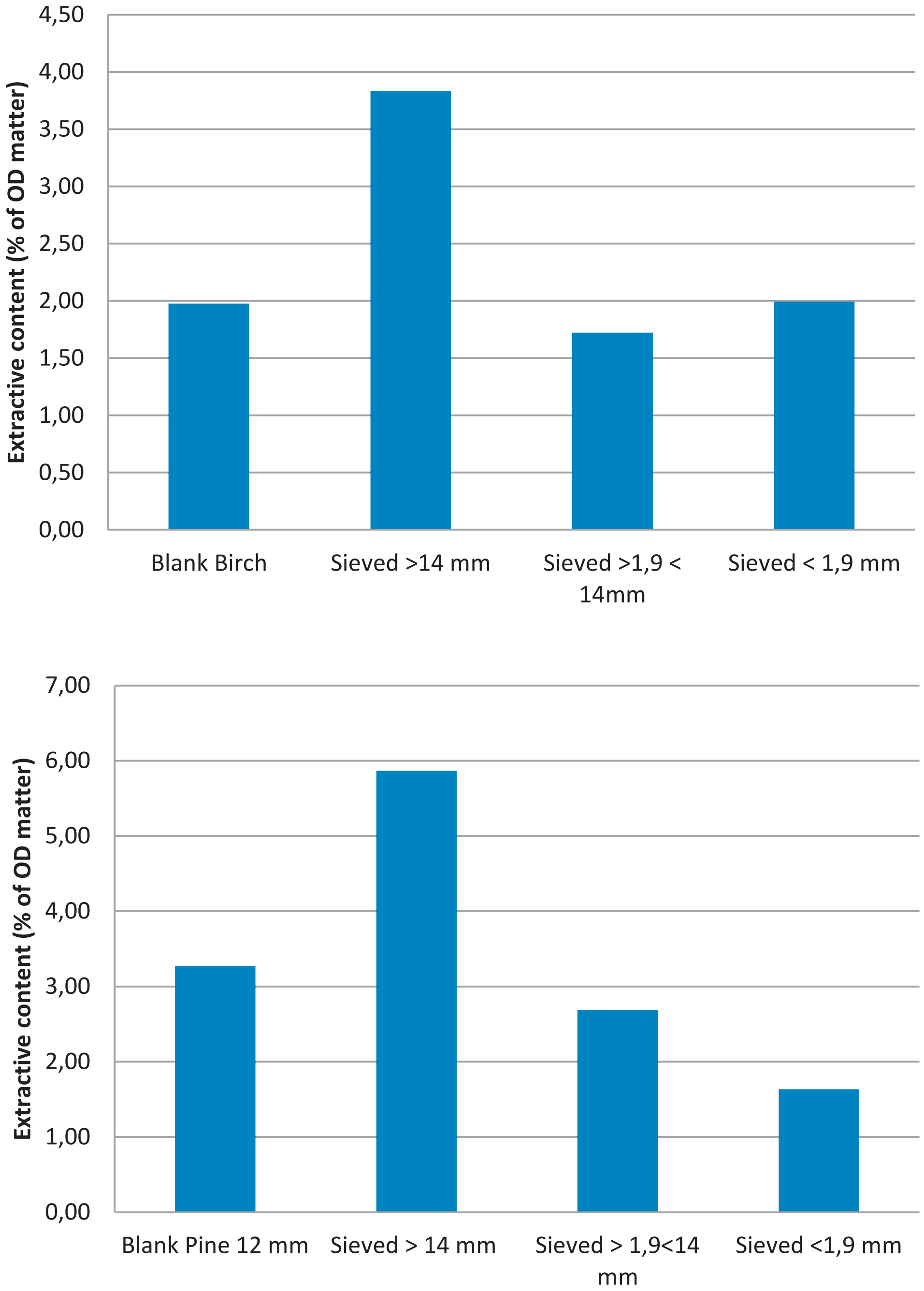


Figure 59. Extractive contents in small pine trees after sieving (lower panel), and small birch trees (upper panel) after sieving.

<u>Combined treatment effects</u>

When both methods of fractioning the material were applied there was a pronounced reduction in ash contents. Generally ash contents were lower in pine samples than in corresponding spruce samples (Fig. 60).

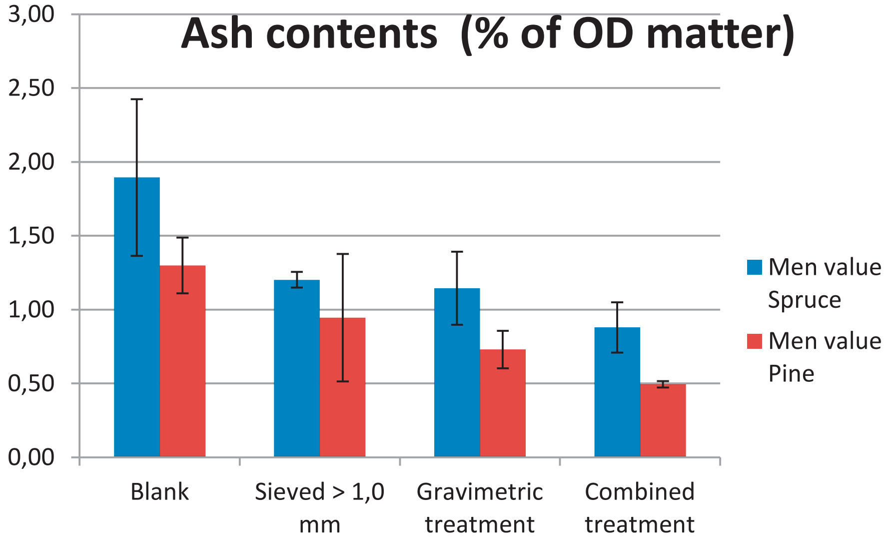


Figure 60. Ash contents in spruce and pine stumps after gravimetric and sieving treatment

The reported results show that sieving and fractionation of chipped small trees can reduce their extractive contents, due in large part to the reductions in amounts of small bark pieces.

As shown in Figure 61, the bark fractions had much high extractive contents (5-20%) than the stem wood of spruce and pine (2-3%). Clearly, an optimized combined sieving and fractioning process can lower the amount of extractives in the chipped material. The results clearly show that the mean ash and extractive contents were reduced by fractionation, but the standard deviations were too high for statistical significance. Thus, novel fractionation techniques are required.

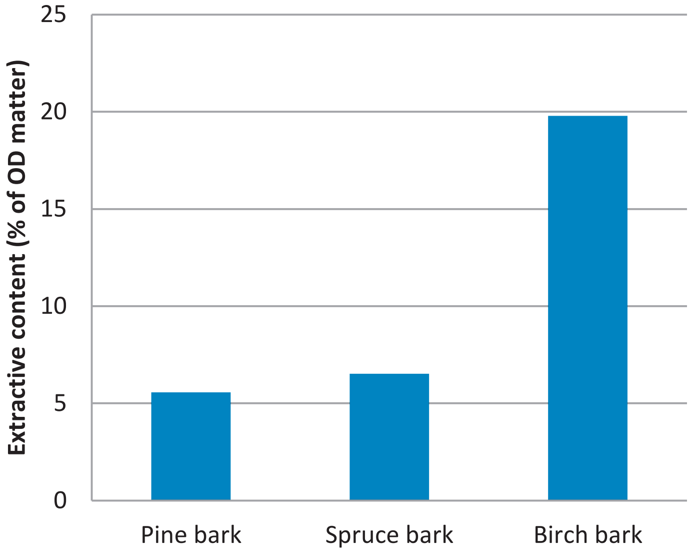


Figure 61. Extractive contents in pine, spruce and birch bark

Pre-treatment, hydrolysis and fermentation of stumps and small trees

Objectives

The objectives of this study were to evaluate techniques for pre-treating, hydrolyzing and fermenting forest biomass, specifically stumps and small trees.

Materials and methods

The raw materials tested were spruce stumps and small spruce trees from early thinnings (mean DBH and height: 8.7 cm and 8.6 m, respectively) harvested in the coastal area of Västerbotten, Sweden. The stumps were extracted a year after clear-cutting then stored for six months before analysis. The small trees were delimbed at the forest site then transported to the Biofuel Technology Centre in Umeå immediately after harvesting, and chipped within a month after harvest. The pretreatment and fermentation steps, described below, were conducted in the Biorefinery Demo Plant in Örnsköldsvik, Sweden.

<u>Pre-treatment</u>

A physicochemical pretreatment method (steam explosion) was initially applied, in which high temperature (215°C) incubation (ca. 5-10 min) at low pH (1.8-1.9) was used to transform the chopped wood into a slurry with high solids content (Fig. 62). For the small trees material, a flow of 70 kg (total weight, including water) per hour was added to the reactor. A set pH (1.8) was maintained by adding conc. sulfuric acid as required, and the total solids (DM) contents was kept at 28-29% by adding water. The generated slurry was collected in a collection tank below the reactor. The aim of the pretreatment was to reach a suspended solids (SS) content of at least 16% in the final slurry. The pretreatment was continued for about 5 hours, when all the raw material had been consumed. This slurry was subsequently hydrolyzed using enzymes and fermented into ethanol with a commercial yeast strain (*Saccharomyces cerevisiae*, Baker's yeast). Dilute acid hydrolysis is one of the most intensively studied pretreatments for softwood. However, a disadvantage is that it can generate several potent inhibitors of hydrolysis and fermentation processes, for example furan aldehydes, phenolic compounds and aliphatic acids, all of which are present in lignocellulose hydrolysates. Thus, in addition to providing effective pretreatment for subsequent hydrolysis, it is important to minimize formation of such degradation products during the procedure. The stump assortment had a higher dry solids content, thus it was fed into the reactor more slowly (40-45 kg total weight per hour). The water flow was increased at the start of the reaction and regulated during the experiment to keep the DM at 28-29%. The temperature and pH were set to similar values to those used for the small trees fraction. The raw material was consumed after about 5 hours. Slurry was filtered through a Munktell No. 5 filter in a Büchner funnel and both the filtrate and retentate were analyzed (monomeric sugar, organic acids, furfural and HMF and extractive contents for the filtrate, and mannan/glucan, lignin, ash and extractive contents for the retentate).

Figure 62. Pre-treatment set-up.

Hydrolysis and fermentation
A first hydrolysis experiment was performed in a 2.5-L Erlenmeyer flask with a total volume of 500 mL. The slurry concentration in the experiment was 12% SS, and the enzyme concentration was 12% (w/w SS). The slurry was hydrolyzed at 50°C with a starting pH of 5.2, and an agitation speed of 160 rpm (Kuhner shaker LT-X) for 70 h. The pH was not regulated during the enzymatic hydrolysis. The yeast used for the first bench-scale fermentation experiments was Baker's yeast. Two 2.5-L Erlenmeyer flasks, each containing 650 ml of YPD (10 g/L yeast extract, 20 g/L peptone, 10 g/L glucose), were inoculated with yeast from a culture plate (with YPD-agar) and grown overnight at 30°C and agitation at 150 RPM. We also attempted to counteract the inhitory effects of compounds that are known to be present in spruce pretreated by steam explosion with an acid catalyst by two strategies: increasing the magnitude of the yeast inoculum (up to 4.5 g/L), or detoxifying the slurry by adding 15 mM sodium dithionite (room temperature, 5 min). A nutrient solution was also added to the fermentation medium to final concentrations of 3 g/L yeast extract, containing 1.5g/L $(NH_4)_2SO_4$, 0.075 g/L $MgSO_4$*$7H_2O$, and 4.77 g/L KH_2PO_4. The yeast was grown at a pH of 5.5 and was not controlled further during the fermentation. Glucose consumption was followed with a glucometer (Bayer Glucometer Elite XL) and the experiment was stopped after 44 h. Final samples were collected for measuring ethanol production and sugar consumption. A second fermentation experiment was performed on stump hydrolysate which was diluted with water prior to fermentation (25, 50, and 75% hydrolysate conc.). The hydrolysate was also detoxified before fermentation (15 mM sodium dithionite, 5 min at room temperature) and the medium, including the nutrient solution described above, was inoculated with 5 g/L dry yeast (Ethanol Red, Fermentis). A final sample was collected after 17 h for measuring ethanol production and sugar consumption.

Bench- and pilot-scale SSF
The yeast used for the simultaneous bench-scale saccharification and fermentation (SSF) experiment was Baker's yeast and the dry yeast used for the pilot-scale experiment was Ethanol Red (Fermentis). The bench-scale experiment was started with a saccharification step in which slurry (100 g, 15% SS), from small trees, detoxified with 15 mM sodium dithionite, was mixed with enzyme (final conc. 12%-w/w) in a 250-mL Erlenmeyer flask with baffles and placed in a shake incubator at 50°C and 150 RPM. After 48 h, the incubator temperature was decreased to 35°C and yeast (and nutrient solution) was added to final concentrations of 2, 5, and 7.5 g/L to start the fermentation. Sugar production and consumption were monitored with a glucometer throughout the experiment and final samples were collected for measuring ethanol production and sugar consumption. The suspended solids concentration was modified to 12.5%

for the pilot-scale experiments. The experiments were performed in a 50-L bioreactor (Belach Bioteknik AB). Slurry (from small trees) mixed with water was detoxified in the reactor (15 mM sodium dithionite, 10 min, 25°C) and the pH was set to 5.2 before adding enzyme (12%-w/w). The mixture was incubated for 22 h to allow saccharification before the addition of yeast and nutrient solution. Dry yeast (Ethanol Red, Fermentis) was rehydrated in sterile water at 35°C for 30 min without shaking (250 g yeast + 1250 g water, final concentration in the reactor 5 g/L) prior to inoculation. For the fermentation step the reactor temperature, pH and stirring speed were to 35°C, 5.3 and 200 RPM (output 100 RPM), and after 41 h the ethanol production and sugar consumption were measured. A similar protocol was applied in the pilot-scale SSF experiment with stumps, except that the duration of the saccharification step was 25 h, and since the stumps slurry was more toxic, a second addition of yeast (5 g/L) was needed to start the fermentation.

Analyses

Samples for final sugar concentration determinations were collected throughout the experiments and sent to MoRe Research Örnsköldsvik AB for analyses. Measurements of concentrations of sugar, organic acids, furan, lignin, glucan, mannan, ash, and extractives in the slurry after pretreatment were also performed by MoRe. The concentration of ethanol in the samples was measured using an enzymatic ethanol kit from Roche Diagnostics.

Results & Conclusion

After the final volume of the raw material had passed through the reactor, the material was homogenized by recirculation overnight within the system. About 150 L of slurry was removed from the collection tank for hydrolysis and fermentation experiments. The SS target (>16%) was reached for both fractions (Table 22). At this SS concentration it should be possible to achieve an ethanol concentration of about 40 g/L (4%). Table 23 shows results of analyses of the slurry (both filtrate and retentate) from the two fractions. A high sugar concentration after pretreatment was obtained from the small trees fraction (70 g/L dissolved monomeric sugar), and the stumps fraction yielded ca. 35 g/L monomeric sugar. The high sugar concentrations indicated that the pretreatment was harsh, and this is also shown by the high concentrations of the degradation products furfural and hydroxymethyl furfural (HMF, see Table 22). Most of the hemicellulose was solubilized in the pretreatment step since concentrations of mannose, arabinose, galactose and xylose were low in the solids fraction after filtration.

Table 22. Dry mass (DM) and suspended solids (SS) contents after pretreatment.

Raw material	DM (%)	SS (%)
Small trees	24.0	16.5
Stumps	22.1	16.2

Table23. Contents of measured compounds in the filtered slurry after pretreatment.

	Extractives	Arabinose	Galactose	Glucose	Xylose	Mannose	Furfural	HMF	Formic acid	Acetic acid	Levulinic acid
Filtrate	(g/kg)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)
Small trees	5.4	2.8	7.8	30.5	9.2	19.5	2.4	4.5	1.9	6.1	2.1
Stumps	5.0	0.7	3.7	22.1	2.5	6.7	2.7	8.5	2.4	5.4	3.6
	Ash	**Extractives**	**Lignin**	**Arabinose**	**Galactose**	**Xylose**	**Glucose**	**Mannose**			
Solids	(%)*	(%)*	(%)*	(g/OD kg)	(g/OD kg)	(g/OD kg)	(g/OD kg)	(g/OD kg)			
Small trees	0.2	13.3	50.2	0.9	2.4	5.1	432.0	7.8			
Stumps	1.1	18.7	58.7	<0.2	0.5	1.3	363.0	1.7			

*dry basis.

Small-scale hydrolysis and fermentation

The slurry was diluted to 12% SS (from ~16%) and the hydrolysis was allowed to continue for 70 h, after which the total sugar concentration was 84.8 and 59.3 g/L for the small tree and stump preparations, respectively (Table 24). The material that was not liquefied during hydrolysis was removed by filtration and the liquid filtrate was used in the following small-scale fermentation experiments. In the enzymatic hydrolysis step, we only observed conversion of cellulose into monomeric glucose, from 26.4 g/L to 57.3 g/L for the small tree samples and from 20.5 g/L to 50.3 g/L for the stump samples (Table 24).

Table 24. Concentrations of monomeric sugars before and after hydrolyzation.

		Arabinose	Galaktose	Glucose	Xylose	Mannose	Total sugar
Material		(g/L)	(g/L)	(g/L)	(g/L)	(g/L)	(g/L)
Small trees	Before	1,8	4,8	26,4	6,0	13,0	52,1
Small trees	After	1,9	5,4	57,3	6,3	14,0	84,8
Stumps	Before	0,5	2,3	20,5	1,8	4,8	29,9
Stumps	After	0,6	2,3	50,3	1,7	4,4	59,3

Results of the two experiments in which yeast was incubated with non-detoxified hydrolysate of small trees were poor, even when a larger inoculum was used (4.5 g/L). With the 4.5 g/L inoculum the yeast consumed sugar, but slowly and only produced 8.2 g/L ethanol after 44 h fermentation. This indicates that the material was toxic to the yeast and increasing the inoculum size was not sufficient to induce robust fermentation. The fermentation experiments with the stumps' hydrolysate (96%, including inoculum and nutrient) were unsuccessful since the yeast consumed almost no sugar during 44 h, probably due to death of the cells (data not shown). A minimal amount of ethanol (4.0 g/L) was produced with the detoxified material. The yeast did not consume any glucose in the non-detoxified stumps material. However, when the stumps' hydrolysate was diluted with water and detoxified with sodium dithionite, and a different yeast strain was used, the yeast survived and performed very well: all sugar was consumed after 17 h and at 75% hydrolysate concentration (43.4 /L sugar consumed) 22.0 g/L of ethanol was produced. It could not be deduced if the reason for the efficient fermentation was dilution of the hydrolysate, the change in yeast strain, or both.

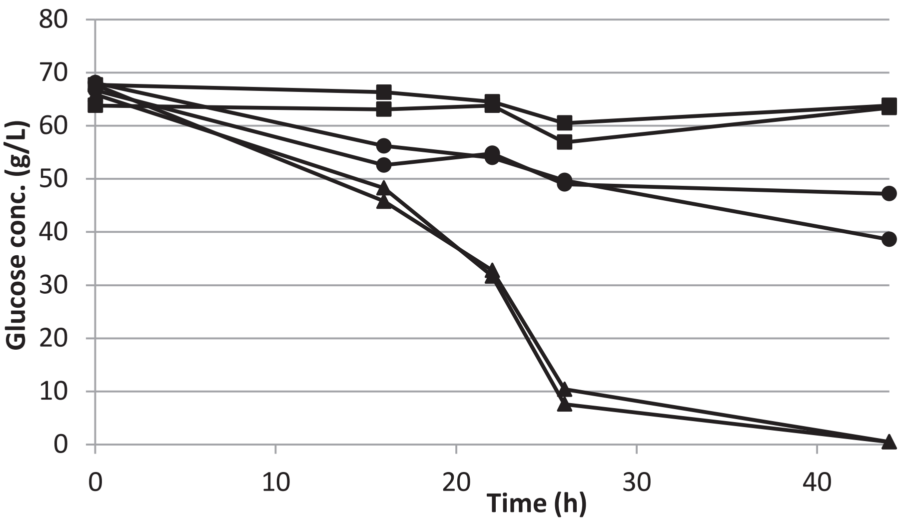


Figure 63. Glucose concentrations during the time courses of duplicate fermentation experiments with the small trees fraction and: no detoxification with 2 g yeast/L inoculum (■); no detoxification and 5 g yeast/L inoculum (●); and detoxification with 2 g yeast/L inoculum.

Bench- and pilot-scale SSF

A bench-scale SSF experiment was performed with the small trees fraction. The material, with high starting suspended solids content (15%), was detoxified and incubated with enzymes to degrade it for 48 h before adding yeast. Monomeric sugar was produced, but the material was too toxic for the yeast to survive and use the sugars for ethanol production. No significant reduction in sugar content was observed after 48 h fermentation (data not shown). Therefore, a lower solids load (12.5%) was used in the SSF experiments in the 50-L fermenter. Two SSF experiments were performed in the 50-L fermenter, one for each raw material. As in the bench-scale experiments, the materials were allowed to saccharify before inoculation with yeast. Sugar production and consumption of the small trees fraction was monitored throughout the whole experiment (Fig. 64A) and ethanol production was measured at five points during the experiment (after 15, 40, 43, 50, and 63 h, Table 25). The highest ethanol concentration measured during the small trees fraction experiment was 29.5 g/L. The stump slurry was more toxic than the small trees' slurry, since a second addition of yeast was needed for growth and both sugar consumption (Fig. 64B) and ethanol production (Table 25).

Table 25. Ethanol concentrations during SSF in the bioreactor. Indicated times are times after start of the experiment.

	Time (h)	**Ethanol concentration (%)**
Small trees	15	0,8
	40	25,5
	43	29,4
	50	29,4
	63	29,5
Stumps	25	1,6
	42	4,4
	47	5,0
	48	5,4
	56	12,1

About 10 g/L of dry yeast was added to the fermentor for the fermentation of the stump hydrolysate: ca. 5-fold too high for economically viable commercial use. Another general threshold for economic viability is that an ethanol concentration of at least 4% (40 g/L) is required for the distillation step. This was not reached in this study, but it should be attainable using these assortments following optimization of some parameters, e.g. use of a yeast strain that is more resistant to toxic compounds at higher solids loads or adjustment of pretreatment methods to reduce concentrations of toxic compounds.

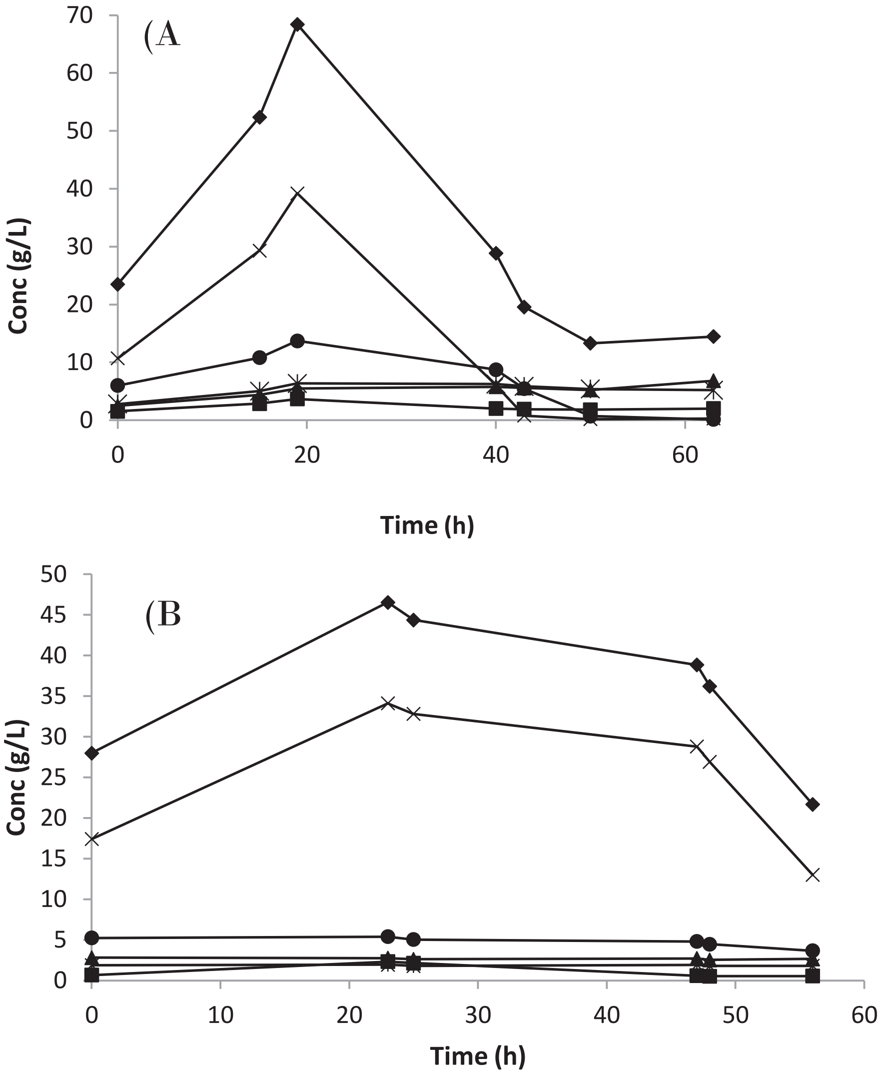


Figure 64. Sugar production and consumption during the pilot-scale SSF experiment: total monomeric sugar (♦), glucose (X), mannose (●), xylose (*), galactose (▲), and arabinose (■). The enzymes hydrolysed the material and, for (A) small trees, the yeast was added after 22 h and started to consume the produced monomeric sugar molecules. For the stumps assortment a first batch of yeast was added after 25 h and another batch 48 h after the experiment was started. The apparent sugar consumption soon after the inoculations is most likely due to a dilution effect.

In summary, liquid slurries of both the stumps assortment and small trees fraction were successfully generated by the pretreatment in the Biorefinery Demo Plant, Örnsköldsvik, Sweden. The volume of the starting material was limited and a larger quantity of material might have improved the performance. The slurries obtained from both assortments were relatively easy to hydrolyze at decreased suspended solids contents (SS=10-12%), and 12.5% SS was also used in the pilot-scale SSF experiments. Ethanol production reached almost 3% and 1.2% for the small tree and stump preparations, respectively, which are encouraging results for an initial experiment with new raw material. Toxicity reduces the potential utility of these assortments in commercial biorefineries, at least without optimization, since a high yeast inoculum and decreased solids content was needed to stimulate growth of the cells. Nevertheless, the results indicate that commercially viable production of bioethanol using both tree stumps and small trees as raw material should be feasible following optimization of the pretreatment, detoxification, saccharification and fermentation protocols.

Systems analyses and energy balances for biorefinery supply chains including handling and transport of upgraded and sorted material to industrial sites

Objectives

The objective of this study was to calculate supply curves for novel assortments from the forest to potential biorefineries located in the cities of Storuman, Umeå and Örnsköldsvik in order to demonstrate the amount of feedstock that can be offered to the market at a given market price.

Materials and methods

The selected approach was to divide the supply chains into operations and model the cost and energy use for each operation: harvesting, forwarding, transportation, feedstock processing at terminals and delivery to the potential biorefinery. The focus was on innovative systems for integrated harvests of stem wood and residual biomass (such as tops, branches and stumps), which were compared to the currently conventional system in the focal region, where stem wood and residual assortments are separated at the forest site and handled in separate supply chains.

<u>Supply curves</u>

A supply curve illustrates the relation between the market price and amount of a product offered to the market. According to conventional economic theory, the market price of a product is a result of the interaction between supply and demand. In this context, supply is the amount of the product that is offered to the market as a function of the market price, as illustrated in Figure 65. A smaller quantity (Q1) of the product can be expected to be offered to the market if the market price is low (P1), while a larger quantity (Q2) can be offered to the market if the price is high (P2), all other conditions being equal. Similarly, the demand describes the amount of the product that customers desire and are willing to purchase as a function of the market price. At a low market price, the demanded quantity can be expected to be bigger than at a high market price.

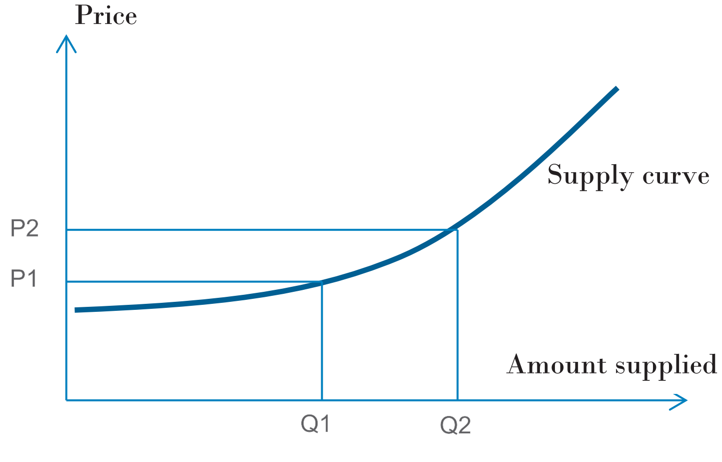


Figure 65. Schematic illustration of a supply curve

Supply curves were created for three locations: Storuman, Umeå and Örnsköldsvik and included forest biomass supply from areas within a radius of 120 km around each of the three locations. The cost information was combined with data on the available forest resource amounts and geographical distributions of the feedstock derived from the NFI for the study region. We focused on estimating supply curves for novel assortments obtained by modification of forest operations and/or forestry regimes (Fig. 66 & Table 26). At the same time we calculated supply curves for conventional assortments, such as pulpwood, logging residues and stumps obtained via conventional forest operations and conventional forest management (Fig. 66 & Table 26). In conventional Nordic forestry, harvesting is performed according to a cut-to-length system, where the trees are delimbed into the forest with a single-grip harvester and the stems are cut into logs of appropriate length at the harvest site. The logging residues (tree-tops and branches) can be collected with a forwarder after the harvesting in a separate operation. An alternative to using separate supply chains for stem-wood and residual biomass is to use systems that integrate the assortments at the harvesting site. Here, we consider two assortments from such integrated harvesting operations: rough-delimbed tree sections from first thinnings (stems with 50% of branches' mass still attached, cut into 5-6 m long sections) and long tops from second thinnings and final fellings (parts of the stems suitable for pulpwood with the branches and tops still attached). In this integrated supply, pulpwood logs can be separated from the residual biomass (branches and tops) in a terminal close to the industrial destination by means of a chain-flail delimber-debarker.

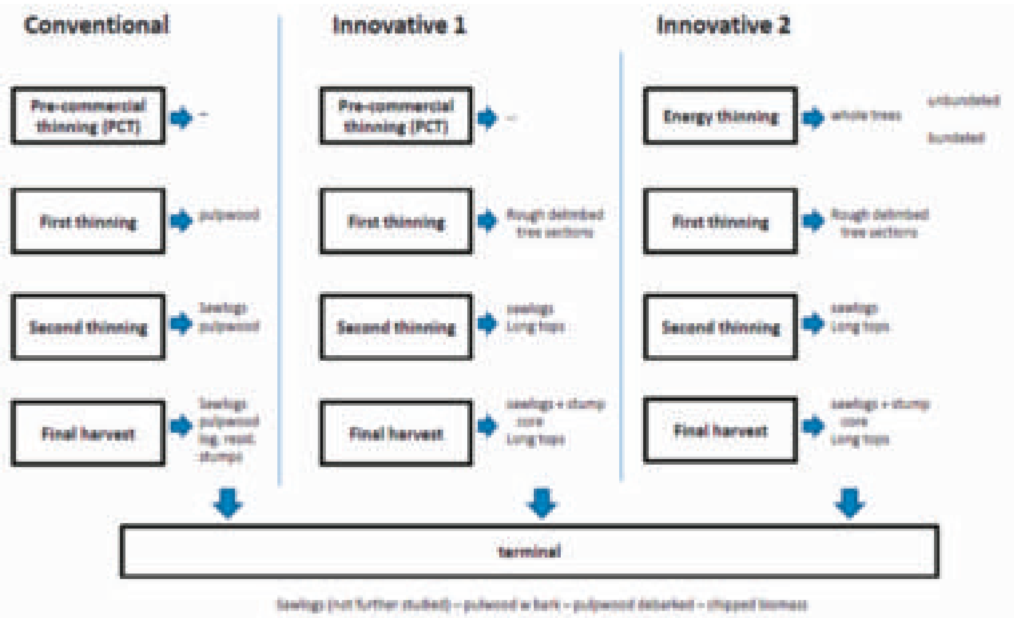


Figure 66. Studied forestry regimes, operations and assortments

Table 26. Description of conventional and novel assortments considered in the analyses.

Conventional (reference) assortments	**Novel assortments**
Pulpwood from first, second thinnings and final fellings (logs with a minimum top diameter of 5 cm under bark) Logging residues from final fellings (branches and tops) Stumps from final fellings (obtained in a conventional separate stump harvest)	Rough-delimbed tree sections from first thinnings (stemwood including 50% of branches mass) Long tops from second thinnings and final fellings (stem wood with a diameter < 12 cm including branches). Stump cores harvested together with saw logs in final fellings. Small whole trees from early thinnings (stem wood including all branches)

Results & Conclusions

<u>Energy thinning whole trees</u>

Figure 67 shows the supply curves obtained for whole trees from early energy thinnings, handled loose or bundled at the harvesting site. The harvested amounts are about 80 000 OD t/year for all three considered locations. Supply costs are markedly lower for the alternative including bundling of the trees at the harvest site (typically less than 800 SEK/OD t) than the alternative in which the trees are handled loose (typically around or more than 800 SEK/OD t). Energy use is also lower for the bundling alternative, by a little less than 1%, and lies around 2-3% of the energy content of the delivered feedstock.

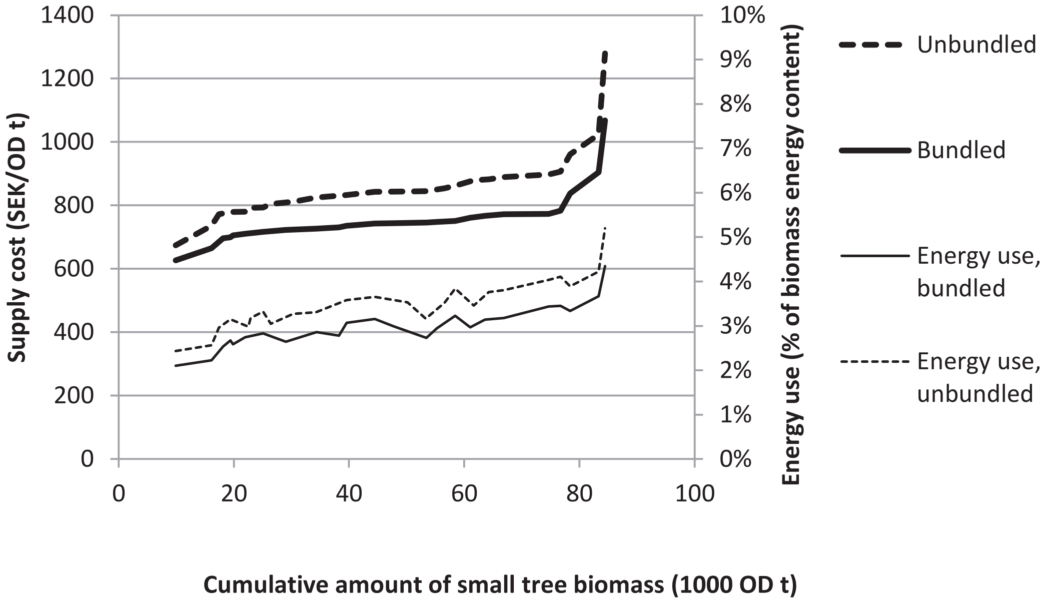


Figure 67. Supply cost and energy use for whole trees from energy thinnings, with and without bundling. (Calculations based on the Örnsköldsvik case study).

<u>Stumps</u>
Figure 68 shows the supply curves obtained for the innovative stump core harvesting integrated with the saw logs supply compared to the conventional separate stump harvesting. The stump core supply costs and energy uses are calculated as the additional costs and energy use required for stump core extraction compared to the same operations with no extraction of stump biomass. In the stump core harvest, only about 20% of the stump biomass is recovered compared to conventional stump harvests, since the available amounts within the 120 km supply radius are much smaller (ca. 100 000 OD t/year). However, the supply cost and energy use per OD t for a given harvesting site is significantly lower for stump core harvesting than for conventional separate stump harvesting. Supply costs for stump core harvesting are ca. 800 SEK/OD t, while those for conventional stump harvesting are ca. 900-1200 SEK/OD t. Energy use is between 2-3% of feedstock energy content with the innovative supply system and 4-6% with conventional stump harvesting.

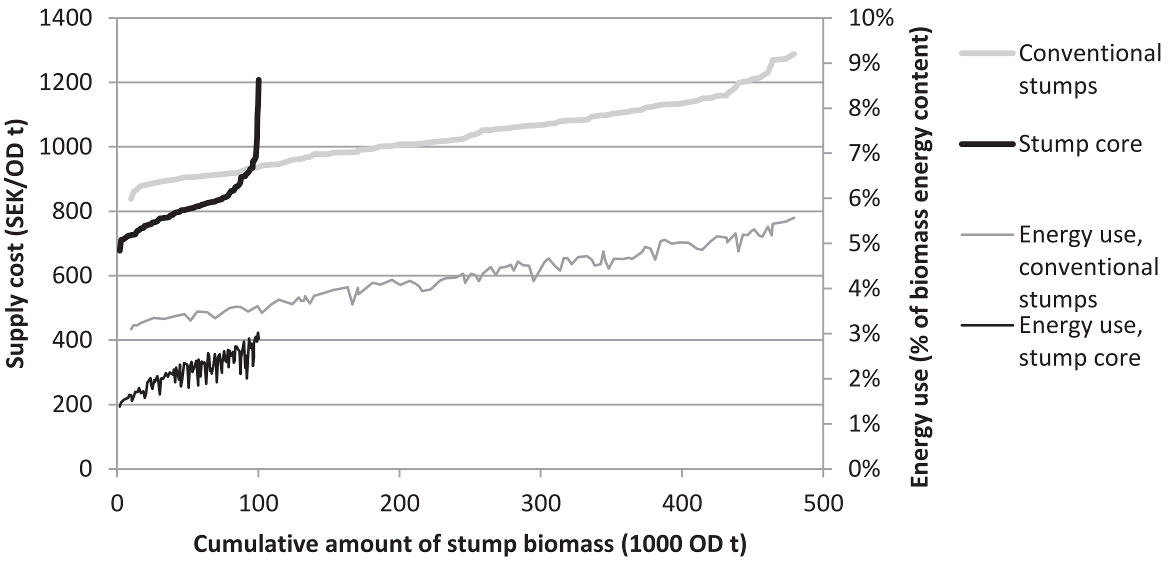


Figure 68. Supply costs for stump core harvest compared to those for conventional stump harvesting. (Calculations based on the Örnsköldsvik case study).

Figure 69 shows the supply cost curves and energy use for delivering residual assortments from rough-delimbed tree sections from 1st thinnings and long tops from 2nd thinnings and final fellings to the potential biorefinery. The tops and branches are separated from pulpwood logs at a terminal close to the industrial plant and the residual fraction is chipped. The costs and energy use are calculated as the difference between the total cost for handling rough delimbed tree sections and long tops, including the delivery of pulpwood and residues, and the costs for delivering only pulpwood with conventional harvesting methods. Hence, the curves for tree sections and long tops in Figure 69 represent the additional costs and energy use for acquiring the residual assortments. The curves for a conventional supply of logging residues from final fellings are shown as references.

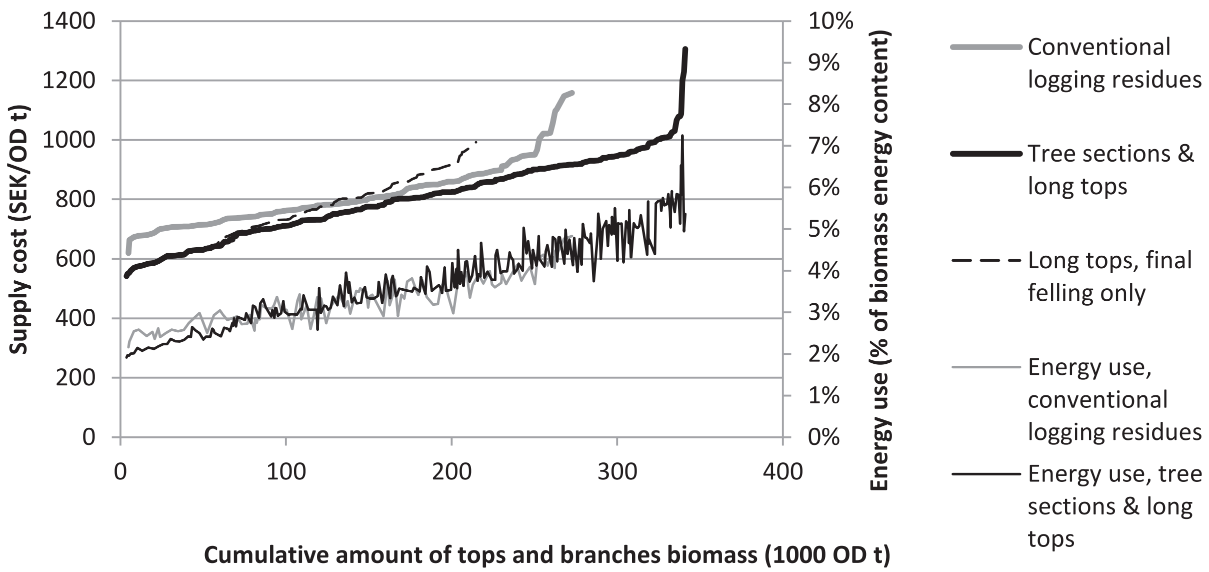


Figure 69. Supply cost and energy use for residual biomass from harvests of rough delimbed tree sections (at first thinning) and long tops (at second thinning and final felling) compared to conventional logging residue recovery (at final felling). (Calculations based on the Örnsköldsvik case study).

The supplied amounts are ranked by increasing supply cost, thus the supply cost curve forms a smooth, increasing line. The energy use is not exactly correlated to the supply cost and hence shows a rugged curve. However, it follows the same general trend, indicating that the more expensive parts of the supply also require more energy to acquire. The supply cost curves for the innovative assortments are generally below the curve for conventional logging residues; a significantly larger amount of residues can be potentially mobilized from the innovative systems when considering thinnings and final fellings together, instead in the conventional case logging residues are considered to be harvested in final fellings only. The dashed black curve in Figure 69 shows the supply cost for residual biomass from long tops harvested in final fellings only. This curve is initially lower than the one for the logging residues from the conventional system, but it has a steeper increase in costs, and lies above the conventional system curve towards the end. The energy use curves are similar for the conventional and innovative systems. They show the same general increasing trend as the cost curves, ranging from ca. 2% to about 8% of biomass energy content. The main part of the energy curves, however, stretch between 2% and 6%, which corresponds to 10-30 L of diesel used per OD t of biomass delivered.

Figure 70 shows results for the innovative system (grey curves) when chipping the tree sections and long tops (stem wood and residual biomass) together without prior delimbing-debarking at a terminal. In the conventional case (black curves) un-barked pulpwood and logging residues are considered both to be chipped and delivered as a joint assortment. The supply cost for all chipped feedstock lies mainly in the range of 700-1000 SEK/OD t. In this case, the innovative system has markedly lower supply costs per OD t biomass than the conventional one. Energy use figures lie around 2-4% of biomass energy content. The variation of the energy use is larger for the conventional case, which could be expected, since pulpwood and logging residues are handled independently and require different amounts of energy, whereas in the innovative system the stem wood and residual biomass are handled together.

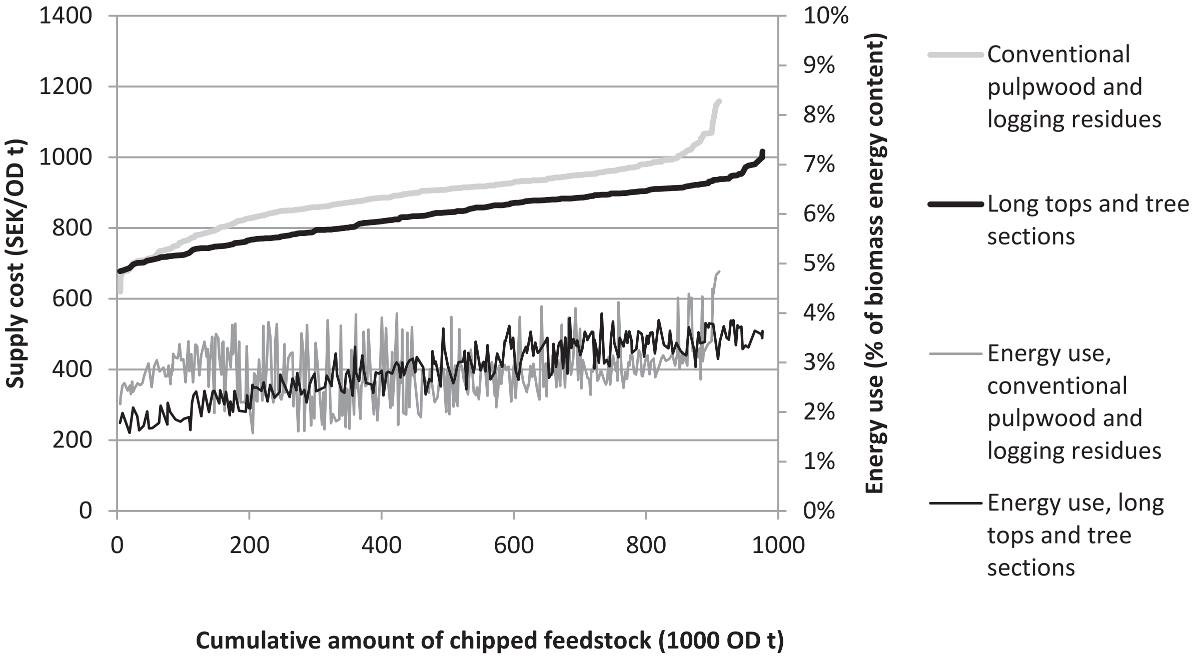


Figure 70. Supply cost and energy use for chipped feedstock with conventional systems and innovative systems when stem wood, tops and branches are all chipped together. (Calculations based on the Örnsköldsvik case study).

Figure 71 shows the supply cost curves obtained for chipped tree sections and long tops for the three locations. The characteristics of the supply cost and energy use curves are similar for Umeå, Örnsköldsvik and Storuman. The main differences are in the total amount of feedstock available within the studied 120 km radius, i.e. residual biomass from long tops and tree sections (274 000, 341 000 and 203 000 OD t/year for Umeå, Örnsköldsvik and Storuman, respectively).

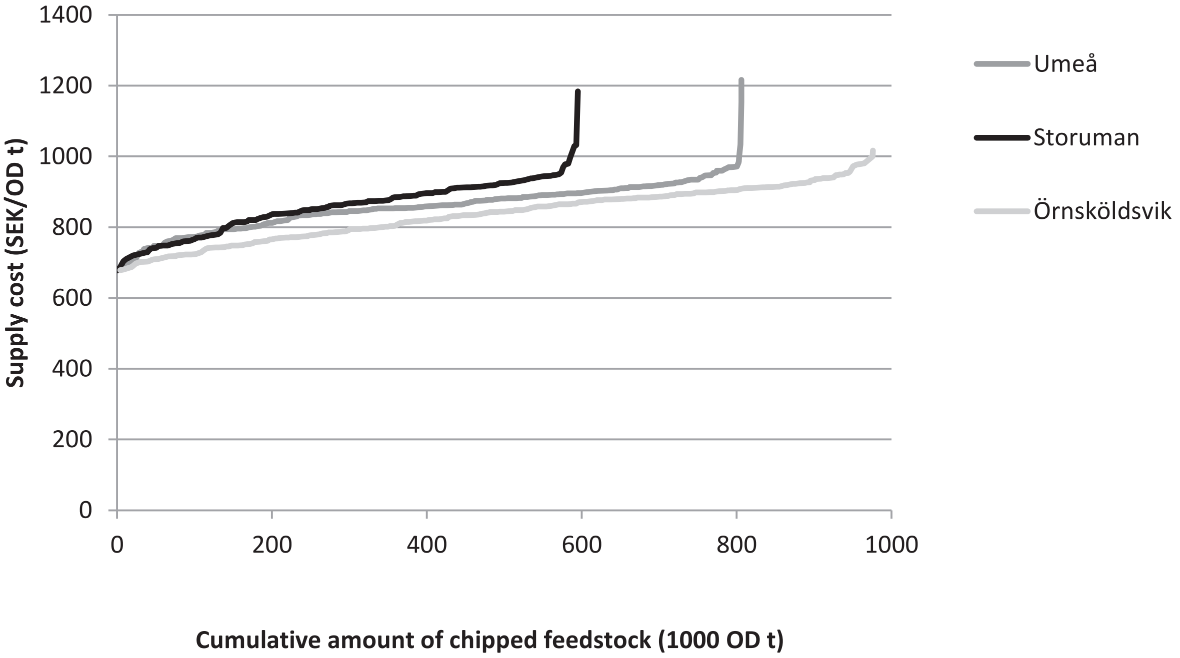


Figure 71. Supply costs for chipped feedstock with innovative systems when stem wood, tops and branches are all chipped together. Comparison of results for the three considered locations.

The results of this study clearly indicate that the supply cost of forest biomass assortments can be potentially increased by integrated harvests of stem-wood and residual assortments. For long tops and tree sections, the reductions are more pronounced when the final product is chipped biomass and no difference is made between stem-wood and residues. This is because the long tops and tree sections can be fed directly to a chipper, omitting a costly delimbing process. This, however, does not take into account the possible benefit of being able to deliver stem-wood chips and residue chips as separate assortments, which is feasible in the conventional system, but not in the innovative sytem. Typically, stemwood chips would have a higher value than chipped residues. Stump core harvest only recovers about 20% of the total stump biomass, but at considerably lower cost, on a per OD t basis, than conventional stump harvest, according to our results. The stump core biomass can also be expected to be much cleaner than conventionally harvested stump wood, which is typically contaminated with dirt, sand and rocks. The stump core harvest system is probably the least developed of the studied systems, and the calculations therefore carry large uncertainties. The low production cost is, partly, a result of the integration of the stump core handling into the conventional saw log supply chain. The results indicate that stump cores can constitute a competitive biomass assortment if this integration can be successfully implemented. Early energy thinning is not commonly practiced today. It is thus a new measure suggested to be performed at a point in time between the time when a conventional PCT is typically performed and the time for the first commercial thinning. Our results indicate that small trees could be recovered from energy thinnings at an attractive cost, compared to conventional logging residues. Bundling of the trees at the harvest site reduced the overall costs for the energy thinning assortment. In conventional PCT, no wood is recovered and the PCT therefore represents a cost to the forest owner with no direct income. If the energy thinning replaces the PCT – fully or partly – this would result in reduced PCT costs for the forest owner. This was not considered in the present study. Allocating the avoided PCT costs to the energy thinning would substantially improve its economics. The geographical area considered was limited to a 120 km radius around each of the three locations. For the coastal locations, the sea covers about half of this area. For the inland location, most of the area is composed of land, hence the total land area covered in the study is much larger for this location than the costal locations. Somewhat surprisingly, the inland location yielded the smallest feedstock amounts. There may be several reasons for this. Firstly, part of the inland area falls in a mountainous region, with little or no forest growth. Secondly, the forest growth is much slower in the inland regions than in the coastal area, so the productivity of the forest is lower. Thirdly, there may be differences in forest age structure between the three areas.

Energy use and supply cost are fairly well, but not entirely, correlated. This is not surprising, since the operation of machines is a main factor in both supply cost and energy use. Almost all energy used in the operations is in the form of diesel. The amount of energy used corresponds to approximately 2-6% of the energy content of the delivered wood feedstock. For the innovative supply systems and when all material is chipped without prior separation, the corresponding energy use is about 2-4%. These numbers are in relatively good agreement with other studies of supply chain energy use.

Discussion

The raw material quality demands of future forest biorefineries are likely to differ from those of traditional forest industries and energy plants. Biorefinery-related R&D is currently intense in Finland and Sweden, but commercial-scale demonstration projects for new technologies are lacking (see Table 20). Ongoing EU programs providing investment support and other developmental incentives are likely to play key roles in overcoming barriers and driving advances, which should stimulate increases in demand for residual forest biomasses. There are vast forest biomass resources in Sweden and Finland, and it is known that annual forest increments substantially exceed demands of existing forest industries (sawmills, pulp mills, heating plants and pellet mills). Thus, there is scope to build new biorefineries without risking shortages of forest biomass. In the extremely long term such shortages might arise, if both types of industries grow, but for the foreseeable future new biorefineries and existing forest industries could co-exist. Additional resources can also be harvested from marginal lands, e.g. forest roadsides, power-line corridors and reforested agriculture lands. Nevertheless, emerging biorefineries will have to face competition for different forest biomass assortments from existing end-users. The interactions involved are highly complex and difficult to predict, but equally important to address.

It is realized that competition will have a significant impact on all forest biomass end users, but this is only briefly discussed in this report. Timber for saw milling is the most expensive assortment today and will provoke most competition. However, it is important to remember that half of the volume that is delivered to a sawmill will consist of process by-products of high interest for biorefineries (e.g. fractions of sawdust, shavings, and bark divided by species, e.g. pine and spruce). Well-defined and clean assortments like pulpwood and sawmill by-products will be of high interest for many processes instead of being used for e.g. heat and power production. Competition is also highly regional and may result in different supply patterns in different regions. The regional focus on the Botnia-Atlantica (BA) program limits the raw material mapping here to a rather small geographical area. This is especially pronounced in Finland. To obtain a more comprehensive picture, it would be of great interest to expand the mapping to cover the whole of Sweden and Finland when discussing future BA markets.

Currently the tree- and wood components that will be required by the biorefinery industry are uncertain. However, this project has provided important knowledge of the supply chain management for future biorefineries, and can be used when developing plant-specific (Table 21) supply chains in which factors such as demand for raw material volumes and qualities, possible raw material surpluses that could be used, harvesting and transportation costs of conventional and innovative systems, effects of storage on the chemical composition of various assortments, possible comminution, fractionation and sorting methods, and the chemical composition and fermentability of different fractions.

In the future, emerging forest bio-refineries may demand other parts of the tree than stem wood. This may influence the supply chain so that the whole tree including branches is harvested and cut into tree sections and then possibly compressed and bundled before transportation. During harvesting operations the most profitable assortments will be produced, regardless of the industrial end user. This means that most harvesting activities will be integrated (harvesting all possible assortments at the same time) and the current system, including (for instance) procurement of logging residues as a separate operation, will be less common, or disappear. Large diameter tree sections, small diameter trees and stumps can all be transported to terminals for fractionation and sorting into several assortments to suit both new and traditional end users' quality demands. However, such developments also require better possibilities to store, handle and transport forest biomass. Demands for raw material will probably differ over time and between types of industry, making terminal nodes more important than today. This approach has several logistical advantages and terminals will probably be more efficient (in cost and energy consumption terms) than current practices.

Supply systems for small diameter trees from early thinnings, and unused pulpwood from commercial thinnings, have particularly strong potential for development in the BA region (Figs. 12 & 15). For example, debarked stemwood could be directed to fermentation industries while the bark and branch fractions could be directed to chemical extraction industries. Studies reported here show that such fractionation could be done highly productively with a chain flail debarker at terminals (Table 18), but at high costs due to the use of insufficiently developed technologies (Fig. 37). According to the industry, processes can be developed to handle different feedstock-related problems (Table 21). However, variation in feedstock properties can be more difficult to handle. The most intensively studied assortments in this project have been forest fuels (logging residues, stumps and young trees). These assortments, especially stumps, often have troublesome variations in properties (particularly moisture and ash contents). To deal with this, pretreatment or fractionation of some kind may be necessary, activities preferably carried out in a terminal. Currently, forest biomass terminals are used as reloading (from trucks to train), storage and/or comminution nodes in the supply chain (Tables 10-12). However, their uses could be extended to exploit their closeness to the forest, and thus low costs for transporting biomass to them. Notably, assortments (loose logging residues, tree sections and stumps) that are currently too bulky to transport over long distances can be fractionated and upgraded in a terminal, thereby generating several different assortments suitable for different end users (see Eriksson et al. 2013. With several assortments available, mixing to match end users' quality demands will be possible. This could substantially improve end users' process efficiency and thus increase the willingness to pay. Today, quality demands differ between small-scale heating plants and large-scale CHPs. Optimal fuel mixes could be delivered just in time to match boiler and seasonal variations in demand. Mixing to optimize payloads on trucks and trains may also be possible, and terminals could be equipped for further compacting loads. These measures could enable raw materials to be exploited that are not currently economically viable due to long transport distances to end users. Eventually, facilities for applying more advanced processes, including pre-treatment, upgrading and semi-industrial activities (e.g. torrefaction, pyrolysis, pelletizing etc.) could also be installed in terminals. All this may contribute to regional development in sparsely populated areas (e.g. the inland areas in Norrland) and provide effective future ways to optimise use of forest biomass. Transport and handling of forest biomass are costly and profit margins are currently low, while loading and unloading are expensive. To make terminals cost-effective, it will be important to develop and optimize their internal logistic design and management. Designs and management regimes for terminals for whole tree utilization were addressed in the late 1970s. Compilation and scrutiny of such knowledge, from a present technical-economical perspective, would boost the coming development of appropriate terminals and their impact on the supply chain and provide a good starting point.

Extractives normally represent only a few percent of a tree's mass, but may be sources of highly valuable chemical substances. However, extractives are highly volatile and will quickly evaporate during storage after felling, especially after comminution. Results acquired in this project show that ca. half of the extractives are lost after only a few weeks of storage (Figs. 39-40). Thus, it is vitally important to transport extractive-rich fractions to appropriate processing sites rapidly after felling the trees in order to exploit the valuable chemicals. As high temperature accelerates evaporation, handling forest biomass during summer should be avoided. It is also known that comminution of bark and needles results in smaller particles than comminution of stem wood (Eriksson et al. 2013) and the degree of fractionation during storage is correlated with the rate of losses. Extractive-rich fractions can be separated from stem wood by gravimetric methods (Fig. 51-53). The stem wood fraction can be used for fermentation, and (as shown in this report) promising yields of 29% ethanol have been reached after 43 hours in a bioreactor (Table 25).

The volumes that can be annually harvested from small diameter trees (in early thinnings) are large and can be geographically predicted for at least two decades. Such harvesting is usually a silvicultural treatment (thinning) intended to increase the value of the remaining stand for conventional forest production (saw-logs and pulpwood). Currently, the main use of harvested small diameter trees is as fuel for use in heating and CHP plants. Thus, early thinnings could provide a long-lasting source of raw material for new biorefineries with only weak competition from other industries. Previous and ongoing R&D work on harvesting techniques and systems for early thinnings, as well as technologies for comminution, transportation and storing of materials, have solved, or indicated possible solutions for, some of the formulated problems (cf. Bergström 2009). However, intense further efforts are required in these fields in order to fully exploit the harvestable biomasses while keeping supply costs low. In conventional systems the harvesting costs account for 50-60% of the total cost of supplying industries with small diameter whole trees. However, a new felling head designed for compression-compression is under development (Fig. 33) and studies reported here show that this system could significantly improve supply efficiency (see data for the MTH-WTrough system in Fig. 48). This system is competitive in stands where the average tree size is within the range ca. 22-50 dm^3. However, new, especially designed felling heads for boom-corridor thinning in combination with bundling units (bundle-harvesters), would theoretically provide significantly higher efficiency for harvesting smaller trees (see data for the AFH-CF-WTB-BC-OPT system in Fig. 48). A new innovative felling head (Flowcut) especially designed for such harvests is currently under construction. The latest version of the Fixteri (Fixteri Oy) bundling system (Fig. 35) shows high efficiency (Fig. 36) and could thus be combined with this new felling technology to form a future concept for harvesting young dense thinning stands. Results indicate that bundle-supply-systems, in which the biomass can be handled with conventional forwarders and trucks, should be developed for deliveries to terminals close to industrial sites and the biomass can then be fractionated into its main components (Jylhä 2011). Analyses of the effects of implementing present ongoing developments of harvesting and handling techniques show that the supply cost for small diameter trees from early thinnings can be reduced by on average 10-15% while significantly increasing the energy efficiency (Fig. 67).

The surplus of stump wood in the BA region is much greater in Sweden than in Finland, because stumps are only harvested on a trial basis in Sweden, but highly used in CHP plants in Finland. Their potentially harvestable volumes are very high, but extracting them with conventional up-rooting systems is associated with problems, including substantial ground disturbance (Berg et al. 2014) and relatively high ash contents due to contamination by gravel and stones (Table 14). Thus, handling them is much more troublesome than handling small diameter trees, despite the large potential extractable volumes. Stump harvesting cannot be regarded as a silvicultural treatment that promotes the development of stands either, unless sites are heavily infected by rot root. In addition techniques and systems for stump harvesting have not been developed as rapidly and intensely as those for harvesting young trees, despite substantial research. For example, this project has shown that contamination contents can be reduced to less than 1% with gravimetric sieving and fractionation (Fig. 56), and that ground disturbance (and ash contents) can be substantially reduced if systems that only harvest the center-part of stumps are used (Table 13). The drawback is that less biomass (ca. 20%, compared to conventional stump harvesting) is retrieved, thus harvesting costs per m^3 removal are high (Berg 2014). However, if low ground impact stump core harvesting systems are developed, the supply cost and energy use per OD t for a given harvesting site should be 11-33% lower, and energy use should also be reduced.

Presented results also show that storage has weaker (but still significant) effects on extractive contents of comminuted stump woods than on the contents of branches and bark from small diameter trees (Fig. 41-42). In addition, with suitable pretreatment stump wood can be fermented, and an ethanol concentration of 12% was reached after 56 hours in the bioreactor (Table 25). The rather low yield (and toxicity) of the stump slurry could possibly be due to the high extractive contents of stumps, thus it would be interesting to test possible pretreatment and storing treatments to reduce the extractive contents. In the future, several assortments of both stumps and young trees should be studied throughout the whole supply chain from the forest to different categories of biorefineries (biochemical, thermochemical and others based on new processes). Several pilot and demo plants are available for this purpose in the region. Successful processing of new assortments would lead to a widening of the feedstock basis for forest-based biorefineries, thereby reducing average transport distances and costs of supplying the same volume of forest biomass. For feedstocks subject to little current competition this could be particularly important as their prices would be lower.

Integrated supply of pulpwood and residual assortments can significantly reduce supply costs compared to separate supply chains. However, the complete picture is highly complex as it is influenced by interactions between supplies of several feedstock assortments and demands from several different users. Costs for separating stemwood from residues at a later point in the chain will reduce or eliminate the benefit of integrated harvest. Hence, the advantages would be greatest when there is little gain from separating these assortments. Examples of processes that could utilize both stemwood and residual assortments are gasification plants and ethanol production plants. However, their ability to pay for the biomass would have to be compared to the ability to compensate competing industries, such as pulp mills competing for pulpwood. Other interesting options are concepts that may allow highly efficient large-scale separation of stemwood and residual assortments. Combined debarking and delimbing in conventional debarking processes is being trialled at pulp mills, where the debarked pulpwood is utilized in the pulping and the residues are utilized for bioenergy applications in nearby facilities. For similar reasons, integrated supply chains may also have attractive potential in systems where terminals are used more extentsively to pre-process feedstock for various applications. The application of integrated supply chains may, conversely, improve the feasibility of terminals. However, more studies are needed before rigorous conclusions can be drawn regarding optimal strategies. The systems analysis also showed the potential feedstock cost reductions that could be obtained by extracting new assortments, such as early thinning wood, and the major benefits that could be achieved by efficient compaction before transport. The available amount of feedstock could also be increased by pre-treatment operations, which could make previously non-viable assortments available. However, any cost reductions thus achieved as a result of increased supply should be weighed against the additional costs for pre-treatment. All in all, the options studied in the project indicate that new practices could potentially provide supply cost reductions of around 10%, compared to current best practices, under certain conditions. It should be noted that there may be significant improvement potential between current actual practices and current best practices, but this was not studied in the systems analysis. The cost reduction potential is dependent on factors such as the future development of existing industries and markets, as well as the realization of new types of industries. The candidate technologies for such new industries are relatively well known and their feedstock quality requirements can be described in general terms. However, the actual impact of the establishment of such a new industry on feedstock competition patterns and supply chain development is difficult to assess in detail, and will be case specific.

How the forest biomass supply chain is designed and managed will directly affect the quality of supplies and indirectly affect the industrial efficiency of conversion/extraction of chemicals. However, the specific quality requirements for future bio-refineries are still uncertain and may change over time. Thus, it is vitally important to ensure that supplies of biomasses with various qualities can be rapidly adjusted and adapted. Terminals will play a key role in this system. Current terminals are mainly used as transition points, where little upgrading is done apart from comminution. Since raw forest biomass cannot be transported long distances, due to its relatively low value, robust value-upgrading at terminals closer to terminals before long distance transportation is likely to be nesessary. Such terminals must be quite sophisticated in order to meet the need for flexible/semi-mobile refineries, i.e. they will need to have access (*inter alia*) to appropriate infrastructure, electricity, water and personnel. As most of the un-exploited forest biomass resources are located in inland areas, particular attention should be paid to developing terminal-refinery-integrated supply chains in these areas for supplying industry-dense areas for further refining or direct use in processes. The systems analysis part of the project provides a useful starting point for more detailed case studies, and showed that the energy used along the entire chain from forest to industry typically corresponds to some 2-5% of the energy content of the biomass feedstock, which is in line with other studies. Furthermore, differences in energy use between new and conventional practices were generally small, which is encouraging from a flexibility perspective, since if a certain system seems to be particularly suitable at a given time and location its implementation should not be barred by energy cost considerations.

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Appendix

Swedish University of Agricultural Sciences (SLU) is a university with a clearly defined role in society: to take responsibility for the development of learning and expertise in areas concerning biological resources and biological production. This responsibility stretches over the wide-ranging fields of agriculture, forestry and the food industry to environmental issues, veterinary medicine and biotechnology. The Department of Forest Biomaterials and Technology (FBT, part of SLU's Forestry Faculty based in Umeå) is particularly focused on issues relevant to this project. It is a new department, formed through merger of the former Department of Forest Resource Management and Unit of Biomass Technology and Chemistry. This initiative is in line with the strategy to focus on training and research on innovative use of biomass to replace fossil fuels. The department has about 40 employees, including nearly 20 staff scientists headed by four professors and three associate professors, and 15 graduate students. The undergraduate education has a clear focus on the biomaterial value chains from forest to industry. It is primarily connected to the forest science programme at SLU. The research at FBT has a corresponding focus, addressing multi-dimensional aspects of the supply chains in collaboration with diverse local, national and international universities, corporations, government agencies and other pertinent actors. SLU is the lead partner in Forest Refine and has been engaged in sub-project numbers 1, 2 and 4.

The Finnish Forest Research Institute (Metla) is a governmental, sectorial research institute, subordinate to the Ministry of Agriculture and Forestry. The current network of 10 research units covers the whole country. Metla develops solutions to the challenges and questions posed by the care, utilization, products, services and intangible value of forests. Metla's duties are defined by the law and statute to promote, through research, the economical, ecological, and socially sustainable management and use of forests. Key objectives are to engage in operations that are scientifically and socially influential, promote the competitiveness of forest-based business activities, and support regional development. Metla's products and services, together with the data and competence Metla generates and actively communicates, are utilized both nationally and internationally in advancement of the bioeconomy. Research activities of the Kannus Unit focus on growing wood biomass, logistics of wood procurement and effects of intensive biomass recovery. Other research concerns include nutrient balances and regeneration of peatland forests, forest management planning, special features of coastal forests and effects of afforestation of agricultural land on greenhouse gas balances. The concerns span multiple spatial ranges (local to global), timeframes and techno-socio-economic dimensions. Thus, the research involves, and requires, close collaboration with local, regional, national and international universities, other research institutions, other Metla research units and local forestry actors. The unit has 10 researchers and about 15 other staff. In Forest Refine Metla has been engaged in subprojects 1, 2 and 3.

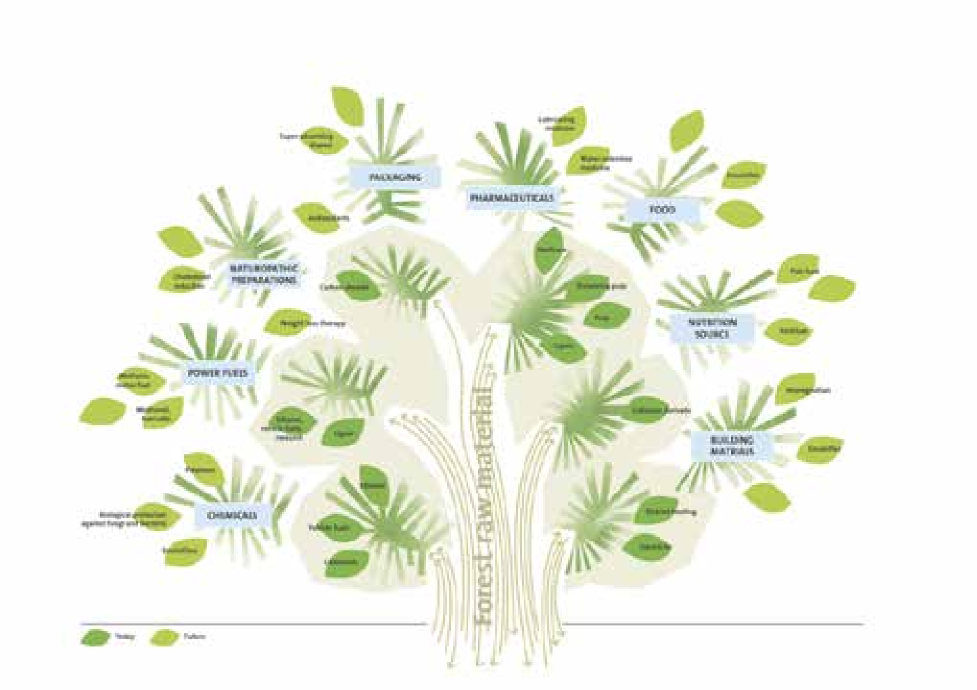
SP Processum AB is a nationally and internationally leading biorefinery initiative, which was established in 2003 and developed from a burgeoning technology park. The company has 16 employees and since June 2013 it has been jointly owned by SP Technical Research Institute of Sweden and the Processum Interest Group, a cluster of companies with biorefinery interests. This cluster currently includes 21 businesses based on the coast of northern Sweden. In close cooperation with other regional initiatives, universities, research institutes and other actors, SP Processum provides an important hub for the development of new products, energy solutions and fuels based on woody raw material. Most of the activities are related to research, development and industrial implementation of innovative technologies and sustainable strategies for: managing, procuring and processing raw materials; generating energy; enhancing biotechnological processes; and extracting or transforming both organic chemicals and inorganic materials with commercially attractive properties. Processum has been engaged in sub-projects 3 and 4.

The Kokkola University Consortium Chydenius acts as a joint institution carrying out teaching and research under the auspices of the universities of Jyväskylä, Oulu and Vaasa. University consortia are umbrella organizations that coordinate the regional activities of various universities, with the objective of improving the visibility of universities in their regions. The Unit of Applied Chemistry was established in 2007, and is headed by Professor Ulla Lassi. Research and education are carried out under the University of Oulu. The Unit employs 25 people and conducts research activities in both Kokkola and Oulu. The main research areas include catalytic materials in process and environmental engineering applications (e.g. conversion of biomass into valuable chemicals), battery chemicals, and chemical precipitation (e.g. in the recovery of valuable metals). In the Forest Refine project Chydenius has been engaged in sub-project 3.

Centria University of Applied Sciences (Centria) is a multidisciplinary, dynamic and international higher education institution that offers students and staff an environment that is innovative, caring and multicultural. A strong focus on entrepreneurship and excellent connections with diverse work environments provide robust foundations for combining theoretical knowledge with career skills in a meaningful way. Centria has a strong international profile as a university of applied sciences that encourages innovation and entrepreneurship. The university's study options as well as the research and development activities respond to the needs of businesses and working life. Centria has three campuses – Kokkola, Pietarsaari and Ylivieska – that offer degree programs in technology, business, social services and health care, culture, humanities and education. It has about 3000 students, about 300 staff, and anually awards degrees to about 500 students. Teaching languages are Finnish, Swedish and English. In the Forest Refine project Centria has been engaged in sub-project 3.

Central Ostrobothnia Rural Institute is part of the Federation of Education in Central Ostrobothnia, which provides vocational upper secondary education and other forms of education and training for youths and adults. The Kannus Unit is one of three units that provide education in the natural resources sector and collectively have about 500 students and 120 staff. The core mission of the Kannus Unit is to promote the vitality and competitiveness of the countryside through education and projects related to agriculture and forestry. In the Forest Refine project, the Unit has been primarily responsible for communicating findings regarding means to develop and enhance the efficiency of raw material supply chains. Key objectives have been to facilitate communication among project partners and disseminate both the researchers' findings and conclusions drawn from the acquired information.

BioFuel Region is a non-profit organisation, equivalent to a public body, which was founded in 2003. It is financed from membership fees, public entities and project funds. Currently it has seven employees and operates according to the triple-helix model. It is a partnership between municipalities, businesses, regional associations, county councils, and universities in the four northernmost counties of Sweden, which cover about 50 % of the country. The overall aim is to provide a hub for exchanging information and fostering initiatives enabling the region to play a leading role in the transition to a sustainable society, economically, socially and ecologically. Key objectives include nurturing the transition from fossil to renewable energy sources in order to mitigate climate change, increase self-sufficiency and promote regional development. Focal areas are renewable energy with emphasis on transport systems and products based on forest biomass. In the Forest Refine project, BioFuel Region has been responsible for management and outreach activitie.



(Source: SP Processum)

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