Stumps as Fuel

– the influence of handling method on fuel quality

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Cover: Norway spruce stump (*Picea abies* (L.) H. Karst).
(photo: E. Anerud)

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Softwood stumps as fuel.

Abstract

Wood fuels make a key contribution to renewable energy sources in the Nordic countries. The growing demand for forest biomass can be partly met by utilising energy-rich stumps left after clear cutting. As fuel, stump wood is commonly associated with a high presence of contaminants, resulting in high ash content. The concentration of contaminants depends on factors such as soil type, weather conditions, harvesting method, storage duration and other handling operations. The high ash content is a major drawback when using stump wood as fuel. Handling methods that could improve fuel quality are therefore highly desirable. To produce a fuel of acceptable quality, *i.e.* with low moisture and ash content and high energy value, the above-mentioned factors require evaluation and quantification. In this thesis, various handling methods within the supply chain for Norway spruce stump and their effects on the biomass as fuel are evaluated. The following handling processes are dealt with: harvesting technique, pre-treatments including stump splitting/fractionation and cleaning using vibration or sieving, storage methods and storage duration. Choice of stump harvesting head proved to have an impact on fuel quality, as splitting of stumps during extraction allowed better drying during storage. Such stumps could be stored directly in windrows, since no difference could be established between this method and storage in heaps prior to windrow storage. In general, storage improved fuel quality. Changes in fuel quality parameters do not reflect the whole picture, however, since dry matter losses occur during storage, and therefore the storage period should be kept as short as possible. During winter months, when demands for fuel are highest, stump ash content can be high, since frozen contaminants are difficult to detach from stumps during transport. To achieve acceptable fuel quality during high demand periods, long storage duration or a pre-treatment involving additional stump cleaning is required. Fuel quality was clearly improved by vibration-based cleaning before the comminution of stumps or by sieving stump wood after crushing. These methods can allow stump wood fuel of acceptable quality to be supplied within a harvesting season.

Keywords: biofuel, bioenergy, contaminant reduction system, forest fuel, fuel quality, procurement system, harvesting, storage, stump wood, vibration.

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Dedication

I dedicate this thesis to Victoria, Therese and Maria.

Contents

List of Publications

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

I Anerud, E., Jirjis, R., Nordfjell. T. (2012). Softwood stumps as fuel – a review of the supply chain from harvesting to end-user including major environmental issues. Submitted to *Renewable & Sustainable Energy Reviews in 2010.*

II Anerud, E., Jirjis, R. (2011). Fuel quality of Norway spruce stumps – influence of harvesting technique and storage method. *Scandinavian Journal of Forest Research* 26, 257-266.

III Anerud, E., Jirjis, R., Gebresenbet, G. (2012). Evaluation of the performance of a three-dimensional vibrating test rig for cleaning stumps. *Australian Journal of Agricultural Engineering 3*(2), 51-58.

IV Anerud, E., Jirjis, R., Gebresenbet, G. (2012). Cleaning of harvested Norway spruce stumps using a vibration-based method. Accepted for publication in *International Journal of Forest Engineering.*

V Von Hofsten, H., Anerud, E. Fogdestam, N., Granlund, P., Eliasson, L. (2012). An alternative supply system for stump biomass – coarse grinding combined with sieving of the produced hog fuel (manuscript).

Papers II - IV are reproduced with the permission of the publishers.

The contribution of Erik Anerud to the papers included in this thesis was as follows:

I Carried out literature review and wrote the manuscript with the co-authors.

II Planned the field experiments with the co-author. Carried out sampling and analyses. Wrote the manuscript with the co-author.

III Planned the study with the co-authors. Carried out sampling and analyses. Wrote the manuscript with input from the co-authors.

IV Planned the study with the co-author. Carried out sampling and analyses. Wrote the manuscript with input from the co-author.

V Planned the study with the co-authors. Carried out sampling and analyses for fuel quality. Wrote the manuscript together with the co-authors.

The contribution of Erik Anerud to the papers was approximately 80% in Paper I and Paper II, 95% in Paper III, 90% in Paper IV and 20% in Paper V.

Abbreviations

AC	Ash content
C	Carbon
CO_2	Carbon dioxide
d.b.	Dry weight basis
FSC	Forest stewardship council
GHG	Greenhouse gases
HHV	Higher heating value, gross calorific value $MJkg^{-1}$, d.b.
LHV	Lower heating value, net calorific value, $MJkg^{-1}$, d.b of w.b.
m^3fub	Cubic solid timber excluding bark
m^3sk	Stem volume over bark from stump to tip
MC	Moisture content
SGS	Sandy glacial till soil
SOS	Sandy organic soil
w.b.	Wet weight basis

1 Introduction

1.1 Background

Concerns about the negative environmental impact of using fossil fuels continue to grow, in line with awareness of the effects and drivers of climate change across the globe. Reversing the trend of increased atmospheric concentrations of greenhouse gases (GHG) is therefore a major global environmental and political challenge. An integrated energy and climate change policy was adopted within the EU in 2008, with the aim of decreasing GHG emissions by 20% compared with 1990 levels and increasing the percentage of renewable fuels by 20% by the year 2020 (European Commission, 2008). This has consequently led to increased interest in the production of energy from reliable renewable resources.

In 2009, renewable fuels comprised 47% of the total energy supply in Sweden, an increase from 33% in 1990 (Anon, 2011). This reflects strong progress toward the national goal for energy production of increasing the share of renewable sources to 50% of all energy supplies by the year 2020. Biofuels are a key energy source that accounts for 57% of the supply of renewable fuels (Anon, 2011). The interest in using forest biomass for energy production has been on the increase in recent years and such biomass is in high demand on the wood fuel market.

Sweden is a forest-rich country, with 22.7 million hectares of productive forest land and a standing volume of 2.9 billion m^3sk (stem volume over bark from stump to tip). The most common tree species, Norway spruce (*Picea abies* (L.) H. Karst), Scots pine (*Pinus sylvestris* L.) and birch (*Betula pubescens* Ehrh. and *Betula verrucosa* Ehrh) contribute 41%, 39% and 12% of the standing volume, respectively. The annual growing stock has increased by more than 80% since the 1920s due to improved silviculture and changes in land use, and reached 111 million m^3sk in 2011. Within the same year, annual gross felling was 89.5 million m^3sk, while net felling reached 72.8 m^3fub (cubic solid timber excluding bark). Of the total quantity generated by net felling, 91% was delivered to forest industries, saw logs and pulpwood and 8% was classified as primary fuel assortments and 1% as other assortments (Loman, 2011). However, this does not reflect the amount of woody biomass or wood components that are used for energy purposes, since by-products such as sawdust, bark and black liquor must be added to this value.

One way to meet the growing demand for forest biomass for energy production, without increasing annual felling or endangering the supply to the timber and pulp wood industries, is to increase the use of forest residues and utilise the stumps left after clear-cutting. By definition, the stump is all belowground and aboveground wood and bark mass of a tree beneath the merchantable timber cross-section (Hakkila, 1989).

Stump biomass contains higher concentrations of energy-rich wood components, such as lignin and extractives, than stem wood (Eskilsson & Hartler, 1973; Hakkila, 1975). This makes stumps highly desirable for energy purposes. Furthermore, studies on root rot fungi such as *Heterobasidon*, *Amarilla* and *Phellinus*, which decrease growth and impair tree quality, indicate that stump harvesting is the most efficient way to reduce infections at clear-cuts (Hypell, 1978; Vasaitis *et al*., 2008).

In Finland, stump wood is considered an acceptable energy source, with the harvested area increasing from 1000 to 2500 hectares per year between 2003 and 2005 (Hakkila, 2004; Strandström, 2006). There is increasing interest in stump harvesting in Sweden, with the Swedish government recently highlighting stump biomass as a potential source of forest fuel (Anon, 2008a).

Utilisation of stumps has been practised in Sweden throughout history, although somewhat inconsistently, being used for various purposes during different periods. For example, stump wood, especially Scots pine, was used as a successful feedstock for the production of tar as early as the 17th century. At the beginning of the 20th century, more than 15 permanent facilities were in use for tar production, producing 30-40 kg tar per ton stump wood (Lundberg, 1914). The number of facilities increased to 147 during World War II, when tar was used as both lubricating oil and as an additive to motor fuel. During this period, around 30 000 tons of tar were produced annually, which is equivalent to 750 000 m^3 clean split and stacked stump wood (Wahlberg, 1958). The stump harvested area must have been extensive, since six stumps with a cross sectional diameter of 25 cm were required to obtain 1 m^3 of tar. In addition, the turnover in 1944 was SEK 20.5 million, which in today’s money is equivalent to more than € 48 million. More recently, during the 1970s and 1980s, attempts were made to use stumps as raw material for pulp production. However, this was discontinued due to a combination of low profitability together with high levels of contamination (Björheden, 2006). Stumps are increasingly regarded as an untapped energy resource that could be used as a complement to other forest fuels (Nurmi, 1997).

In 2008, the Swedish Energy Agency estimated that the gross potential of stumps and forest residues harvested at clear-cuts, without applying any restrictions, could be 57.5 TWh and 36.3 TWh per annum, respectively (Anon, 2008b). Taking environmental, technical and economic restrictions into consideration, the net potential of stumps is more likely in the order of 20.7 TWh, which is more than the net potential of 15.5 TWh from forest residues under the same restrictions. However, this is far larger than the predictions of stump harvesting at 5-10% of the annual clear-cut area made by the Swedish Forest Agency, which would only yield 1.3-2.6 TWh.

Although restricted large-scale utilisation of stumps for energy production has been accepted by the Swedish Forest Agency (Anon, 2009), stump harvesting is still perceived as controversial due to differing levels of understanding and opinions on its environmental impacts. These concerns were highlighted by Egnell *et al*. (2007) and, more recently, in reviews reported by Walmsley & Godbold (2010) and Berch *et al*. (2012). To close knowledge gaps, extensive research has been conducted focusing on potential environmental impacts such as biodiversity, soil, water, carbon balance and increment. In Sweden, full-scale stump harvesting is not yet accepted for those areas certified by the Swedish forest stewardship council (FCS). Knowledge about the environmental impact could increase the extent of full-scale stump harvesting in coming years.

1.2 Stump wood characteristics

The major components of woody biomass are cellulose, hemicelluloses and lignin, which comprise 40-50%, 25-35% and 20-30% of dry weight, respectively (Saarman, 1992). Furthermore, wood contains extractives and minerals. These chemical components contain different amounts of energy, with lignin and extractives contributing the highest energy (White, 1987). The concentrations of the major wood components depend on factors such as species and geographical location. Moreover, the chemical composition of different parts of a tree varies considerably depending on their specific primary functions. Stumps absorb and conduct water and minerals, translocate and store energy and anchor the tree. The crown size of a tree is positively related to the absorption conducted by the fine roots, which also have the highest concentrations of nutrients (Hellsten *et al*., 2009). The lateral roots and taproots, which anchor the tree, have the highest concentrations of lignin and extractives (Eskilsson & Hartler, 1973; Hakkila, 1975). The concentration of lignin in Norway spruce stumps is around 28%, while extractives are in the range of 1-2.8% of dry matter (Nurmi, 1997).

1.3 Wood fuel quality

A number of parameters are used to describe the quality of wood fuel, including heating value, moisture content and ash content. Other characteristics of wood fuel such as particle size distribution and homogeneity are also of considerable importance, since they can affect the fuel feeding process and the evenness of combustion. Heating value, which is a reflection of chemical composition, can be expressed as higher heating (gross calorific) value (HHV) or lower heating (net calorific) value (LHV). By definition, the HHV is the theoretical number of heat units liberated during complete combustion of a solid fuel in an oxygen-filled bomb calorimeter where all vapour condenses to water at a certain temperature (Swedish standard, 1990). The HHV is expressed on a dry weight basis. The LHV is the energy that can be generated without condensation of vapour and is calculated by deducting the energy used for evaporation of water from the calorimetric value. This value can be expressed on a dry weight or wet weight basis (Figure 1).

The moisture content, which is the amount of water in relation to the total green weight of the woody material, is an important quality parameter mainly because evaporation of water during combustion reduces the amount of effective energy that can be extracted from the biomass.

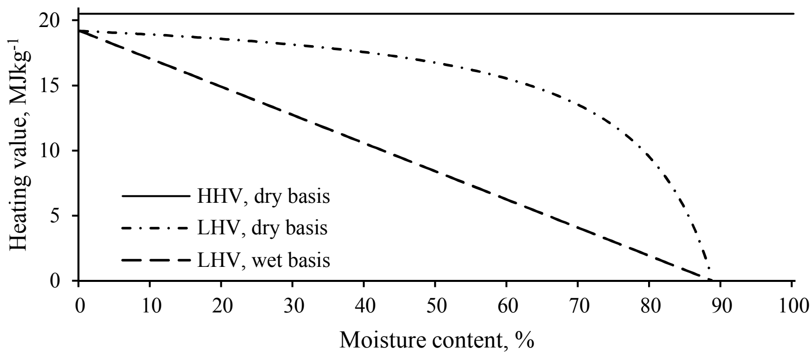

Figure 1. Correlation between moisture content and heating value, expressed as higher heating value (HHV) or lower heating value (LHV).

Ash, the by-product of wood fuel combustion, usually results from two components; natural unburnable minerals originating from the biomass as salts bound in the carbon structure (inherent), and inorganic components present as mineral particles in contaminants. The presence of the latter in a fuel causes a number of problems during the comminution phase and combustion. High levels of contaminants in wood fuel, such as sand, gravel and stones, increase wear and tear on comminution machinery, which is a key reason why blunt equipment such as crushing machinery is used instead of chippers for size reduction of stumps. Depending on the chemical composition of the fuel, different combinations of minerals can affect the ash melting temperature during combustion, which can lead to sintering and drift problems (van Loo & Koppejan, 2008).

The chipping or crushing of woody biomass results in particles of various sizes. The presence of high contents of fine fractions, *i.e.* particles less than 5 mm in diameter, can cause problems during fuel utilisation, such as blockages in the feeding process and a very compacted fuel bed. Furthermore, small fractions can contain high ash concentrations due to accumulation of fine particles from the contaminants (Gärdenäs, 1989). The homogeneity of the fuel is also an important quality factor, not only regarding the particle size distribution, but also the moisture content, since it enables better process control (van Loo & Koppejan, 2008).

The presence of soil contamination, which usually surrounds the stumps, is a major drawback in the process of energy production, as it results in high ash content and reduced HHV. This, together with the low profitability mentioned earlier, has weakened the interest in using stumps as fuel. Therefore, stump biomass can offer an acceptable fuel if the contamination rate can be reduced efficiently. Using a handling and storage system that could sufficiently improve the fuel quality of stumps by decreasing both ash content and moisture content is therefore highly desirable.

1.4 Supply chain from clear-cuts to end-user

The supply chain of stumps normally includes harvesting, storage, transport and comminution (Figure 2). Some form of stump cleaning, which can be performed either before or after comminution, is necessary to improve the fuel quality.

Technical development in stump harvesting machines has been stagnant in recent years, leading to obsolete harvesting systems (base machine and stump harvesting head). Development of fast and efficient cleaning processes is required to reduce the need for an extended period of storage. Moreover, improved logistics in transportation and comminution is a key factor in increasing load capacity. A holistic approach to the supply chain, addressing issues of harvesting techniques, fuel quality and economics, is required to ensure the production of fuel of reasonable quality at an acceptable price.

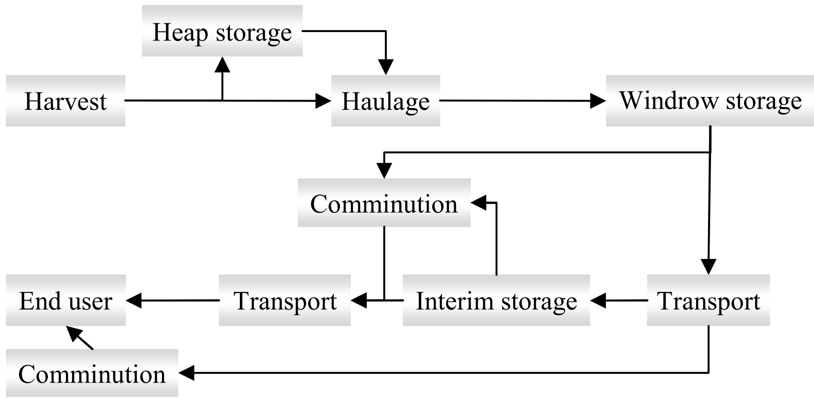

Figure 2. Flow diagram showing various stages in the supply chain of stumps.

1.4.1 Harvesting

An excavator, usually weighing 21-23 ton and equipped with a lifting head weighing 1-2 ton, is currently used in all techniques (Kährä, 2008; Athanassiadis *et al*., 2011). This is in principle the same technique developed during the 1970s (von Hofsten, 2006). The two main methods commonly used for the extraction involve either a shearing or refractive head (Figure 3). The main difference between these two heads is that the forked part of the shearing head is pressed against a wedge in order to split the stump in the ground before lifting, while a refractive head is equipped with prongs and extracts the stump by pressing the largest prong under the stump and then pulling it up (von Hofsten, 2010). Using a refractive head does not always split the harvested stump.

Norway spruce stumps are easier to extract and contain less contaminants than stumps of Scots pine, due to their shallow root system (Nylinder, 1977). Furthermore, Norway spruce stumps contain more biomass owing to their thick lateral roots (Hakkila, 1989). The combination of these factors makes spruce stumps more suitable from an energy supply perspective despite their lower HHV when expressed on an ash-free basis.

Suitable stands for stump harvesting are nutrient-rich, clear-cut areas from which logging residues have been removed. One of the reasons why stumps are not extracted from thinning sites is to avoid the risk of damaging the remaining trees and their root system, which could increase the risk of fungal infections such as root rots.

A considerable amount of soil and other contaminants always adheres to harvested stumps and some can also be enclosed within the stumps. The amount of contaminants depends on a number of factors such as soil type, harvesting season, weather conditions at the time of extraction and tree species (Nylinder, 1977). To reduce the amount of contaminants, stumps are normally shaken during the harvesting process (Athanassiadis *et al.*, 2011). This cleaning process is time-consuming, frequently inadequate and requires long storage duration for further cleaning.

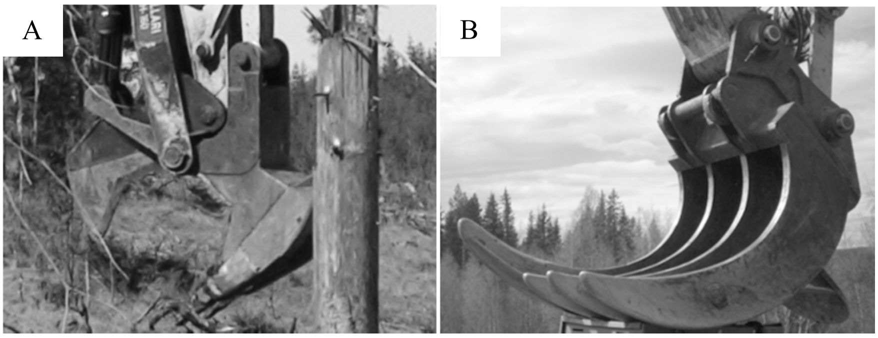

Figure 3. Commonly used stump harvesting heads. (A) shearing head (Pallari KH 160 HW) and (B) refractive head (Aalto).

1.4.2 Storage

The highest demand for wood fuels, usually used for heat production, occurs during the colder seasons, which in Sweden is autumn and winter. Harvesting during this period is not practical, as the stumps are in most cases frozen or covered by snow, which make them difficult to locate. Furthermore, it makes the shaking process, usually used to remove contaminants, ineffective and time-consuming. Stumps are therefore harvested and stored during the warmer seasons. Storage for a few months is necessary to meet the uneven annual demand for wood fuel and, more importantly, to remove contaminants and moisture and thereby improve the fuel quality. A few reported studies combined with a good deal of practical experience support the view that storage can improve fuel quality by reducing the amount of contaminants (Alakangas, 2005; Anerud & Jirjis, 2011).

After harvesting, the stumps are normally piled in small heaps in the clear-cut area and stored for a few months before they are gathered into windrows by the roadside. Storing the stumps in about 1.5 m high heaps or as stump parts placed in rows in the clear-cut, instead of directly hauling them into windrows, is based on the assumption that the cleaning process is more efficient if a large surface area is exposed to sun and precipitation. However, the stumps are sometimes hauled to a windrow immediately after harvesting to facilitate regeneration measures such as soil scarification and planting in the clear-cut.

In the supply chain commonly used today, harvested stumps are stored for varying periods before they are consumed as fuel. In Finland, practical experience has shown that stumps normally need at least one year of storage (Alakangas, 2005). During storage moisture content (MC) decreases, with a small-scale storage trial showing a decline from approx. 50% to 22% (wet basis) in split Norway spruce stumps after 14 months of storage (Nylinder & Thörnqvist, 1981). More recently, similar observations have been reported by Laurila & Lauhanen (2010) and Anerud & Jirjis (2011). In the latter study, stumps had the lowest MC in the following summer and were re-wetted by a few percent during autumn.

An extended storage period can lead to substantial dry matter losses, however, since freshly harvested stumps can be a suitable substrate for microorganisms such as fungi. Depending on their specific ability to decompose the wood components, a fungal attack can cause considerable losses of combustible biomass. Losses of dry matter have been estimated to be 4% after 14 months of storage (Nylinder & Thörnqvist, 1981). Similar observations have been made for windrowed split stumps stored in windrows for 16 months (Anerud & Jirjis, 2011).

1.4.3 Transport and comminution

The supply of stumps from clear-cut to the end-user is primarily performed by forwarding and truck transport. Stumps can be transported before or after comminution (Laitila, 2006). Either way, stumps have to be comminuted before combustion at the heating plant or combined heating and power plant (CHP). Comminution is performed using robust crushers (Hakkila, 2004). These can for instance be based on a toothed solid steel rotor, which by fast rotation crushes the stumps (Anerud & Jirjis, 2011). Prior to storage, the transport of non-comminuted biomass is preferable, since these stumps have better storage properties. However, transport of comminuted biomass increases truck load, which is otherwise limited by volume rather than weight (Ranta & Rinne, 2006). According to Ala-Fossi *et al*. (2007) and Korpinen *et al*. (2007), the load volume capacities on trucks is limited to 18.5-20% due to the bulky shaped stumps (Figure 4), while the load volume capacity for comminuted stumps, transported using chip-trucks, is 31-34%. Similar conclusions were reached by Ranta & Rinne (2006), but with higher values for bulk density in both systems. The differences can be related to particle size and degree of bundling.

A system combining the advantages of storing non-comminuted material and cheaper central comminution is used in interim storage terminals. In Finland, all comminution occurs either at terminals or at the end-user, according to Asikainen (2010). Small mobile crushers moving from landing to landing can be a hot “just in time” system. One of the disadvantages of this system is that the fuel can be further contaminated if the biomass is not separated from the ground, which can be avoided if handling is carried out on an asphalted surface at the terminal. Moreover, rough handling during loading/unloading and transport can decrease the ash content (Anerud & Jirjis, 2011). The lack of space at landing, road conditions, clear-cut size and logistic aspects are all challenges that have to be considered.

One way to increase haulage gains is to introduce a system combining crushing to coarse chips and cleaning. This can be performed with a commercially available drum sieve machine (von Hofsten & Granlund, 2010). In that study, fuel characteristics, MC, AC and HHV were improved due to the reduction in contaminants. In addition, the combination of increased fuel density and increased payload decreased the transportation and comminution costs (von Hofsten & Anerud, 2010). As an example, the AC in freshly harvested stumps declined from 3.9% to 1.1%, while that in the removed material was 34%. The majority of burnable material lost by sieving consisted of fines and soil, which are undesirable during combustion. This system is most suitable in “just in time” delivery, since high dry matter losses, which can result during storage, can be avoided (von Hofsten & Anerud, 2010).

Another way of reducing stump contaminants and shortening storage time, without compromising fuel quality before comminution, is to use a cleaning method based on vibration. This has been successfully used in sectors of the industry, with unwanted material being separated and removed through vibration. The use of vibrations has been considered a potential method since the 1970s (Nylinder, 1976; Jonsson, 1985; Hakkila, 1989).

Figure 4. Bulky Norway spruce stumps loaded on a forwarder.

2 Aims, objectives and structure of the thesis

2.1 Aim and objectives

The aim of this thesis was to study and evaluate various handling methods within the supply chain of Norway spruce stump and their effects on the biomass as fuel. Changes in fuel quality and the overall effect on the supply chain were the main focus. The work covered the following handling processes:

- Harvesting technique
- Pre-treatments, including stump splitting/fraction and cleaning using vibration
- Storage method and duration

The following specific objectives were set to achieve the overall aim of the study:

- Review the literature concerning technical, biological and environmental issues related to stump removal for energy purposes.

- Determine the effects of harvesting technique on the main physical and chemical characteristics of extracted stump biomass.

- Evaluate changes in fuel quality during long storage periods in different forms at two geographical locations.

- Evaluate the efficiency of cleaning freshly harvested and stored stumps using a vibration-based method.

- Evaluate the efficiency of cleaning stumps reduced to coarse wood and subsequent drum sieving.

- Study changes in energy content as a result of different handling methods.

2.2 Structure

The thesis examined variations and changes in fuel quality of Norway spruce stumps within the supply chain.

A literature review on stump harvesting allowed existing information on technical, biological and environmental aspects and issues related to stump harvesting to be collated and summarised (Paper I).

The main chemical and quality characteristics of harvested stump biomass from two sites were then studied using three different stump harvesting heads. The study involved two full-scale field trials, located in central and northern Sweden. Changes in fuel quality and energy content during 16 months of storage under different conditions were evaluated (Paper II).

A test rig designed for carrying out vibration-based cleaning of stumps in order to reduce the amount of contaminants was described and evaluated (Paper III).

The efficiency of this vibration test rig in cleaning stumps from adhering contaminants was evaluated using freshly harvested and stored stumps and applying vibration in one or three dimensions at different settings of vibration (Paper IV).

The feasibility of cleaning stumps by crushing them into coarse wood and subsequently sieving the biomass in a sieving drum was evaluated in a final study (Paper V).

3 Materials and methods

3.1 Material

The material used in field and laboratory studies was stump woody biomass extracted from mature stands dominated by Norway spruce (*Picea abies* (L.) H. Karst). This biomass was obtained from a total of five locations ranging from northern to southern Sweden. All stumps were extracted from stands growing on sandy glacial till soils except for one, which was on a sandy organic soil. All samples used to determine fuel quality parameters were taken after comminution of freshly harvested and stored stumps.

3.2 Methods

3.2.1 Harvesting technique

A 21-ton excavator equipped with a stump harvesting head was used for harvesting. In Paper II, a shearing head, Pallari KH-160 HW, was used as a reference technique at two sites (Figure 3). The other heads used were a refractive Aalto head (Figure 3) and a Rotary Cutter (Figure 5). The harvesting method using the Rotary Cutter is based on a rotating toothed cylinder that saws and detaches mainly the central part of the stump, which leads to substantially less biomass.

The Pallari KH-160 HW stump harvesting head was used in the experiments reported in Paper IV. In that study all stumps were split into 2-4 pieces. The stump pieces were not shaken, which is usually the normal procedure.

In Paper V, the stumps were also extracted with the Pallari KH-160 HW head. The technique then followed the normal procedure and all stumps were shaken in connection with harvesting.

In addition to the above-mentioned techniques, a Biorex 30 was used at two sites for an evaluation of the impact on splitting rate on contamination presence

(Figure 5). Stumps extracted with this head were divided into three classes; gross (split into 2 pieces), normal (split into 3-4 pieces) and fine (lateral roots without crotches).

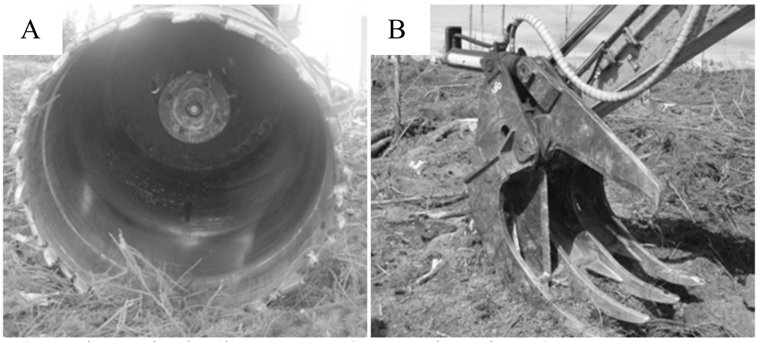

Figure 5. Stump harvesting heads; A: Rotary Cutter and B: Biorex 30.

3.2.2 Storage methods

In Paper II, stumps harvested with different heads in May 2008 were stored separately in two forms, 4 m high windrows at the roadside and 1.5 m high heaps at each of the two harvesting sites. Ten heaps and one windrow were built for each harvesting technique. The prevailing wind direction and maximum sun exposure were considered when storage locations were chosen. The windrows were marked in four zones, with two levels per zone, to indicate sampling location. To evaluate dry matter losses, some randomly chosen stumps were brushed and cleaned thoroughly by removing all visible contaminants. These stumps were weighed, placed in net plastic bags and then placed in marked zones inside the windrows.

The heaps were gathered into windrows after three summer months of storage and then stored in heap-windrows for another 13 months, until September 2009.

The stumps extracted during June 2010 and used for the vibration trial using the test rig (Paper IV) were studied before and after three months of storage in small heaps in the clear-cut prior to forwarding to the roadside.

3.2.3 Vibrating device

A vibrating test rig, specifically designed for stump cleaning, was examined in Papers III and IV (Figure 6). In this device, the vibration amplitude and frequency can be regulated by changing the settings for the distance between the centre mass of the rotating discs and the shaft and the rotation velocity. An accelerometer, centrally fixed underneath the test rig, was used to monitor vibrations in three dimensions.

Extracted stumps that were not shaken were randomly chosen and stump samples were individually forwarded to the roadside on a small trailer drawn behind an all-terrain vehicle. The parts resulting from splitting the stumps during harvesting were separated into three weight classes (<40 kg) (40-65 kg) and (>65). Samples were weighed and placed on top of the test rig, then vibrated for 30 seconds at a certain setting of the device. Sample weight was then recorded before further vibration. This procedure was repeated until the stumps were vibrated for 120 seconds.

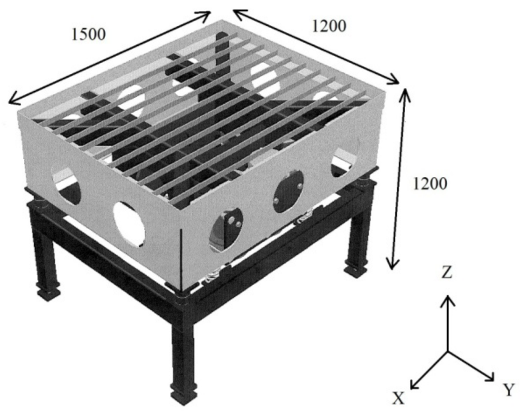

Figure 6. Illustration of the test rig showing dimensions (mm) and directions of vibration.

3.2.4 Sampling procedures

To determine various biomass properties, stumps extracted with different heads were gathered and sampled in connection with extraction and during storage (Paper II). Stumps stored in windrows were collected from the marked zones on four occasions, after 3, 9, 13 and 16 months of storage. Stumps stored in heaps and heap-windrows were sampled in a similar way. On each occasion, a number of stumps were selected and transported to a terminal near the site, where they were crushed with a CBI Magnum force 6400 equipped with gratings (mesh size 80 mm x 120 mm). Samples used for the determination of MC were weighed immediately at each site. Parallel samples used for the determination of other fuel quality parameters were kept frozen until needed. The specially prepared and cleaned stump samples for the determination of dry matter losses were weighed immediately after retrieval from the windrows (Paper II). For the determination of AC, HHV and chemical analyses, all samples were milled in a Retsch mill equipped with a mesh sieve (mesh size 0.25 mm).

Sampling after vibration for 120 s (Paper IV) was performed by removing small pieces of the stumps using a chain saw. In addition, samples from the contaminants detached during vibration were collected on a tarpaulin sheet underneath the test rig.

A Doppstadt Büffel DW 3060 crusher combined with a drum sieve was used when evaluating the cleaning efficiency of sieving in Paper V. Samples of the coarse wood (hog fuel) and the material separated by sieving were collected and used for quality analyses (Figure 7).

Figure 7. Sieving of coarse wood following crushing.

3.3 Experimental design

The experimental designs used in Papers II-V are shown in Tables 1-4 and the experimental design used for evaluating the impact of splitting rate on contaminant level in Table 5.

Table 1. *Experimental design used for evaluating fuel quality changes during storage*

Parameter	Number	Comments
Sites	2	Northern Sweden and central Sweden, both on sandy glacial till soil.
Harvesting techniques	2	Pallari & Aalto, Pallari & Rotary Cutter
Storage methods	2	Windrows and heaps. Heaps were gathered into windrows after three months of storage (Heap-windrows).
Sampling	5	Before storage and then after 3, 9, 13 and 16 months of storage.
Samples	20	Heating value, moisture content and ash content

Table 2. *Experimental design used for evaluating the vibrating test rig*

Parameter	Number	Comments
Vibration dimensions	2	Three-dimensional, X, Y, Z, and one-dimensional, Z
Stroke length	3	Distance between centre mass of discs and shaft of12, 18, 24 mm
Rotation velocity on discs	3	18.75, 21.88, 26.56 Hz
Samples for analyses	5	Acceleration and frequency

Table 3. *Experimental design used for evaluating the cleaning efficiency of vibration*

Parameter	Number	Comments
Material	2	Freshly harvested and stored stumps
Soil type	2	Sandy glacial till soil, sandy organic soil
Weight class	3	(>40 kg), (40-65 kg) and (>65 kg)
Vibration dimensions	2	Three-dimensional, X, Y, Z and one-dimensional, Z
Stroke length	3	Distance between centre mass of discs and shaft of 12, 18, 24 mm
Rotation velocity on discs	3	18.75, 21.88, 26.56 Hz
Vibration duration	4	30, 60, 90 and 120 s
Samples for analyses	1*	Weight reduction, moisture content, ash content, acceleration and frequency.

*In total, 288 samples were measured in duplicate.

Table 4. *Experimental design used for evaluating the cleaning efficiency of drum sieving following crushing to coarse wood (Paper V)*

Parameter	Number	Comments
Material	2	Freshly harvested and stored stumps
Sieving	2	Sieved and unsieved
Samples for analyses	10	Heating value (HHV), moisture content and ash content of coarse wood and the reject material.

Table 5. *Experimental design used for evaluating the impact of splitting rate on fuel quality*

Parameter	Number	Comments
Splitting rate	3	Gross, normal and fine
Samples	8	Moisture content and ash content of coarse wood.

3.4 Analysis

3.4.1 Fuel quality

The fuel quality of stump biomass was analysed using the standard methods listed in Table 6. Determinations of the heating value, moisture content and ash content were carried out at SLU. Chemical analyses were performed at an accredited commercial laboratory.

Table 6. *Standard methods used for the determination of various parameters*

Parameter	Standard	Year of publication
Heating value	SS 18 71 82	(1990)
Moisture content	SS 18 71 70	(1997)
Ash content	SS 18 71 71	(1984)
Content of C, H, N	CEN/TS 15104	(2006)
Lignin	TAPPI T 222 om-06	(2006)
Extractives	Scan-CM 49	(2003)
Volatile matter	SS-ISO 562:1	(2008)
Silica content	SS EN: 13656	(2002)
Particle size distribution	SS 18 71 74	(1990)

3.4.2 Determination of dry matter losses

Dry matter losses were calculated as the percentage loss of dry weight and expressed on an ash-free basis (Paper II). Determination of weight loss was performed after retrieving and weighing the cleaned stumps before and during windrow storage.

3.4.3 Energy balance during 13 months of storage

The percentage change in net calorific value (LHV) on a wet weight basis (w.b) in windrowed stumps was calculated using equation (1):

$$\Delta\,(\%) = \frac{\{LHV_2 \text{ x } (DM \text{ x } DML + AC_2) \text{ x } 100/\,(100\text{-}MC_2)\} - \{LHV_1 \text{ x } (DM + AC_1) \text{ x } 100/\,(100\text{-}MC_1)\}}{LHV_1 \text{ x } (DM + AC_1) \text{ x } 100/\,(100\text{-}MC_1)} \quad (1)$$

where LHV_1 is lower heating value before storage (MJ kg^{-1}, w.b.); LHV_2 is lower heating value after storage (MJ kg^{-1}, w.b.); DM is initial dry matter (kg ash-free basis); DML is dry matter loss (%); AC_1 is ash content (%, d.b.) before storage; AC_2 is ash content (%, d.b.) after storage; MC_1 is moisture content (%, w.b.) before storage; and MC_2 is moisture content (%, w.b.) after storage.

3.4.4 Vibration

The software programme Labview (National Instruments, 2009) was used to monitor vibrations in three directions (X, Y and Z) with an accelerometer sensor centrally fixed underneath the test rig. The recorded values in volts (V) were then automatically filtered by a combined analogue and digital filter (National Instruments, 2008). The filtered values were divided by the calibration constant after adjustment of the offset value provided by the manufacturer. The values were then analysed using fast Fourier transform in Matlab (MathWorks, 2008), which is a widely used method for obtaining spectral information (Marchant, 2006).

3.4.5 Statistical analyses

All trials were treated as complete randomised factorial trials. For the statistical analyses of variance (ANOVA), fixed-effect models and mixed-effect models were used. The analyses were performed in STATISTICA v.10 and SAS v.9.2. Differences between factors and interactions were considered statistically significant at $p<0.05$. A general linear model which utilises the method of restricted maximum likelihood for estimating model parameters, under the assumption of homogeneous generic variance across factor levels (Searle *et al*., 1992), was used in Paper II. In Paper IV, the ANOVA were analysed with general linear models (GLM). Stump samples were used as random factors, while factors such as soil type, weight class and all settings of the test rig were assumed to be fixed. Additionally, pair-wise analyses were performed with Tukey's HSD test.

4 Results

In the literature review concerning technical, biological and environmental issues related to stump removal for energy purposes (Paper I), it was found that information about stumps as fuel was limited. This was mainly because the focus in the past was on finding complementary substrates for the paper and pulp industries. The approaches and knowledge concerning technical aspects are discussed in the Introduction section of this thesis.

Evaluation of the performance of the vibrating test rig described in Paper III showed that the accuracy of the different vibration parameters was acceptable. It was concluded that the rig was suitable for use in evaluating the cleaning efficiency of vibration for soil-contaminated stumps.

In evaluations of changes in fuel quality caused by various handling methods, the main quality parameters studied were heating value, moisture content and ash content. In addition, dry matter losses and a number of chemical analyses relevant to fuel quality were studied.

4.1 Influence of harvesting technique and storage methods on fuel quality of stump wood (Papers II, IV)

4.1.1 Moisture content

The average moisture content (MC) of fresh stumps harvested using conventional shearing and refractive heads was around 42% on a wet weight basis, while that of stumps harvested with the Rotary Cutter was 47% (Figure 8).

Regardless of treatment, the MC declined significantly after three months of storage. Stumps extracted with the Rotary Cutter had consistently higher MC than those harvested with the conventional Pallari technique. Furthermore, stumps harvested with this prototype head clearly benefited from storage in small heaps in the clear-cut, while Pallari-harvested stumps, and whether stored in heaps or windrows, did not show any differences. Stump biomass was marginally re-wetted during autumn, but average MC declined again during the following spring and summer.

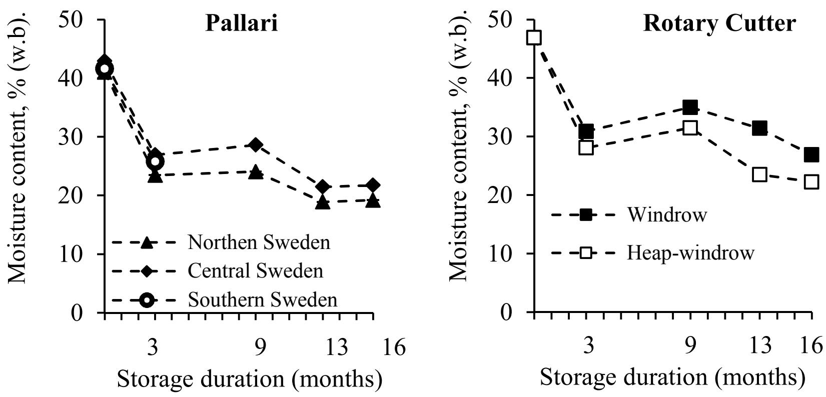

Figure 8. Average moisture content (%, wet weight basis) of (left) Pallari-harvested windrowed stumps and (right) Rotary Cutter-harvested stumps during storage in windrows and heap-windrows.

Precipitation in the month before stump harvesting was higher in central Sweden than in northern Sweden and, consequently, the soil moisture of the contaminants removed from stumps by brushing was higher in central Sweden. The soil moisture in contaminants removed by vibration was on average 11.4% and 42.6% for stumps extracted from the sandy glacial till and sandy organic soil, respectively.

4.1.2 Ash content

The ash content (AC), determined after transport and crushing of freshly harvested stumps, was almost twice as high in central Sweden as in northern Sweden (Figure 9). Stumps harvested by techniques which removed a large proportion of the shallow root system, such as Pallari, contained more contaminants and resulted in a higher AC than stumps harvested using the Rotary Cutter. Splitting rate had only a marginal effect on AC when stumps were shaken in connection with harvesting, while the AC was clearly reduced by splitting the stumps into 2-3 fractions before shaking. In general, the low AC in shaken stumps in northern and central Sweden decreased to values below 4% after three months of storage, irrespective of storage method. In unshaken stumps harvested from a sandy glacial till soil in southern Sweden, the AC was reduced by more than 50% after three months of storage. The AC contaminants removed from stumps extracted from the sandy glacial till soil was on average 94.2%, while that in contaminants from stumps extracted from the sandy organic soil was only 51.4%.

At sampling of shaken stumps after nine months of storage, the ambient temperature was below 0°C and the contaminants were visibly frozen onto the stump surface. The stump samples taken after transport and comminution had a higher AC than the initial value. However, the AC declined again in all treatments in central Sweden after 13 months of storage and was further reduced in the last three months of storage, while the low AC remained unchanged in northern Sweden (Figure 9).

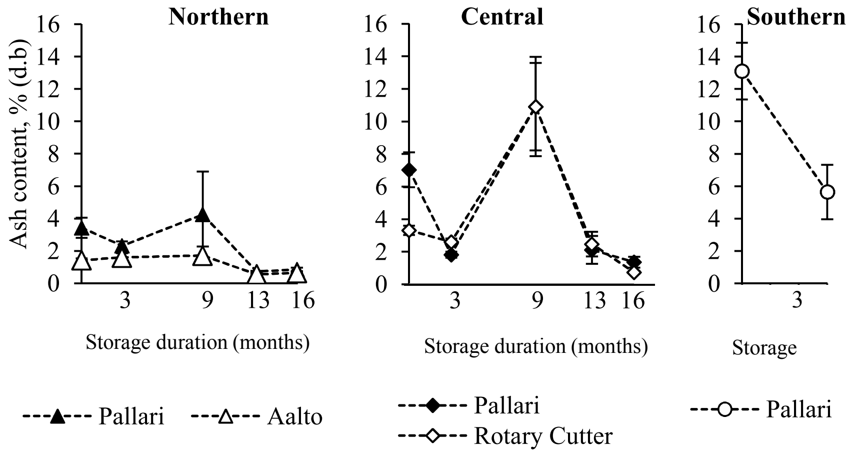

Figure 9. Average ash content (%, dry basis, 95% confidence level) of stumps harvested with different techniques and stored in windrows at three locations in Sweden.

4.1.3 Heating value

The HHV in fresh stumps harvested by the three different heads (Pallari, Rotary Cutter and Aalto) varied between 19.2 and 19.9 MJ kg^{-1} dry weight, which on average was equivalent to 20.5 MJ kg^{-1} when calculated on an ash-free basis. During storage, changes in HHV closely followed fluctuations in AC. The HHV values after three months of storage were similar (20.1 MJ kg^{-1}) in stem wood samples determined for each site. There were minor variations between harvesting techniques, storage methods and locations, but these were not statistically significant.

The LHV in fresh stumps, which was in the range 8.7-9.9 MJ kg^{-1} on a wet weight basis, clearly followed the variation in AC and MC, in particular the latter.

4.1.4 Dry matter losses

The woody biomass stored in the experimental windrows for three months showed dry matter losses in the range 1.5-3.4% dry weight (ash-free basis). After nine months of storage, the cumulative losses reached 7.7% and 5% in stumps harvested in central Sweden with the Rotary Cutter and Pallari head, respectively. The losses measured in stumps harvested and stored in Northern Sweden were significantly lower, on average 2.5%. In June 2009, 13 months after construction of the windrows, visible fungal growth, identified as *Oligoporus* spp., was observed in central Sweden. This increased the cumulative losses to 8.3% and 5% in stumps harvested with the Rotary Cutter and Pallari heads, respectively. During the same period, the dry matter losses increased to an average of 4.3% in Northern Sweden.

4.1.5 Change in energy content

The LHV (wet weight basis), calculated per stump wood ton delivered, increased in all treatments, particularly at temperatures above 0 °C (Figure 10). However, this did not include the overall change in total energy amount available after storage due to dry matter losses. In both cases, the net energy content increased during the first three months of storage as a result of cleaner and dryer stump biomass. For split stumps (harvested with Pallari and Aalto heads), the increase in LHV was in the range 4.7-9.7%, while in stumps harvested with the Rotary Cutter it increased by only 1%. Further storage continuously decreased the net energy increment in all treatments.

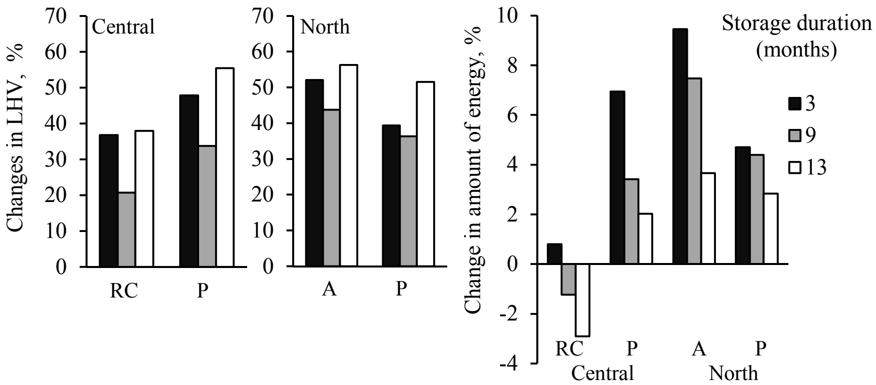

Figure 10. Changes in (left) net calorific value (LHV, wet weight basis) and (right) total amount of energy in stumps harvested and stored in windrows in northern and central Sweden. The harvesting heads used were Rotary Cutter (RC), Pallari (P) and Aalto (A).

4.2 Cleaning stumps with vibrations (Papers IV)

4.2.1 Cleaning efficiency

Contaminants were efficiently removed by vibrations irrespective of stump weight, soil type and the settings of the test rig (Figure 11). The highest reduction in contaminants was found in fresh massive stumps [>65 kg] harvested on sandy glacial till soil (SGS). However, these stumps were still more contaminated after vibration than the stumps from the other weight classes.

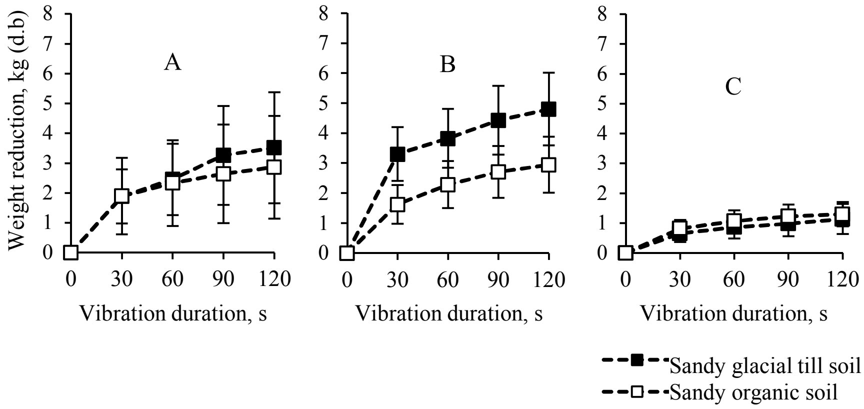

Figure 11. Cumulative weight reduction of contaminants after stump vibration in (A) the Z dimension and (B) and (C) in three dimensions. Vibration was performed with freshly harvested stumps in (A) and (B) and stored stumps in (C). The bars show 95% level of confidence.

The average AC in fresh stumps harvested from the SGS was reduced from 13.8% to 6.4% after 30 seconds of vibration in three dimensions, while 90 seconds of vibration were required to achieve an acceptable AC of below 4% (Figure 12). After 120 seconds, the AC was only 2.2% and the presence of contaminants was scarcely visible on the material (Figure 13).

Vibration in only the Z dimension was just as effective as vibration in three dimensions in reducing the presence of contaminants in stumps (Figure 11). On average, it was sufficient to vibrate the stumps for 30 seconds when vibrating only in the Z dimension, which reduced the AC from 11.2% to 2.5%. However, the contaminants attached to the stumps were slightly dryer and in particular the presence of larger stones was less common in this soil. Further vibration in the Z dimension did not have a significant effect on ash content. The vibration duration required for cleaning stumps harvested from the SGS was 30 seconds, irrespective of vibration dimensions (Figure 12).

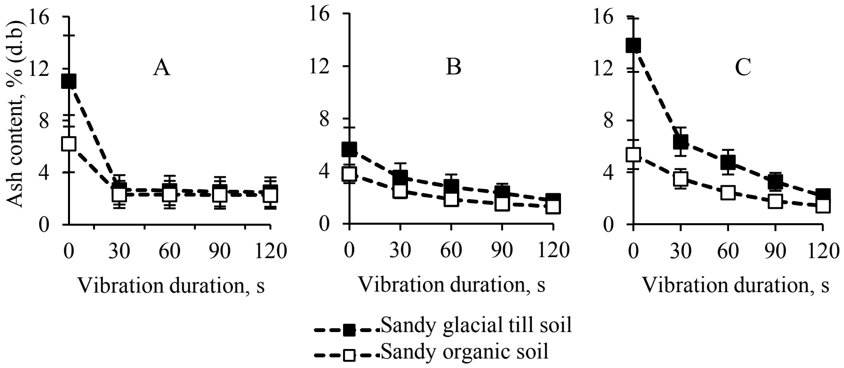

Figure 12. Average ash content in stumps harvested from two soil types after vibration in (A) the Z dimension and (B) and (C) in three dimensions. Vibration was performed with freshly harvested stumps in (A) and (B) and stored stumps in (C). The bars show 95% level of confidence.

Vibration of summer stored stumps reduced the average AC from 4.7% to 3.0%. The reduction was not correlated to the acceleration amplitude and the frequency when stumps were vibrated in three dimensions, while the highest acceleration amplitude, 5.15 g, when stumps were vibrated in only the Z dimension significantly (p<0.05) favoured a reduction.

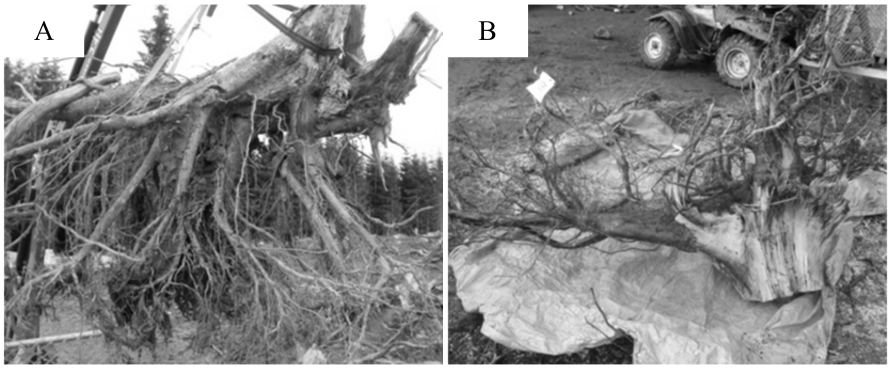

Figure 13. The same Norway spruce stump harvested from the sandy glacial till soil (A) before and (B) after vibration for 120 seconds.

4.2.2 Vibration impact on net calorific value

Vibration in three dimensions for 30 seconds increased the LHV (w.b) from 8.6 to 9.2 MJ kg^{-1} in stumps harvested from SGS. This was the only significant increase in LVH in terms of wet weight. However, the LHV on a dry weight basis increased with vibration duration, although more moderately, after 30 seconds of vibration.

4.3 Impact on fuel quality of drum sieving coarse stump wood fuel

4.3.1 Cleaning efficiency

The direct impact of sieving after crushing on fuel quality was that both MC and AC decreased significantly ($p<0.05$), even though the contaminants were firmly attached due to frozen conditions. In stored stumps, which after comminution had an AC of 9.2% and a MC of 27.3%, post-crush sieving reduced the AC to 1.1% and the AC to 24.8%. The lost material, which mainly comprised soil contamination, fines and ice, had an AC of 34% and a MC of 34.9%. For freshly extracted stumps, 20% of the comminuted material was lost. The MC in the coarse stump wood fuel decreased from 37.8% to 35% and, more importantly, the AC decreased from 7.3% to 1.5%, while the lost material had an AC of 30.9% and a MC of 38.9%.

The sieved coarse stump wood fuel was stored uncovered in heaps from October until September of the following year. The AC remained unchanged during the whole storage period. However, the MC increased, which decreased the LHV. Moreover, dry matter losses determined on an ash-free basis after 7 months of storage reached 1.4% and 4.3% in heaps of stump coarse wood fuel produced from stored and freshly harvested stumps, respectively. These dry matter losses increased to 4.2% and 8.4%, respectively, after 11 months of storage.

4.3.2 Comparison of a standard supply system with sieved coarse stump wood fuel

One of the standard stump supply systems was compared with a system for sieved coarse stump wood fuel (Figure 14). Both included the same base machines, *i.e.* stump harvester and forwarder, but different machines for comminution and transport.

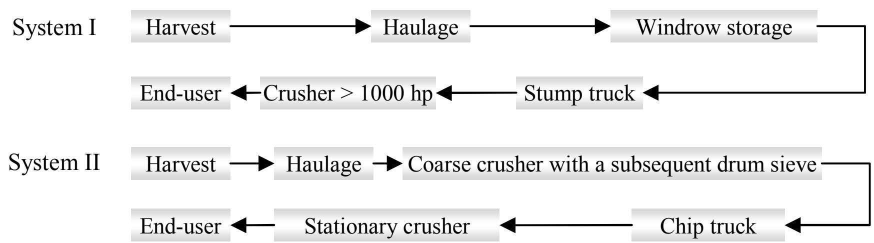

Figure 14. Flow diagram comparing the standard stump supply system (I) with a system involving on-site crushing and drum sieving (II).

Based on previous results, the fuel composition of freshly extracted stumps was assumed to be: C 48%, H 5.8%, S 0.1 %, N 0.1 % and O 38.5%. The initial ash content was set to 7.5% and the moisture content to 40%. The HHV was calculated to be 19.5 MJ kg^{-1} and the LHV 9.9 MJ kg^{-1} (w.b) by including these assumed values in equations (2) and (3), respectively:

$$HHV = 0.3491\ X_C + 1.1783\ X_H + 0.1005X_S - 0.0151X_N - 0.1034X_O - 0.0211X_{Ash} \quad (2)$$

where X_C is carbon content; X_H is hydrogen content; X_S is sulphur content; X_N is nitrogen content; X_O is carbon content; and X_{Ash} is ash content.

$$LHV\ (w.b.) = HHV\ (1\text{-}w/100)\ -2.444\ (w/100) - 2.444(h/100) \times 8.936(1\text{-}\ w/100) \quad (3)$$

where w is MC (wt.%); 2.444 is the enthalpy difference between gaseous and liquid water at 25 °C; and 8.936 is M_{H2O}/M_{H2}, *i.e.* the molecular mass ratio between H_2O and H_2

Assuming that MC decreased to 30% and AC to 4% in system I, the HHV increased to 20.3 MJ kg^{-1} and the LHV to 12.5 MJ kg^{-1}. In addition, dry matter losses reached 4% in this system, so that the amount of energy from an initial ton (wet weight basis) amounted to 5.0 MWh ton^{-1} (d.b.) and 3.3 MWh ton^{-1} (w.b.).

In system II, it was assumed that the MC decreased to 38% and the AC to 2%, which increased the HHV to 20.7 MJ kg^{-1} and the LHV to 11.1 MJ kg^{-1}. The material lost in sieving amounted to 20% (w.b), but the loss in total amount of energy expressed as LHV was 14% on a dry weight basis and 11% on a wet weight basis.

An economic comparison was made in an Excel-based programme for system analyses (von Hofsten, 2006). The results from this evaluation indicated that the cost (M Wh^{-1}, d.b. delivered biomass), if accepted at the end-user, is lower in system I than in system II until the transport distance exceeds 70 km.

5 General discussion

The introduction of tree stumps as a complement to high-demand forest fuels can increase the share of indigenous renewable biofuel in total energy consumption and contribute to the replacement of fossil fuels. However, some issues concerning environmental effects related to stump harvesting for energy are still unknown, and therefore it cannot be stated that stump harvesting is environmentally fully justifiable.

As fuel, stump wood in commonly associated with a high presence of contaminants, resulting in high AC and operational problems such as sintering during combustion. One of the major tasks of the stump procurement process is to reduce the level of contaminants. The concentration of contaminants depends on a number of factors, such as soil type, weather conditions, harvesting method, storage duration and other handling operations. The high AC, which is often above the generally accepted value of 4%, is the major drawback when using stump wood as fuel. Handling methods that could improve fuel quality are therefore highly desirable. In order to produce acceptable fuel quality, an evaluation of the influence of the above-mentioned factors is necessary. Such an evaluation is presented below.

5.1 Effect of soil type

Contaminants attached to stumps mostly originate from the soil, which implies that soil composition is reflected in ash mineral components. Different soil types contain different amounts of non-combustible material, which results in different AC. A higher AC can be expected in mineral soil, *e.g*. SGS, than in sandy organic soils like SOS. This was evident in the results of ash measurements made on contaminants collected after vibration of stumps extracted from these two soil types.

Another factor that affects contamination level is the moisture content of the soil. The results in Paper IV showed that dry soil had less adhering contaminants, and thus lower ash content, than wet soil. This confirms findings that the risk of soil adhesion increases in soils with high water content (Spinelli, 2005). It is therefore reasonable to expect that there will be a lower level of contaminants attached to stumps during harvest in spring and early summer than in autumn. The general variations in contaminant rate relating to soil type and harvesting season presented in Papers II-V are in line with previous reports (Nylinder, 1977).

5.2 Choice of harvesting method

A number of factors related to the effect of different harvesting methods on soil compaction and soil disturbance, as well as fuel quality and total production costs, must be considered when choosing a harvesting method. Stump biomass used as fuel must have a quality that is accepted by the end-user. The fuel must also be produced at a reasonable cost, without compromising fuel quality. In addition, negative silvicultural effects must be mitigated.

A number of stump harvesting heads, mainly heads that split the stump, are available today. The choice of extraction head affects the major parameters (MC, AC and HHV) throughout the whole supply chain. In addition, expected dry matter losses and the amount of available energy must be considered. Splitting stumps facilitates the drying process due to exposure of a larger surface area. Rapid drying of the surface also hinders the establishment of wood-degrading fungi that can cause dry matter losses.

Splitting stumps with current techniques, shearing and refractive heads, enables extraction of more biomass than the Rotary Cutter, which mainly extracts the central extension of the stem. The extraction productivity, measured in E_{15} h^{-1}, is almost the same for all heads but the extracted volume of the Rotary Cutter is less than 50% (von Hofsten, 2007). However, using shearing and refractive heads allows the contaminants present between roots to remain on the harvested material.

Root size and root morphology are, at least initially, crucial for the amount of contaminants attached to extracted stumps. In general, more contaminants were found to be present on stumps split into few parts. This confirmed earlier observations (Nylinder, 1977). However, further splitting of stumps did not lead to further improvement in fuel quality and the initial difference in ash content was offset by following handling steps of transport and comminution (von Hofsten *et al.,* 2012).

As regards the effects of harvesting heads on soil disturbance and soil compaction, extraction of only the central part of the stem could be preferable to the current practice. This is because roots that are left in the soil could serve as structural reinforcement and reduce soil damage. However, stump extraction removing only the central stem will not reduce existing infections of root rot. Fungi survive in roots, which can infect the next tree generation by root contact.

Stump extraction is therefore better performed employing heads that can split and shake the stump during extraction.

5.3 Choice of storage system

The time gap between possible harvesting season and the period of highest demand for wood fuels creates a need for storage. Moisture content, in both contaminants and stump wood, often declines during storage. Dry contaminants can be reduced by precipitation and handling during transport, which thereby cleans the biomass and improves fuel quality. The current practice is based on the assumption that storage in heaps on the clear-cut for a couple of months can contribute to a reduction in contaminants. However, direct storage in windrows is still an available option. In the Nordic countries, the contaminants are usually frozen on the stumps when the fuel is required during late autumn and winter. The results in this thesis confirm that the AC in stumps is higher under such conditions.

The results for storage in heaps and direct storage in windrows showed similar values for MC and AC as long as the stumps were split. This is most probably due to favourable placement of heaps and windrows, in which the stored material was exposed to maximum sun and wind. However, such favourable placement is not always possible.

Gathering split stumps directly into windrows at the roadside instead of storing them in small heaps in the clear-cut provides two advantages. The logistics for forwarder use for collecting forest residues can be more efficiently coordinated with stump removal from the clear-cut area. Such coordination of forwarding, when possible, can reduce transport costs. Windrow storage at the roadside also facilitates regeneration operations, which can result in one year faster tree establishment.

The reduction in MC in stumps extracted with the Rotary Cutter head was favoured by storage in small heaps. This was probably due to the shape of the stump and the lack of roots, which meant that windrows built with these stumps were more compact than the other windrows.

The larger surface area of the split stumps improved the drying process during storage. The MC in spring-harvested stumps rapidly decreased during the first three months of storage, from approximately 40-50% to around 25%. Similar results have been reported previously (Nylinder & Thörnqvist, 1978; Laurila & Lauhanen, 2010). A similar decline in MC has been reported in studies dealing with other forest fuel assortments (Pettersson & Nordfjell, 2007). In Paper II, the average MC in split stumps was, in general, significantly lower than that in Rotary Cutter-harvested stumps, especially when the stumps were directly stored in windrows for 13 months.

In general, large amounts of contaminants, which become drier after storage, can fall off the stumps during the following handling operations, such as loading/ unloading, transport and crushing.

The HHV was found to be strongly correlated with the AC and closely followed variations in the latter during storage (Paper II & IV). It is also possible that changes in wood components during storage could affect the HHV in both directions. However, our results showed no significant correlation between these two parameters.

The LHV of the fuel generally reflected changes in MC. However, using heating value to compare the effect of storage duration on the energy content of a fuel does not show the entire picture, since dry matter losses, which can occur during storage, are not taken into consideration. The dry matter losses steadily increased during the first nine months of storage in all treatments in Paper II. The losses were significantly higher in stumps harvested with the Rotary Cutter, which also consistently showed higher MC. The latter could be the cause of establishment of wood-degrading fungi. However, the dry matter losses were still small compared with those reported for other forest fuel assortments (Jirjis & Nordén, 2002; Pettersson & Nordfjell, 2007; Anerud & von Hofsten, 2010).

When dry matter losses were included in the calculation of changes in total amount of energy, storage for a period longer than three months reduced the energy content. However, shorter storage duration can affect the possibility to sufficiently remove contaminants. To solve such a problem, faster and more efficient methods to clean the stumps are highly desirable.

5.4 Possibility of improving fuel quality before or after comminution

To improve stump fuel quality and increase its value, a cleaning method at an early stage of the supply chain, either before or after comminution, could be considered. Two cleaning methods, vibration and sieving were evaluated in this thesis. In general, all fuel quality parameters were improved by using the cleaning methods tested. However, both methods have advantages and disadvantages that need to be considered.

5.4.1 Cleaning stumps before comminution using a vibration-based method

The vibration-based method was efficient for cleaning freshly harvested stumps and stumps stored for three months. However, the stumps were vibrated individually, with no influence from other stumps, which gave maximum cleaning effect.

It was clear that acceleration amplitude and its frequency did not significantly affect the cleaning efficiency when using vibrations in three dimensions, as could otherwise have been expected. This was probably due to a combination of factors related to contamination level, composition and distribution of these contaminants. Moreover, the cleaning efficiency was at least as effective when stumps were vibrated in only the Z dimension compared with in three dimensions (X, Y and Z). This suggests that a one-dimensional vibration device is sufficient for cleaning stumps.

Stumps could be efficiently cleaned by using the vibration-based method in connection with extraction or after a few months of storage, *i.e.* when the ambient temperature is above 0 °C. By using this method, fuel with improved AC, HHV and LHV can be produced and utilised in the same season as the stumps are extracted. If further storage is required, clean un-comminuted stumps will suffer lower dry matter loss than comminuted biomass (Anerud & Jirjis, 2011; von Hofsten & Anerud, 2010). In this case, the energy density will also be improved, but the transported volume will remain unchanged.

The implementation rate and whether it is practically feasible to introduce a large-scale vibrating device other than at terminals are impossible to predict. In addition to the cost of the vibrating machine, the cleaning efficiency in operational practice with such a device is an uncertainty that has to be accounted for.

5.4.2 Cleaning stump wood after comminution using a drum sieve

The results showed that it is possible to clean stumps after comminution process (crushed biomass) by sieving it. This method was effective in reducing contaminant levels and improved both fuel quality and energy density. More importantly, it showed that it was possible to separate contaminants even when the material was frozen. This is a clear advantage, since the method could be performed all year round and the fuel could be used in the same season as it is harvested. Moreover, higher payload will be achieved during transport of stumps crushed into coarse wood, which could make it more profitable than a supply system in which stumps are delivered by truck to the end-user. This is especially true when transport distance exceeds 70 km. Furthermore, extraction productivity can be increased if stump cleaning can be performed by sieving instead of shaking the stumps during extraction.

However, considerable amounts of combustible material are lost in this handling method, even though most of it is unwanted fines. In addition, higher dry matter losses are inevitable if storage is required. The overall benefits of this method can, however, outweigh the disadvantages depending on contaminant rate and transport distance.

5.5 Possibility of mitigating some constraints of stump harvesting

The environmental benefit of stump harvesting is that it can contribute to the replacement of fossil fuels and thus reduce CO_2 emissions (Melin *et al.,* 2010). The benefit of replacing fossil fuels with forest biomass increases with long-term perspective (Lindholm, 2010; Zetterberg, 2011; Repola *et al.*, 2012). However, harvesting will decrease dead wood left after clear-cut. This may lead to reduced biodiversity if not compensated and further research is required to close knowledge gaps (Persson, 2012).

As to the risk of decreasing terrestrial carbon sink, recent studies showed somewhat different results (Grelle *et al.*, 2012; Strömgren & Mjöfors, 2012). This could be due to various factors such as choice of soil scarification method, soil type and soil moisture.

A slight increase in soil compaction following harvesting has been reported in many studies (Thies & Westerlind, 2005; Hope, 2007; Zabrowski *et al.*, 2008). It is uncertain whether stump harvesting leads to more damage than ordinary silvicultural practices such as soil scarification by harrow (Paananen & Kalliola, 2003). However, it is reasonable to assume that the risk of deformation in moist soils is larger after stump harvesting followed by forwarding, since the shallow reinforcement provided by roots is removed. The risk can possible be reduced by better logistic solutions and route planning.

Improved soil stirring can be advantageous for the establishment of tree seedlings and it was shown that seedlings increased in stands where stumps were removed (Kardell, 2007). In addition, seedling mortality decreases (Piiri & Viiri, 2009). A general negative effect on individual tree growth after stump removal cannot be firmly stated, since many conflicting results have been reported (Wert & Thomas, 1981; Wilson & Pyatt, 1984; Weber *et al*., 1985; Froehlich *et al*., 1986; Thies & Nelson, 1988; Kazerskii, 1990; Wass & Senyk, 1996; Wass & Smith, 1997; Page-Dumaroese *et al*., 1998; Thies & Westerlind, 2005; Hope, 2007). On the other hand, stump harvesting is the most effective way to reduce the presence of root rot (Hypell, 1978; Vasaitis *et al*., 2008), which decreases the annual forest increment and causes damage to stem wood quality.

The issues mentioned above are few of many aspects related to possible consequences of stump harvesting. The question is whether the benefits of stump harvesting outweigh those of leaving the stumps in place in the clear-cut. Studies seeking to answer this question must address different points of view, since there are conflicting national goals. Bearing this in mind, both environmental and technical issues must be considered.

6 Conclusions and final remarks

At present, it cannot be concluded that stump harvesting is environmentally justifiable. Furthermore, it is not known whether the threat to biodiversity or the soil carbon balance is larger than that posed by conventional silviculture in Sweden.

To achieve acceptable fuel quality, the procurement method for stump wood, including extraction machinery, storage procedure and suitable pre-treatments, should be carefully planned before harvesting. Choice of stump harvesting head, *i.e.* whether it splits stumps or not, has an impact on fuel quality, since splitting of stumps to 2-4 pieces during extraction allows better drying during storage. In addition, more biomass is extracted. However, increasing the splitting rate compared with the conventional procedure is unnecessary and does not lead to further improvements in fuel quality. Techniques that allow splitting during extraction should be the first choice as long as the risk of soil damage and soil compaction is moderate.

Some form of storage is necessary to meet the uneven demand for wood fuel during the year. It is better to store stumps before they are comminuted, since dry matter losses increase as the particle size of stored biomass decreases. However, choice of storage method for stumps, *i.e.* whether stumps are stored in heaps or directly in windrows, does not affect fuel quality as long as the stumps are split and not comminuted. Immediate storage of stumps in windrows at the roadside is preferable, since this can allow regeneration operations to go ahead in the clear-cut. In general, fuel quality can be improved after storage, since moisture content and ash content decrease, resulting in a higher heating value. This does not reflect the whole picture, however, since dry matter losses occur during storage, and therefore the storage period should be kept as short as possible. However, contaminants are usually frozen on the stump surface during winter, which is the period when wood fuel is in highest demand. Therefore storage for periods longer than a year may be necessary to achieve acceptable fuel quality.

Improving the supply chain of stumps by reducing the storage time would require the use of rapid and efficient methods for removing contaminants at an earlier stage of the supply system. Two such methods were evaluated here. A vibration-based method proved to be very efficient in cleaning harvested stumps. Commercial development of such a method is possible, but issues relating to machine cost, cleaning efficiency on a large scale and suitability for use at clear-cut sites remain unsolved. Cleaning stumps by sieving them after crushing to coarse wood also proved to be effective in improving fuel quality and increasing energy density, which can decrease transport costs. The benefits of this method can outweigh the disadvantages, depending on transport distance and level of contamination.

Use of efficient cleaning methods can allow acceptable wood fuel from stump biomass to be supplied during a single harvest season.

7 Recommendations for practical implementation

- Stump harvesting heads that can split the stump are generally preferable.

- Storage form has a minor effect on quality parameters if the stumps are split. Therefore, windrow storage is preferable since it makes it easier to clear the site for other stand regeneration operations.

- Stumps harvested in favourable conditions in early spring can be used as a fuel in the same season if handled before winter months. Stumps extracted later in the season must be stored until the next season unless an efficient cleaning method is used.

- Stumps should, if possible, not be transported and comminuted at temperatures below 0 °C in order to avoid higher rates of contaminant adhesion, which considerably increases the ash content of the fuel.

- An efficient method for cleaning stumps can improve fuel quality at an earlier stage. This can decrease the storage duration required and lower the dry matter losses.

- If active cleaning, such as sieving, is performed as a separate procedure, the harvesting productivity can be increased by at least 20% due to the shaking step being avoided.

- Cleaning stumps through sieving of coarse stump wood is an efficient method to increase fuel quality and decrease transport costs.

8 Future research

Technical developments are required in several steps within the procurement system for stump wood. For instance, it is desirable that the development of base machines and stump harvesting heads leads to the replacement of excavators in favour of large commercial forwarders. Harvesting methods that decrease the risk of soil compaction and lower the soil disturbance are desirable. Moreover, finding methods that lower the energy consumption across the supply chain should always be a goal, both for environmental and economic reasons. A procurement system for stump wood where the cleaning process is separated from harvesting provides many advantages. This is one area where research is urgently needed, since it could:

- Increase productivity
- Reduce production costs
- Improve fuel quality

These advantages would clearly increase the profitability of the supply system.

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