Stump as a fuel – the influence of harvesting technique and storage method on fuel quality of Norway spruce

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Abstract

Uncertain long-term availability of fossil fuels and the negative environmental impact of using it have created an urgent need for reliable renewable energy sources. Wood fuel, particularly forest residues is one of these sources which are in high demand in Sweden today. Stumps can be used as a complement to these, since they contain high concentrations of energy-rich lignin and extractives. However, stump removal can have negative environmental effects such as reduction of biodiversity and disturbance of nutrient balance in the soil. As to the fuel quality of stump biomass, there are some concerns connected with the utilisation of stumps since presence of excessive contaminants leads to high ash contents which reduce its value as fuel and causes operating problems. To ensure the supply of fuel of acceptable quality, an optimal system for harvesting, handling, and storage must be devised for stump procurement. The main aim of this work was to evaluate various stump harvesting techniques, storage methods (windrow or heaps), and different storage durations at two geographical locations and examine their effect on the fuel quality of Norway spruce stump biomass. Fuel quality parameters moisture content, ash content and calorific value were evaluated on five occasions during May 2008 - September 2009. Stump harvesting techniques that split the stumps allowed better drying during 13 months of storage. Storage method had no clear effect on these stumps. The ash content decreased considerably, particularly when transport and crushing took place at temperatures exceeding 0°C. In general, fuel quality was improved in all treatments after storage. However, as the storage time progressed, the net energy increment became continuously smaller due to the increased substance losses.

Keywords: ash content, calorific value, moisture content, stump wood, wood fuel quality.

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Dedication

To Victoria 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 Stumps as a fuel – a review of the supply chain from harvesting to end-user. Anerud, E. Jirjis, R. Nordfjell, T. (2010) *To be submitted to Renewable & Sustainable Energy Reviews.*

II Anerud, E. & Jirjis, R. (2010). Fuel quality of Norway spruce stumps – Influence of harvesting technique and storage method. Submitted *to Scandinavian Journal of Forest Research.*

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

I 80 % of the total work including the study of literature, writing and preparing the paper for publication

II 80 % including projection of field experiments, sampling, chemical analyses, writing and preparing the paper for publication

1. Introduction

Uncertain long-term availability of fossil fuels and their negative environmental impact have created an urgent need for reliable renewable energy sources such as biofuels. In 2008, renewable fuels comprised 44.1% of the total Swedish energy supply of 612 TWh (Anon, 2009a). Forest logging residues (*e.g.* branches and tops) constitute the major renewable assortment used for energy today and are 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 3 billion m^3 (stem volume over bark from stump to tip). The most common species, Norway spruce (*Picea abies* (L.) H. Karst) and Scots pine (*Pinus sylvestris* (L.) H. Karst), contribute 41% and 38% of the standing volume, respectively. With an annual final felling area of around 200 000 hectares, the harvested volume per year reached 87 million m^3 between 2005 and 2007 (Anon, 2009c). One way to meet the growing demand for forest biomass for energy production, without increasing the annual harvesting volume of stem wood, is to utilise stumps. By definition, the stump is all belowground and aboveground wood and bark mass of a tree beneath the merchantable timber cross-section (Hakkila, 1989). The stump, including roots thicker than 5 cm, constitutes 23-25% of the stem volume (Hakkila, 2004). Stump wood has been utilised during different periods for various purposes, such as tar and pulp production. Today, stumps are not used for either of these purposes and can be a potential source of energy. There is currently increasing interest in stump harvesting in Sweden, with the Swedish government recently highlighting this as a potential source of forest fuels (Anon, 2009b). From an energy perspective, extracted stumps from cleared felled sites could increase the annual contribution of renewable fuels by 57 TWh (Anon, 2008). When technical, economic and environmental restrictions are taken into consideration, this figure decreases to 21 TWh. The Swedish Forest Agency (2009) has estimated that taking account of these restrictions, stump extraction is practically feasible on 5-10% of regeneration felling sites, which would correspond to an annual energy supply of 1.3-2.6 TWh.

Harvesting of stumps for energy purposes are not uncontroversial and several issues concerning the environmental effects have not yet been resolved (Egnell *et al.*, 2007; Walmsley & Godbold, 2010). Extraction of stumps can decrease biodiversity, since stumps constitute the largest proportion of dead wood, which is a vital habitat for a variety of fungi, lichens, mosses and invertebrates. However, it is not likely that any species is specifically linked to stumps (Dahlberg, 2008). Stump harvesting increases stirring of the soil, which may lead to increased mineralisation and leaching of minerals. Furthermore, there is a risk that the terrestrial carbon sink will decrease (Egnell *et al.*, 2007). It is not known whether stump harvesting increases these risks compared with ordinary scarification. On the other hand, stump harvesting is the most efficient way to reduce the amount of root rots (Hypell, 1978; Vasaitis *et al.*, 2008), which annually decrease the forest increment and cause damage to stem wood quality corresponding to approximately €50 million in Sweden alone. Increased stirring of soil also increases the total number of established tree seedlings (Kardell, 2007) and decreases seedling mortality (Piiri & Viiri, 2009).

1.1 Quality parameters of wood fuel

A number of parameters are used to describe the quality of wood fuel, mainly including heating value, moisture content and ash content. Other characteristics of wood fuel are also of considerable importance. For example, particle size distribution can affect the fuel feeding process and the evenness of combustion, amongst other things. *Heating value* can be expressed as calorific value ($qv,_{gr}$) or net (or effective) heating value ($qp,_{net}$). By definition, the calorific heating value 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. The heating value of a type of biomass (without contaminants) is a reflection of its chemical composition. The net heating value is the energy that can be generated without condensation of vapour and is calculated from the calorimetric value by deducting the energy used for evaporation of water. This value can be expressed on either a dry basis or for a specific moisture content.

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 *moisture content*, which is the amount of water in relation to the total green weight of the woody material, is an important quality parameter since evaporation of water during combustion reduces the amount of effective energy that can be extracted from the biomass. Moreover, high moisture content affects the whole supply chain negatively, especially during storage and transport.

Ash is the by-product of wood fuel combustion. Wood ash usually contains two components; natural unburnable minerals originating from the biomass and inorganic components from soil, sand, stones and other 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 increase wear and tear on comminution machinery, which is the main reason why equipment such as crushing machinery is used instead of chippers for size reduction of stumps. Depending on the composition of the minerals, different combinations of minerals during combustion can either increase or decrease the ash melting temperature. This 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, *e.g.* particles less than 5 mm in diameter, can cause problems during fuel utilisation such as blockages in the feeding process and a highly compacted fuel bed. Furthermore, small fractions may 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.

1.2 Stump wood characteristics

The primary functions of stumps include absorption and conduction of water and minerals, translocation and storage of energy and anchoring of the tree. Absorption of minerals takes place in the fine roots, which also have the highest concentrations of nutrient (Hellsten *et al.*, 2009). The lateral roots and the taproot are the anchoring parts of the stem, while the central part of the stump is in principle an extension of the stem. The chemical composition of the different parts of the tree varies considerably depending on their specific primary function. Stump biomass, particularly the lateral roots and the taproot, contains higher concentrations of extractives and lignin than stem wood (Eskilsson & Hartler, 1973; Hakkila, 1975; Nurmi, 1997). The concentrations of the major wood components also depend on other factors such as species and geographical location.

Stumps are usually covered with contaminants that increase their ash content and reduce their calorific value. These two problems are the main quality issues that have weakened the interest in using stumps as a fuel. However, stump biomass can still be an acceptable fuel if treated correctly. It is necessary to employ a suitable handling and storage system that can considerably improve the fuel quality of stumps by decreasing the ash content and moisture content.

1.3 Supply chain

1.3.1 Harvesting

Stumps harvested today are extracted from 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 can increase the risk of fungal infections such as root rots. The techniques used are in principle the same techniques developed during the 1970s (von Hofsten, 2006). An excavator, usually weighing 21 to 23 metric tons and equipped with a stump lifting head, is used in all techniques (Kährä, 2007). The two main methods commonly used for the extraction of stumps involve either a shearing or refractive head. The main difference between these two heads is that the shearing head splits the stump in the ground before lifting by pressing a forked part of the head against a wedge, while the refractive head is equipped with prongs and extracts the stump by pressing the largest prong under the stump and then pulling it up. Using a refractive head does not always split the harvested stumps.

The stumps of Norway spruce contain more biomass than those of Scots pine owing to the presence of thick lateral roots in the former (Hakkila, 1989). Norway spruce stumps are also easier to extract, which makes them more interesting for energy production. A considerable amount of soil and sand always adheres to harvested stumps, while other contaminants such as gravel and stones 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 around the extraction time and tree species (Nylinder, 1977).

The various fractions of contaminants have different adhesion capacity, *e.g.* small fractions are more tightly bound to the stump-root system. This binding is particularly strong if the soil contains clay (Spinelli *et al.*, 2005). High soil water content increases the risk of strong adhesion and weather conditions during the extraction and handling of stumps are decisive in this regard. In general, dry contaminants are easier to remove. Due to the superficial root system of Norway spruce, its stumps contain less contaminants than Scots pine, which has a deeper root system (Nylinder, 1977). To remove the contaminants, the stumps are normally shaken immediately after extraction. Further decontamination occurs during storage and rough handling during the other phases of the supply chain, *e.g.* hauling, transport and crushing.

1.3.2 Storage

In the supply system commonly used today, harvested stumps are stored for varying periods before they are consumed as a fuel (Figure 1). There are two reasons behind this practice; to meet the uneven annual demand for the wood fuel and, more importantly, to remove excess dirt and moisture and thereby improve the fuel quality. In Sweden, the major use for biofuels is in heat production. The main demand occurs during the colder periods, autumn and winter, when stumps cannot be harvested. Storage for a few months is therefore necessary. During storage, the moisture and ash contents are usually decreased, which consequently increases the heating value of the stumps. After extraction, the stumps are normally piled in small heaps and stored in this form for a few months before they are gathered into windrows by the roadside. Sometimes the stumps are hauled to a windrow immediately after extraction. Storing the stumps in about 1.5 m high heaps instead of directly hauling them into windrows is based on the assumption that the cleaning process is facilitated by having a large surface exposed to sun and precipitation. In Finland, based on practical experience, the stumps are normally stored for at least one year (Alakangas, 2005). Results from a small-scale storage trial showed that the moisture content of Norway spruce stumps decreased from approx. 50% to 22.4% (wet basis) during 14 months of storage of split stumps (Nylinder & Thörnqvist, 1981). In that study, the stumps were extracted in autumn and had the lowest moisture content in the following summer. Further storage until autumn caused re-wetting of the stumps. Re-wetting of woody biomass during autumn and winter has also been reported during the storage of non-chipped forest residues (Jirjis, 1995).

A very few reported studies and a good deal of practical experience support the view that storage can improve the fuel quality by reducing the amount of contaminants. The freshly extracted stumps can be a suitable substrate for microorganisms, which can cause substantial dry matter losses during long storage periods. However, there are no data available on the amount of dry matter losses that can be caused by storage. The extent of biological degradation of woody biomass depends on the type of fungi that colonise the material. Moulds and stain fungi cannot destroy the cell wall as rot fungi do. Different types of rot fungi have a specific ability to decompose various wood components, *e.g.* brown rot and soft rot specialise in degrading cellulose and hemicelluloses, while white rot fungi can decompose lignin, which is the highest energy carrier among the cell wall components. Such a fungal attack can cause considerable losses of combustible biomass.

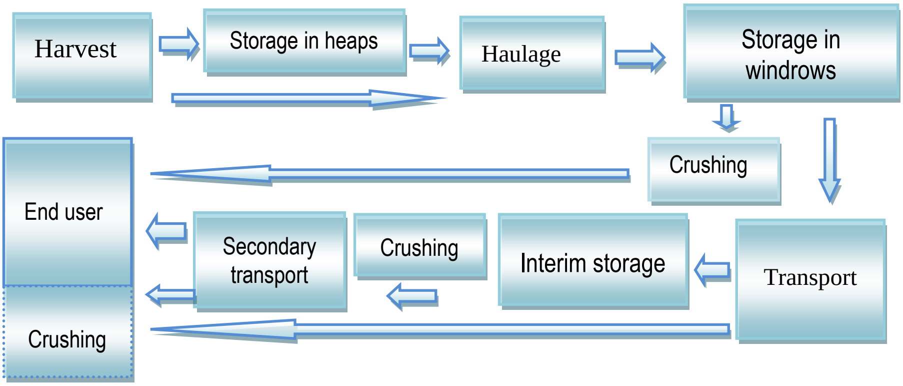

Figure 1. Flow diagram showing various stages in the supply chain of stumps.

1.3.3 Transport

The transport system includes forwarding and truck transport. The bulky shape of the stumps makes it difficult to achieve full payload on trucks, which increases the transport costs (Hansen, 1977). A similar problem has been encountered during the transport of other assortments of wood fuel such as forest residues, trees and tree sections (Nilsson, 1983). The payload increases if the stump root-system is stowed or size-reduced at the loading site (Carlsson & Larsson, 1981). However, there is a risk of increasing the contaminants if the crushing is performed at the loading site (Liss, 2006). The situation becomes even worse if the fuel needs further storage, since dry matter losses during storage of comminuted wood are known to be higher than those during storage of whole branches and tops (Lehtikangas, 1999). The stumps are normally transported directly to a terminal close to the end-user for crushing, but they can also be transported to a terminal for interim storage or for crushing before further transport (Figure 1).

1.3.4 Crushing

Heating plants and combined heating and power plants (CHP) normally burn the wood fuel as chips, and a size reduction step (chipping or crushing) during procurement of the fuel is therefore necessary. Due to the high level of contamination in stump wood, more robust crushers are used instead of chippers for stump size reduction (Hakkila, 2004). These are based on a toothed solid steel rotor, which by fast rotation crushes the stumps (Figure 2). The machine used in the study presented in Paper II, a CBI Magnum Force 6400 crusher, weighs around 30 metric tons and has a throughput of 182 metric tons per hour (Figure 2). However, the throughput of this crusher has been reported to be 80 metric tons per hour when stump wood is crushed. The crushing capacity depends on stump shape, volume and the amount of stumps fed into the system (Lindberg, 2008).

Figure 2. CBI Magnum Force 8400 horizontal hog with European chassis

2 Aims and objectives

An optimal system for stump procurement requires careful choice of suitable harvesting and storage methods to ensure the supply of fuel of acceptable quality at the right price. It is highly desirable to employ an efficient harvesting method that allows easier handling and causes minimal damage to the site. It is also important to choose an effective storage method that facilitates faster drying and sufficient cleaning and de-contamination of the material. Moreover, there are a number of biological and economic advantages in reducing the storage duration needed to produce fuel of good quality, *i.e.* low moisture content, low ash and contaminant contents and high energy content. Shorter storage duration can reduce dry matter losses during storage and lower the production costs of the fuel.

The main aim of this work was to evaluate various harvesting methods and storage alternatives at two geographical locations and examine their effect on the fuel quality of Norway spruce stump biomass.

Specific objectives were to:

- Review available literature concerning technical, biological, environmental and political issues related to stump removal for energy purposes.
- Determine the main physical and chemical characteristics of stump biomass extracted from two sites using three different techniques.
- Study two forms of stump storage, windrows and heaps, during 16 months of storage and evaluate their influence on fuel quality and changes in energy content during storage.

3 Material and methods

The work reported in this thesis is based on Papers I and II. Paper I comprises a review of the literature on stump procurement and utilisation as a fuel, including the relevant biological, technical, environmental and policy aspects. Paper II comprises practical experiments in the field to evaluate the effects of stump harvesting technique, storage method, storage duration and geographical location on stump fuel quality

3.1 Experimental design in Paper II

Two large-scale field experiments were conducted according to the experimental design shown in Figure 3.

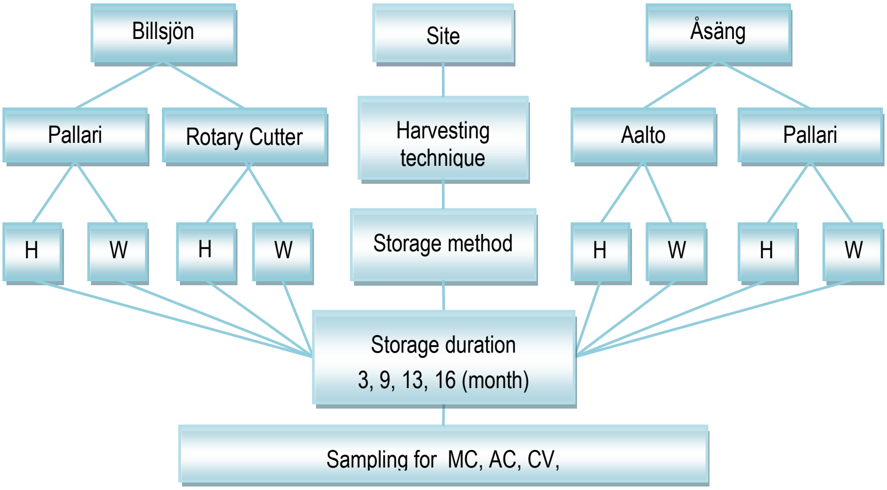

Figure 3. Experimental design of the two storage trials, in which H represents heap storage for 3 months before windrow storage and W represents continuous windrow storage.

The experimental sites were located in Billsjön (central Sweden) and Åsäng (northern Sweden). Both stands had been previously dominated by mature Norway spruce (*Picea abies* (L.) H. Karst), and had similar site properties such as soil type, diameter and age of stumps. Harvesting of stumps was carried out during late April-early May 2008.

3.1.1 Harvesting heads

Three different harvesting methods were evaluated, two in each stand. As a reference method, a shearing stump extracting head (Pallari model KH-160 HW) was used (Figure 4, A). The same stump harvesting head, excavator and machine operator were used at both sites for extraction of stumps with the reference method. The other method used for harvesting the stumps at Billsjön was the Rotary Cutter head (Figure 4, B). The harvesting method with this stump lifting head is based on a rotating toothed cylinder that saws and detaches mainly the central part of the stump. The stump is neither split nor shaken after lifting. This head is just a prototype and not commonly used for stump extraction. The second stump harvesting head used at Åsäng was a refractive head of model Aalto (Figure 4, C).

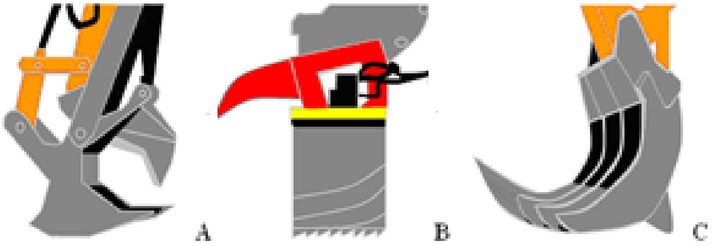

Figure 4. Stump harvesting heads used for extraction. A) Pallari, B) Rotary Cutter and C) Aalto.

3.1.2 Storage methods

After harvesting, the stumps were either stored directly in a 4 m high windrow or gathered into 1.5 m high heaps. These heaps were then gathered into a windrow after three months of storage and stored for another 13 months, until September 2009. These windrows are referred to below as heap-windrows. During the whole storage period changes in ambient temperature were recorded at the stands and inside the windrows build with Pallari-harvested stumps using Tinytag® plus 2 loggers. Data on local precipitation at the experimental sites were obtained from the Swedish Metrological and Hydrological Institute.

3.2 Determination of dry matter losses

To determine dry matter losses during storage, a number of randomly chosen stumps were brushed and cleaned thoroughly by removing all visible and accessible soil, stones and other contaminants (Figure 5). The stumps were weighed and placed into 1 m^3 net plastic bags and then stored inside the windrows. The contaminants removed from these stumps were weighed and then kept frozen for further analyses. Stump samples from each technique were collected at the time of construction of windrows and small heaps. During storage, samples were collected on four occasions from two marked levels (Figure 2 in Paper II). Dry matter losses were calculated as the percentage loss of dry matter on an ash-free basis.

Figure 5. Fresh stumps harvested with the Rotary Cutter. A) untreated, B) brushed and C) prepared sample.

3.3 Laboratory Chemical analyses

The collected stumps were transported to a terminal where they were crushed. Samples were collected for moisture content (MC), ash content (AC), calorific value (CV) and chemical analyses. Samples of the crushed material were also taken for determination of particle size distribution. All analyses followed standard methods (Table 1).

Table 1. *Standards used for the determinations of various parameters*

Parameter	Standard	
Moisture content	SS 18 71 70	(1997)
Ash content	SS 18 71 71	(1984)
Calorific value	SS 18 71 82	(1990)
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)

The calorific value of the stumps was compared with that of samples of stem wood taken at breast height from 10 standing trees at each of the two sites.

3.4 Energy balance

The percentage change in net calorific value was calculated using equation (1), taking into consideration the measured values of MC, AC, CV and dry matter losses. This change in energy content was only calculated for windrowed stumps during 13 months of storage.

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

Where

LHV_1 = lower (net) calorific value before storage (MJ/kg wet weight basis)

LHV_2= lower (net) calorific value after storage (MJ/kg wet weight basis)

DM = initial dry matter (ash-free basis) (kg)

DML = dry matter after losses (%)

AC_1 = ash content (% dry weight) before storage

AC_2 = ash content (% dry weight) after storage

MC_1 = moisture content (% wet weight basis) before storage

MC_2 = moisture content (% wet weight basis) after storage

3.5 Statistical analyses

For the statistical analyses of the data, the two areas were treated as two completely randomised factorial trials. Data from each site were analysed using equation (2):

$$y_{ijkr} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + e_{ijkr} \quad (2)$$

where

α_i = the effect of stump harvesting head, with i ={1,2}

β_j = storage method, j ={1,2}

γ_k = storage time, k ={1,2,3,4}

$(\alpha\beta)_{ij}$, $(\alpha\gamma)_{ik}$ and $(\alpha\beta\gamma)_{ijk}$ = interactions between the factors

e_{ijkr} = residual error.

This general linear model 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).

4 Results

The results of the studies performed during this licentiate work are presented in detail in papers I and II. A short summary is given below.

4.1 Temperature and precipitation

The ambient temperature during storage at both stands was close to the annual average. The heat development inside the windrows was very limited and closely followed the temperature outside (Figure 3 in Paper II).

In the first month of the storage, the total precipitation was 33.8 mm at Billsjön and only 2.3 mm at Åsäng. However, the total precipitation at the two sites was almost the same during the first year of storage, with 653 mm in Billsjön and 678 mm in Åsäng, which was close to the annual mean of around 625 mm. After 16 months of storage, the total precipitation at the sites was 1101 mm at Billsjön and 866 mm at Åsäng.

4.2 Moisture content

The moisture content of stumps harvested with the Rotary Cutter was 46.9% (wet basis), while for Pallari-harvested stumps in the same stand the moisture content was 42.9%. The difference between these two techniques (used at Billsjön) was small but significant. At Åsäng, the average initial MC was 42.7% in Aalto-harvested material and 41.0% in Pallari-harvested material.

The moisture content dropped significantly in all treatments after three months of storage (Figure 6). At Billsjön, the stumps harvested with the Rotary Cutter had higher MC in both heaps and windrows compared with Pallari-harvested stumps. At Åsäng, there was no difference between the harvesting techniques or the storage methods. There was no significant difference between the storage methods when the reference technique was used. Marginal re-wetting of the stumps occurred in all treatments after nine months, but moisture content decreased again after 13 months of storage. When stored in windrows for 13 months, the stumps harvested with the Rotary Cutter had significantly higher moisture content, reaching above 31%. In all other treatments the MC was below 24%. However, after 16 months of storage the MC was reduced even for the stumps harvested with the rotary cutter.

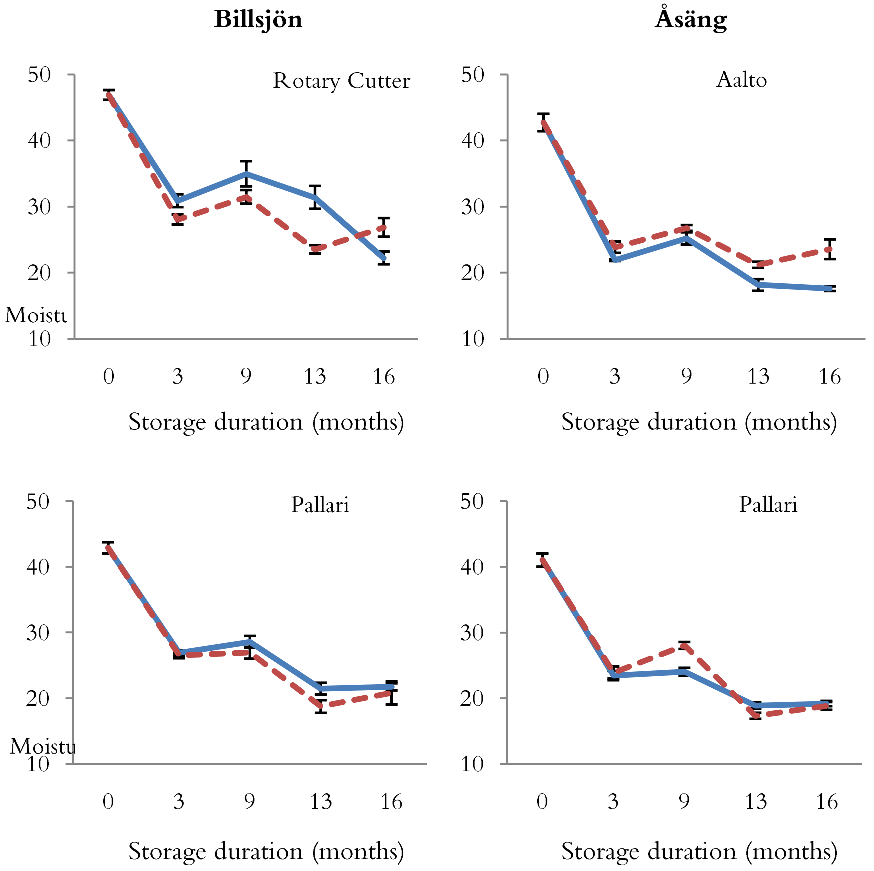

Figure 6. Average moisture content (%, wet basis, 95% confidence level), in stumps harvested with different techniques at Billsjön (left) and Åsäng (right) during 16 months of storage. The blue lines represent stumps built immediately into windrows and the red lines represent the heap-windrows.

4.3 Ash content

There were distinct differences in ash content between stumps harvested using different techniques in the same stands (Figure 7). When the reference technique Pallari was used, the average amount of freshly harvested stumps was twice as high at Billsjön as at Åsäng. After three months of storage, the ash content decreased in all treatments except for Aalto-harvested stumps stored in heaps (Åsäng). Sampling after nine months of storage showed a significant increase in ash content at Billsjön, reaching 10.9% in the stumps stored in windrows. This difference was not significant for stumps harvested at Åsäng. The ash content declined again in all treatments after 13 months of storage. A further reduction occurred at Billsjön after 16 months of storage, while at Åsäng the ash content remained unchanged.

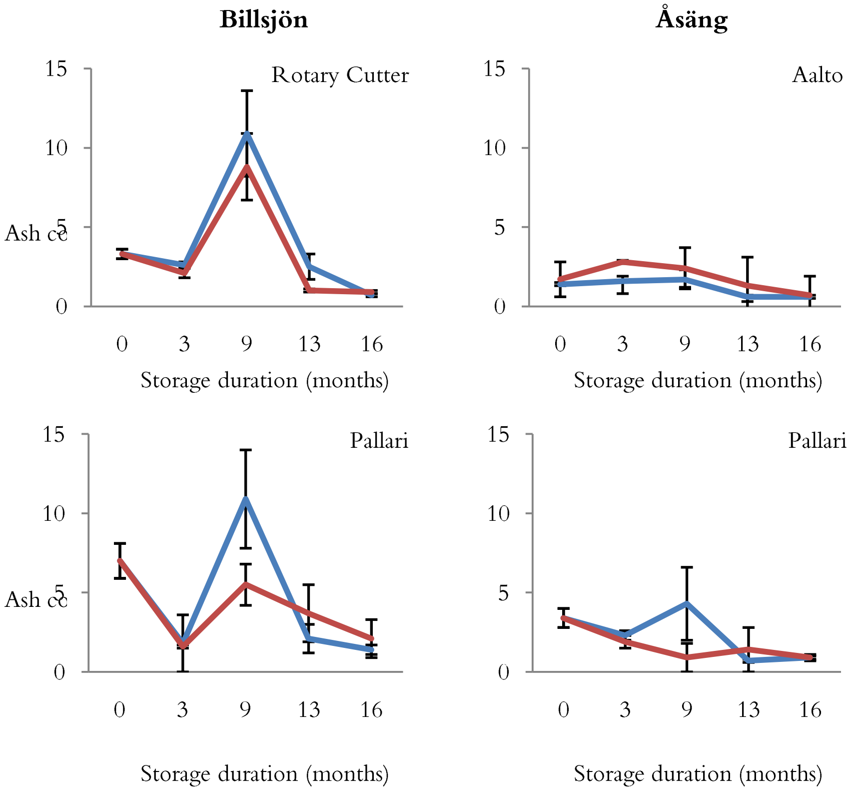

Figure 7. Average ash content (%, dry basis, 95% confidence level) in stumps harvested with different techniques at Billsjön (left) and Åsäng (right) during 16 months of storage. The blue lines represent stumps built immediately into windrows and the red lines represent the heap-windrows.

4.4 Calorific value and net calorific value

The calorific value of fresh stumps harvested with the different techniques varied between 19.2 and 19.9 MJ/kg dry weight (Table 1 in Paper II). The of stem wood samples from each stand reached an average value of 20.1 MJ/kg dry weight. During storage the changes in CV were generally marginal and closely followed the changes in AC. After 16 months of storage, the average CV of all treatments was around 20.2 MJ/kg. The variations between different techniques, storage methods and locations were not significant. The initial net calorific values were in the range 8.7-9.9 MJ/kg (wet weight basis). These values were significantly elevated and closely followed the changes in MC during storage. The average net calorific values after storage increased to 14.1 MJ/kg (wet weight) at Billsjön and 15 MJ/kg at Åsäng (Table 1 in Paper II).

4.5 Chemical analyses

The concentration of extractives was 3.4% (dry weight) at Billsjön and 4.6% at Åsäng at the beginning of the storage trial. After 16 months of storage, the concentrations of extractives remained unchanged and no differences could be established between the two harvesting techniques at either site. The initial concentration of lignin was on average 32% (dry weight) at Billsjön and 30.6% at Åsäng. These values decreased to 29.1% and 29.5% for the stumps harvested with Rotary Cutter and Pallari head, respectively. However, the differences measured for different storage times and harvesting techniques were not significant. The chemical composition C, H, N and O showed minimal changes after 16 months of storage compared with freshly harvested stumps (Table 2 in Paper II).

A correlation between the silica content and the AC ash content was evident in all treatments. At Billsjön, the initial silica level was 10 756 and 26 275 mg/kg dry weight when harvested with rotary cutter and Pallari head, respectively. These values were considerably lower after storage, 1150 and 3725 mg/kg, respectively. At Åsäng, the value decreased from 3925 to 1100 mg/kg in Aalto-harvested stumps and from 10 400 to 1150 mg/kg in Pallari-harvested stumps.

4.6 Impurities

The amount of contaminants per kg dry weight and the moisture content were significantly higher at Billsjön than at Åsäng (Table 2). At Billsjön no difference in either contamination weight or moisture content could be established between stumps extracted with the different harvesting heads. Stumps extracted at Åsäng contained a significantly lower inorganic contaminant weight when the Aalto stump harvesting head was used compared with the Pallari head. However, the moisture content of the contaminants was similar for both harvesting techniques. After 13 months of windrow storage, hardly any visible adhering contaminants could be found on stumps harvested at Åsäng (Figure 8).

Table 2. *Average content of inorganic contaminants (g/kg dry weight) and moisture content (%, wet basis) in all contaminants adhering to harvested stumps. Confidence level 95%*

	Billsjön		Åsäng	
	Rotary Cutter	Pallari	Aalto	Pallari
Inorganic contaminants	58.3 ± 31.5	40.2 ± 5.3	6.7 ± 2.3	20.7 ± 3.7
Moisture content, % (w.b)	21.3 ± 11.4	20.5 ± 1.8	14.9 ± 4.5	3.6 ± 0.9

Figure 8. Split stump wood after 13 months of storage, with no visible contaminants.

4.7 Particle size distribution

Sieving of material from stumps harvested using the Aalto and Pallari heads and crushed with the same machine showed no significant difference in particle size distribution at Åsäng (Figure 9). After 16 months of storage, the percentage of the fine fraction (≤ 5 mm) decreased with both techniques.

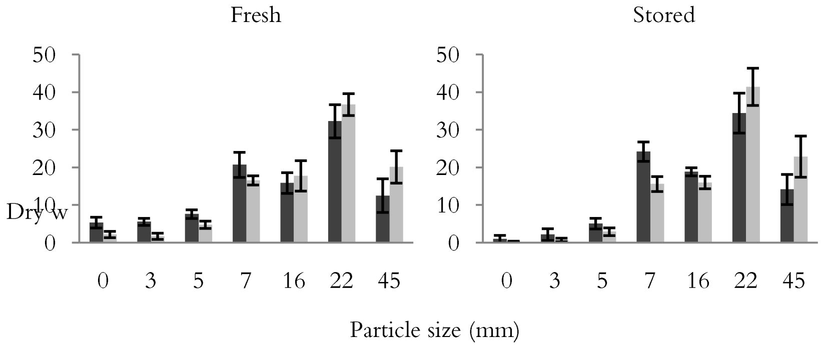

Figure 9. Particle size distribution (%, dry weight basis and 95% confidence level) of freshly crushed stumps (crushed with a CBI Magnum Force 6400) and of crushed stumps stored for 16 months in windrows at Billsjön (light bars) and Åsäng (dark bars).

4.8 Dry matter losses

After three months of storage, the dry matter losses were in the range 1.5-3.4% of dry weight on an ash-free basis (Figure 10). Differences between various harvesting techniques and geographical locations were not significant. After nine months of storage at Billsjön, the cumulative losses in stumps harvested with the Rotary Cutter and Pallari heads increased to 7.7% and 5%, respectively. The dry matter losses were 8.3% and 5%, respectively, by the end of 13 months of storage. Intensive visible fungal growth with fruit bodies, identified as *Oligoporus* spp., was observed on many of the Rotary Cutter-harvested stumps at Billsjön (Figure 11). The losses were significantly lower at Åsäng, with an average of 2.5% for Pallari and Aalto harvesting heads after nine months and increasing up to an average of 4.3% by the end of 13 months of storage.

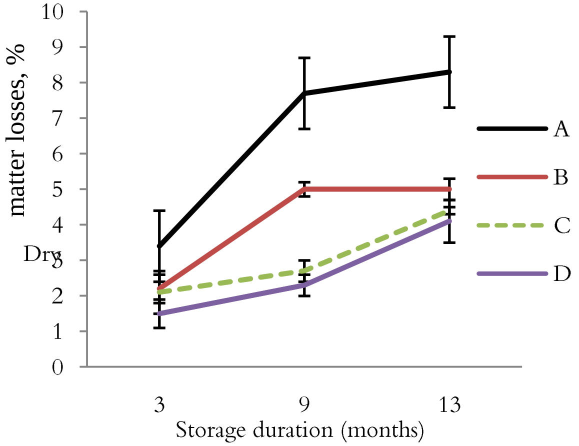

Figure 10. Cumulative losses of dry matter (%, ash-free) during storage of stumps harvested with different techniques: A) Rotary Cutter and B) Pallari at Billsjön; and C) Aalto and D) Pallari at Åsäng.

Figure 11. Fruit bodies of *Oligoporus* spp. growing on stumps extracted with the Rotary Cutter harvesting head.

4.9 Changes in energy content

Calculations of changes in the net energy content per ton stump wood delivered showed that the net energy was increased in all treatments after three months of storage. It decreased by a few percent compared with the earlier sampling during freezing conditions in February, but increased again after 13 months of storage (Figure 12).

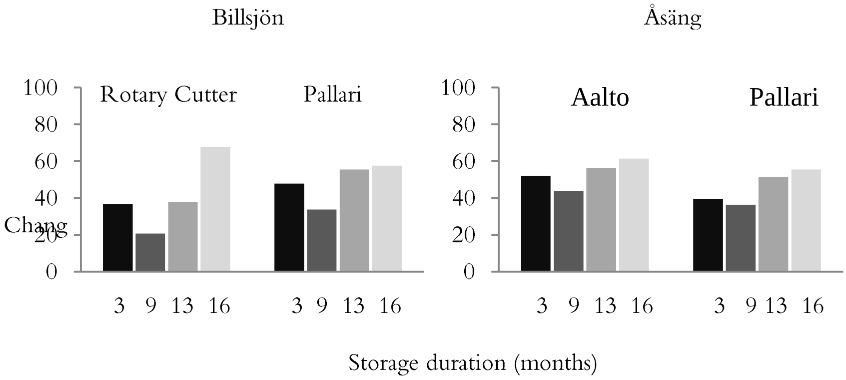

Figure 12. Changes in net calorific value (green weight basis) per unit weight delivered after storage in windrows at Billsjön (left) and Åsäng (right). The stored stumps were harvested with different techniques.

The total amount of energy, expressed as net calorific value on a wet weight basis, increased in all treatments after three months of storage (Figure 13). With longer storage duration, the net energy increment became continuously smaller but it remained positive except for the Rotary Cutter stumps, which showed a few percent reduction in net energy content.

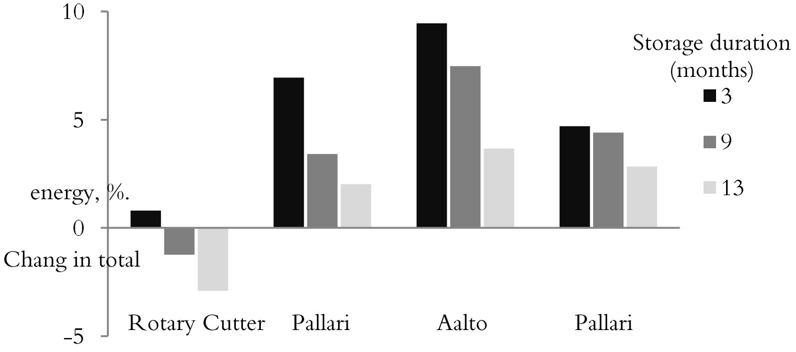

Figure 13. Changes in total amount of energy during stump storage in windrows, expressed as changes in net calorific value. The stumps were harvested with different techniques at Billsjön (Rotary Cutter and Pallari, left) and Åsäng (Aalto and Pallari).

5 Discussion

There are several important issues concerning the environmental effects of harvesting stumps for energy production. On one hand the use of fossil fuels must be decreased and replaced by renewable energy sources, but on the other the use of renewable sources, such as forest fuel, is governed by technical and environmental restrictions. Stump harvesting for energy purposes can positively contribute to reduced use of fossil fuels, with output energy up to 25-fold higher than input energy (Lindholm, 2010). Moreover, stump harvesting is currently the most efficient way to reduce root rot infections (Hypell, 1978; Vasaitis *et al.*, 2008). A decrease in the number of insect pests in infected stands has been reported on stump-harvested sites (Piiri & Viiri, 2009). The increased stirring of the soil during stump removal improves the establishment of tree seedlings, particularly the pioneer species (Kardell, 2007). Nevertheless, stump harvesting decreases the amount of dead wood, which acts as a substrate for insects, invertebrates, fungi, lichens and mosses. There is also a risk of increased nutrient leaching to water courses and of higher emissions of CO_2 from the ground due to increased stirring of the soil (Egnell *et al.*, 2007).

Stumps can be regarded as having great renewable potential for energy production and it is clearly possible to improve the quality of the stump wood.

The main difference between the stumps extracted with the different harvesting heads in Paper II was whether they were split or not. The Rotary Cutter extracts the stump in one piece with very little roots attached, while the other heads split the stump and pull up some of the root system. The latter types of harvested stumps therefore have a larger surface area, which facilitates the drying process. Compared with all the other treatments, after 13 months of storage the moisture content was significantly higher in stumps harvested with the Rotary Cutter, especially when directly stored in a windrow. This was probably due to both the form of the stump and the lack of roots, which made this windrow more compact than the other windrows.

A comparison of direct windrowing and heaping for three months followed by windrowing showed that the difference in moisture content was small when the stumps were split. This could have been due to the favourable placement of the windrows and heaps, which allowed the best conditions for drying at the site. In general, the moisture content of stumps decreased with storage duration, irrespective of harvesting technique or storage method. The largest decrease occurred during the first three summer months of storage, which was expected and has also been reported for other forest fuel assortments (Pettersson & Nordfjell, 2007).

Stumps with a high presence of roots, as in Pallari- and Aalto-harvested heads, allowed more contamination on the stump surface. This resulted in a higher initial ash content in stumps extracted with these shearing and refractive stump harvesting heads. However, the ash content was generally very low, especially at Åsäng, compared with that in other studies (Korpinen *et al.*, 2007). This was probably due to the low precipitation before and during stump harvesting, which made contaminant removal by shaking much easier. The time and intensity of shaking the stumps cannot be excluded as one part of the low ash content. However, the harvesting process was performed by the same machine operator at both sites. The contaminants became drier during storage and a large amount fell off the stumps. Other handling processes, *e.g.* loading, transport, unloading and crushing, can lead to further removal of contaminants. However, in stump samples removed at ambient temperatures below 0 °C, the contaminants were firmly attached to the stumps even after transportation. This explains the increase in ash content in samples taken during winter after nine months of storage. However, the ash content was below the limit value of 4% (van Loo and Koppejan, 2008) in all treatments after 13 and 16 months of storage.

Calorific value was generally strongly associated with ash content and closely followed changes in the latter. The increase in net caloric value measured during storage was mostly a result of the marked decrease in moisture content of the stumps. The concentration of fine particles was within the recommended value for combustion (van Loo and Koppejan, 2008). The particle size distribution of the stored material was distinctly improved, with a lower percentage of fine particles. The most probable reason for this was the reduction in sand and other contaminants.

The dry matter losses steadily increased during the first nine months of storage in all treatments. After 13 months the losses in split stumps were similar, irrespective of harvesting head and storage site. However, the losses were significantly higher in whole stumps extracted with the Rotary Cutter head. This is probably the result of the consistently higher moisture content in these stumps, which created favourable conditions for the establishment of wood-degrading fungi. This may also explain the marginal decrease in lignin content after storage. Moreover, the faster drying of the stumps at Åsäng probably allowed less microbial establishment, which in turn reduced the risk of dry matter losses. However, the losses in all treatments were small compared with those reported for other forest fuel assortments (Jirjis and Nordèn, 2002; Pettersson and Nordfjell, 2007).

In this thesis, the weight of the extracted stumps per hectare was not included in the total energy calculation. However, it is worth mentioning that the amount of biomass produced per hectare can be considerably lower with the Rotary Cutter compared with the other harvesting heads, since the former method only removes the material within the head diameter.

The total energy calculations excluded the energy that can be recovered through flue gas condensation and energy was calculated in terms of the net calorific value. In comparisons of energy content (MJ/kg) per metric ton delivered, the amount of dry matter increased due to the reduction in moisture content. A short time of storage improved the fuel quality and the changes in moisture and ash content during storage indicate the amounts of energy that could be extracted from the fuel. However, this does not show the change in the total amount of energy that could be extracted. The improved fuel quality and small dry matter losses after three months of storage increased the total amount of energy available in all treatments. However, storage for more than three months led to a reduction in the total available energy, mainly due to substantial dry matter losses.

6 Conclusions

The review of literature dealing with stump removal identified a number of unresolved environmental issues. Therefore, it cannot be stated at present that harvesting of stumps is environmentally justifiable.

Regarding the fuel value of stumps and the technical aspects of stump handling, the choice of stump harvesting head for extraction has an impact on fuel quality parameters; moisture content, ash content and heating value. Splitting of stumps during harvesting allows better drying during storage. However, storage for more than a year can further reduce moisture and ash content, regardless of type of harvesting head, storage method or location.

Of the factors studied here, storage method had no clear effect on most parameters measured except for stumps extracted with the Rotary Cutter. Stumps harvested with this technique dried better in heaps during the first three months of storage compared with storage in windrows. However, this effect was offset by the subsequent storage in windrows.

The ash content decreased considerably during the first year of storage. In general, it could be concluded that stump quality as a fuel can be improved by storage, which decreases the moisture and ash content and results in higher heating value. However, high ash content is a major problem in stump fuel. Improving the supply chain of stumps by reducing the storage time would require the use of more efficient methods to remove contaminants at an earlier stage of the procurement chain.

7 Recommendations for practical implementation

- Stump harvesting heads that split the stumps into at least two pieces are generally preferable.

- For stumps removed from sandy-silty glacial till soils, 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 regeneration operations.

- Stumps extracted during spring with shearing stump harvesting heads from sandy-silty till soils can be used as a fuel in the same season. However, stumps extracted later in the season require longer storage periods due to higher ash content.

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

8 Future research

The productivity of stump harvesting machines is one of the important factors which affect the cost of producing stump fuel. Cleaning the stumps by shaking it, which comprises up to 50% of energy use in the whole extraction cycle, is a necessary step to improve fuel quality. This process reduces the productivity and thereby increases the production cost. Storage for a long period, exceeding one year is an additional costly step which is used today to ensure acceptable fuel quality. Despite stump shaking and storage, ash content can still be high. Methods to decrease the contamination level more efficiently are therefore desirable as they could:

- Increase productivity
- Reduce storage time
- Reduce production costs
- Improve fuel quality

These advantages will positively affect the supply chain through higher flexibility and gain. Alternative, more efficient methods for shaking the stumps to remove contaminants is highly desired. Vibration can be one of these methods. Another weak link in the supply chain is transport due to low payload. Therefore, measures which increase the bulk weight of transported material, such as pre-crushing, are desirable.

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