Can forest fuel contribute in the transition towards a sustainable society?

– A cross-disciplinary analysis of economic, environmental and political aspects across Sweden

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Abstract

This thesis is a pilot study for cross-disciplinary analysis with the aim to compare the prerequisites for sustainable harvesting of forest residues/fuels in southern and northern Sweden from both environmental and societal perspectives. It has three main focus areas: **(A)** Potential to produce forest fuels; **(B)** Effects on the nutrient budget; and **(C)** Practical aspects and attitudes within the forestry sector. **(A)** is calculated for 16 forest sites (8 in the North and 8 in the South of Sweden) at 2 harvesting intensities (Scenario 1: 80% slash and 50% stumps; Scenario 2: 60% slash and 30% stumps), based on input data from the Swedish Forest Agency, using the software application *StandWise*. **(B)** includes net balances of Ca, Mg, K, P and N, calculated for two forest sites (one in the North and one in the South of Sweden), at 4 different harvesting intensities (Scenario 1 and 2 as in A; Scenario 3: stems only; Scenario 0: no harvest), using the steady-state soil chemistry model PROFILE. **(C)** is an interview study based on 17 semi-structured qualitative interviews with representatives from the Swedish forestry (the Swedish Forest Agency, the forest industry, forest owner associations, researchers and forest conservationists) active in northern and southern Sweden. The results show that the conditions for forest fuel production vary across the country due to differences in forest properties, environmental conditions and socio-economic factors. **(A)** In southern Sweden the forest fuel potential is about 60% higher per hectare than in the North, due to more biomass per hectare. This corresponds to 520 MWh ha^{-1} in the South and 320 MWh ha^{-1} in the North in Scenario 1. **(B)** The removal of nutrients is larger in the South compared to the North. 2,5 times more Ca, 10 times more Mg and more than 3 times more K in are lost from the South than the North in Scenario 1. The N loss is about 3 times greater in the North than in the South and for P the balance was around 0 in the North and almost 1 kg ha^{-1} in the South. The differences between harvesting scenarios show that harvesting intensity is the most influential factor determining the net balances of studied nutrients, which further indicate higher risk of nutrient depletion in the South than in the North when removing forest fuels. **(C)** The level of extraction and the limiting factors vary across the country, although during current practical and economic conditions, a large-scale extraction of forest fuels is judged as impossible to achieve. Attitudes towards increased biomass extraction, prices, infrastructure and ownerships structure determine the actual forest fuel extraction. There is a conflict between the climate benefit of forest fuels, and biodiversity and nature conservation, as well as between maintained nutrient balance and the risk of soil damages as forest fuels are extracted. There is however a discrepancy between actor groups regarding current environmental state in Swedish forests, and hence in attitude towards the severity of the effects of forest fuel extraction. Most actors ask for clear regulations of how and where to extract forest residues, and agree that the Swedish Forest Agency has limited power to conduct law enforcement. Better planning before and improved knowledge during forestry operations are identified as important measures to achieve sustainable extraction of forest fuels. This study shows that a trans-disciplinary approach can improve the basis for decisions and planning concerning future forest fuel production and that the different conditions in different parts of Sweden have to be handled more thoroughly than at present.

Key words

Forest fuels, forest residues, Energy potential, Nutrient balance, Nature consideration, Forest fuel extraction

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Wordlist and abbreviations

Biofuels	Fuels where biomass or peat is the original material. The fuel can have passed through chemical processes or transformation or other use.
Dbh	Diameter at breast height.
Forest fuels and forest residues	Wood fuel which has not had any previous use, typically bark and/or tree residues from felling (tops, branches, stumps, etc.), terminals, sawmills, and pulp industries.
Forwarder	Off-road vehicle that transports the wood material from the forest (trackless terrain) to a storage area accessible to trucks.
m^3fo	Stem volume above the stump, including bark and top.
Productive forest land	Land within a contiguous area where the trees have a height of more than 5 meters and a crown cover of more than 10%, or have the potential to reach this height and crown cover without measures to increase production, and which, according to established criteria, can produce an average of at least one m^3 ha^{-1} $year^{-1}$ (Anon, 2007b).
Recycled wood fuel	Wood fuel that has had a previous use i.e. recycled construction wood.
Regeneration felling	Replaces the term ‘final felling,’ thinning and cleaning excluded.
Wood balance	Volume of a forest stand (stems, bark and tops) in forest cubic meters (m^3fo).
Wood fuels	All biofuels where the raw material is trees or parts of trees. The fuel could have had previous use, e.g. recycled building material.
Small-diameter wood	Wood that is thinner than the minimum dimensions of such timber that is processed economically.

Part I - Forest fuels in a context

1.1 Introduction

The combination of a dwindling supply of fossil fuels and the need to reduce the greenhouse gas emissions has led to an increasing demand for renewable raw materials, both on a global and on a national level. Sweden has a binding target under the EU Sustainability directive (2009/28/EC) to reach 49% renewable energy by 2020, and in 2006 a goal to phase out the use of fossil fuels for heating was formulated (Prop. 2008/09:16).

The Swedish forest is often referred to as "Sweden's green gold," because of the immense supply of renewable resources it provides and its crucial importance for the Swedish economy. The Swedish government puts high hopes to the forest in order to reach the EU-targets and sees a good potential to increase the production of forest biomass, without compromising with the forest policy's equal environmental and production goals. An important measure in order to achieve higher production is to increase the extraction of forest residues (tops, branches and stumps) (Prop. 2007/08:108). The Swedish Energy Agency has a vision that the Swedish forest shall deliver another 20-30 TWh per year in 2020, from today's 143 TWh, and by 2050 the amount should have increased to 230 TWh (SEA, 2011a).

The extraction of forest residues, especially of stumps, is still a restricted activity, even though the trend is positive all over Sweden. The Swedish Forest Agency has instructions to promote increased harvesting among forest owners and provide production advice in accordance with necessary nature consideration; and the Swedish Energy Agency together with the forest industry have invested in comprehensive research programmes on forest fuels.

The harvesting of forest fuels represents an intensification of current forestry, it occurs within the same legal framework and with conventional forest management practices. However, the increasing demand for energy from the forest can be expected to have numerous effects, both for the forest ecosystem and for different components of Swedish forestry. The comprehensive Commission on Swedish climate politics from 2008 pointed out that, "despite Sweden's exceptionally good natural conditions forest fuels will become a scarce resource with risks of increasing prices, competition for raw materials within forestry and negative effects on biodiversity among other things" (SOU 2008:24). As nutrient rich biomass is increasingly removed the nutrient balance of the forest soil could be disrupted with consequences both for the coming forest stand and for surrounding environments. The Swedish forests further hold enormous amounts of carbon, in living biomass and bound in the soil, and almost all measures involved in the production and utilisation of forest residues affect the carbon balance of the forest ecosystem (Olsson, 2010b).

How well the goals for forest fuels correspond to the different environmental and practical conditions is a much debated question among researchers, the forest industry, authorities and civil society. Is there a limit to extraction and who sets the boundaries? Many have great hopes for the production potential of forest fuels, if it is carried out according to the regulations. Those most reluctant to a large scale extraction of forest residues point to the poor general nature consideration in Swedish forests and warn that the demand for forest fuels will further exacerbate the situation.

1.1.1 Objective

The aim of this project is to compare the prerequisites for sustainable harvesting of forest residues in southern and northern Sweden from both environmental and societal perspectives. The study should be seen as a pilot study for cross-disciplinary analysis of different aspects of increased biomass harvesting in different parts of Sweden and does not cover all environmental and societal effects. The focus is on:

- Potential to produce forest fuels
- Effects on the nutrient budget
- Practical aspects and attitudes within the forestry sector

1.1.2 Disposition

The thesis consists of five parts that differ both in focus and method. The first (I) part is a literature-based introduction, which places forest fuels in a political, practical and environmental context. In the second (II) part the potential extraction of forest residues in northern compared to southern Sweden, is calculated using the software application *StandWise* (Version 1.3) developed in the Heureka research programme. It is created and managed by the Swedish University of Agricultural Sciences (SLU). The third (III) part aims to investigate the effects on the nutrient budget of two forest sites, one placed in the North and the other in the South of Sweden, after forest residues are harvested, using mass balance calculations and the steady-state soil chemistry model PROFILE. The fourth (IV) part is an interview study based on 17 semi-structured qualitative interviews with representatives from the Swedish forestry (the Swedish Forest Agency, the forest industry, forest owner associations, researchers and forest conservationists) active in northern and southern Sweden. The findings of the study are concluded in a fifth and final part.

1.1.3 Limitations

This thesis does not pretend to cover all aspects of forest fuel extraction and does not go deep into any one topic. The effects on biodiversity are briefly presented in Part I based on existing literature on the topic, but no explicit study has been carried out. The issue is further discussed in Part IV, but also in more general terms. For comprehensive syntheses of the current state of knowledge regarding forest residues see i.e. [Egnell, 2009; SEA, 2006; de Jong *et al.*, 2012; SLU, 2008; SLU, 2010; SEA, 2007].

Forest fuels include several categories of wood material: slash (tops and branches), stumps, small dimension trees, burned or dried wood, wood damaged by root rot and in various stages of decay. In this thesis I focus on slash and stumps, and the terms *forest fuels* and *forest residues* are used as synonyms to refer exclusively to these two categories.

I have chosen to limit the scope of the study to forest fuel extraction during final felling, which is also the basis for the calculations in Part II and III. However, there is a strong trend to remove forest residues in combination with cleaning and thinning operations (Näslund *et al*., 2010; SEA, 2011a).

I do not consider the effects climate change is expected to have on Swedish forests (i.e. increased growth, more attacks by pests and higher risk for forest fires). The calculations and discussions are based on current conditions.

1.2 Swedish forest politics – a historical review

Swedish forestry has gone through major transformations during the last centuries. As the iron production expanded during the 1600s the need for forest products, such as timber and charcoal, increased significantly. Large-scale saw-milling industry didn't start until the mid-1800s but was then rapidly spread from the South of Sweden to the North (Fries 2011). Forest management was at that time completely deregulated, and the disposal[1] and sale of public forests had substantially increased the proportion of forests owned by companies, estates and peasants, so-called individual forests (Enander, 2007). At the beginning of last century, in 1903, the first national Forestry Act was introduced, which required owners to replant after forest felling. Since then a number of comprehensive investigations of the prevailing forestry politics have been carried out, which have resulted in revisions of and additions to the Forestry Act. After World War II forestry practices shifted towards a widespread even-aged stand management system, a model based on final felling with subsequent planting or natural regeneration. This model still constitutes the fundaments of Swedish forestry (ibid.).

1.2.1 Rising environmental concern

Up to the 1970s nature conservation was something that was left to the individual forest owner to voluntarily take into consideration. The environmental movements were early on critical of how Swedish forests were managed and during the sixties the public opinion grew stronger against prevailing forestry. This, combined with results from on-going research on environmental effects of forestry, were important driving factors behind the decision in 1979 that, for the first time, legislate about general consideration of nature conservation at harvest (Enander, 2007). During the following decade most areas concerning forest protection and harvesting were regulated. After the 1983-year amendments of the Forestry Act all forest owners were obligated to keep after young stands (cleaning and thinning), to harvest a certain percentage of older forests, to establish new forest if the forest was sparse and consisted of inappropriate tree species, to settle over-aged forest, and to establish mandatory forest management plans (ibid.).

1.2.2 A shift in forest policy

Changes in forest policy have often coincided with the change of governments. In 1991 the social democrats lost power to the conservatives, which was reflected in the 1993 government forest policy bill (Prop. 1992/93:226). The bill was preceded by a Parliamentary Commission investigation (SOU 1993:76) and resulted in a major change of the Forestry Act (Nylund, 2010; Enander, 2007). The most profound change was the introduction of an environmental goal, which was given equal importance to the production goal, and formulated in the opening paragraph (Enander, 2007). Several areas were deregulated, i.e. the cleaning obligation, giving forest owners more freedom in the management of their forests. Meanwhile the duty of regeneration and the principle of sustainable forestry were enforced, resulting in more responsibility being placed upon private and corporative owners to achieve the goals (ibid.). Still today "freedom under responsibility" and "sector responsibility" are foundational concepts of the Swedish forestry model (Näslund *et al*., 2010). The Parliament further announced that 5% of the productive forest all over the country was to be protected from forestry, and the Swedish Environmental Protection Board formulated a set of rules concerning green forest management (Nylund, 2010).

[1] The division of land between the Crown and the people. Beginning in the late 1600 century to early 1900s land ownership relations between the Crown and the people were established in northern Sweden, first in order to meet the mills' needs for wood products and then to promote new settlements (Egerbladh, n.d.).

An increasing global awareness of biodiversity and sustainability issues, Sweden's membership in the European Union and the general opinion in the society contributed to several environmental policy measures during the following years. Different commissions on environmental conservation (SOU 1997:97 and SOU 1998:95) were launched, action plans for biodiversity were presented in 1995 and 1996, and a new government bill was prepared in 1997 (Prop. 1996/97:75). Fifteen national environmental objectives were set up, one of which specifically concerns forests (Prop. 1997/98:145), and in 1998 all existing environmental legislation was gathered under a reinforced Environmental Code (Nylund, 2010).

1.2.3 A rising concern for climate change

As the issue of climate change and peak-oil forecasts have received more attention the interest in biofuels has grown rapidly, both at a political level, within the forest industry and among environment protection organisations. In 2006 the government appointed an expert group which was given the task to present suggestions on concrete measures for how to make Sweden fossil fuel independent by 2020. The group, referred to as the Oil Commission, saw use and development of energy resources from the forest as an important part to achieve this (COI, 2006).

No major change of the Forestry Act has been made since the 1993 amendments, however, some important new guidelines were presented in the government bill *A forest policy in line with the times* (Prop. 2007/08:108). Forest management was to become more production-oriented, primarily by increasing growth but also by more effective use of land and fertilisers, better maintenance of young stands and increased harvesting of biofuels. The bill further suggested a modification of the opening paragraph of the Forestry Act, emphasising that forest is a renewable resource (Enander, 2007).

1.2.4 Intensive forestry

The Government also recommended an investigation of the possibilities for intensive forestry on abandoned agricultural land and on forested land of low value for nature conservation (Prop. 2007/08:108). It resulted in the much disputed MINT-report, prepared and presented by the Swedish University of Agricultural Sciences (SLU) in 2009. It suggested several production models for intensive forestry, including nutrient optimisation systems, use of vegetatively-propagated spruce (Spruce clones), and the production of Lodgepole pine and hybrid poplar (Larsson *et al*., 2009). It was estimated that where such management methods were applied forest yields could potentially be doubled.

Despite the expected negative environmental effects, such as increased nitrogen leaching and loss of biodiversity, effects on cultural and recreational sites, and negative consequences for reindeer management, the positive effects for the climate were estimated to weigh over. In the concluding remarks SLU points out that "it is necessary to take immediate actions in order to facilitate increased forest growth if an increased demand for renewable forest products is to be expected" (Larsson *et al*., 2009). To implement the suggested measures the current legislation would have to be modified, especially the areas that concern nature consideration (30§ Forestry Act) (Flyckt, 2010). At present no formal decisions have been taken.

1.2.5 Climate and energy policies

Forests' importance to secure the national energy supply and as a renewable energy source has been further elaborated since the forest policy bill in 2007. EU's climate and energy package was adopted in 2008 and included three targets to be reached by 2020: to reduce the emissions of greenhouse gases by 20%, to increase the energy efficiency in the EU by 20% and to reach a 20% share of renewable energy of the total energy consumption in the EU. In the Renewable energy directive (2009/28/EC) all EU member states were obliged to set binding national targets for their overall share of renewable energy and develop a national action plan for how to reach their targets. Sweden's commitment was to reach 49% renewables of total energy by 2020. The same year the Swedish government presented an integrated climate and energy policy (Props. 2008/09:162-163), containing several national climate goals as well as action plans for the promotion of renewable energy, energy efficiency and a fossil fuel independent transport sector. Some of these goals are summarised in Table 1.

Table 1: Swedish climate goals (SEA, 2010)

	2020	2030	2050
Proportion of renewable energy of total energy	50%		
Proportion of renewable energy in the transportation sector	10%	100%	
Reduction of greenhouse gas emissions (compared with 1990)	40%		100%

1.3 Energy supply and use in Sweden

The total Swedish energy supply in 2009 amounted to 568 TWh, out of which 22% were biofuels, peat and waste (Figure 1a). About 45% of the total energy use was renewable energy, an increase of more than 30% since 1990. Forest fuels, including spent liquors[2], are the dominating form of renewable energy used in Sweden, and represent about one tenth of the total final energy use. Half of the biomass energy is used within the forest product industry itself, but apart from that, district heating is the largest end-user of bioenergy (40%) (Figure 1b). Private use of fuel wood and pellets represent 11%. Even if most of the bioenergy is produced domestically Sweden still imports a significant share (5-9 TWh) (SEA, 2010).

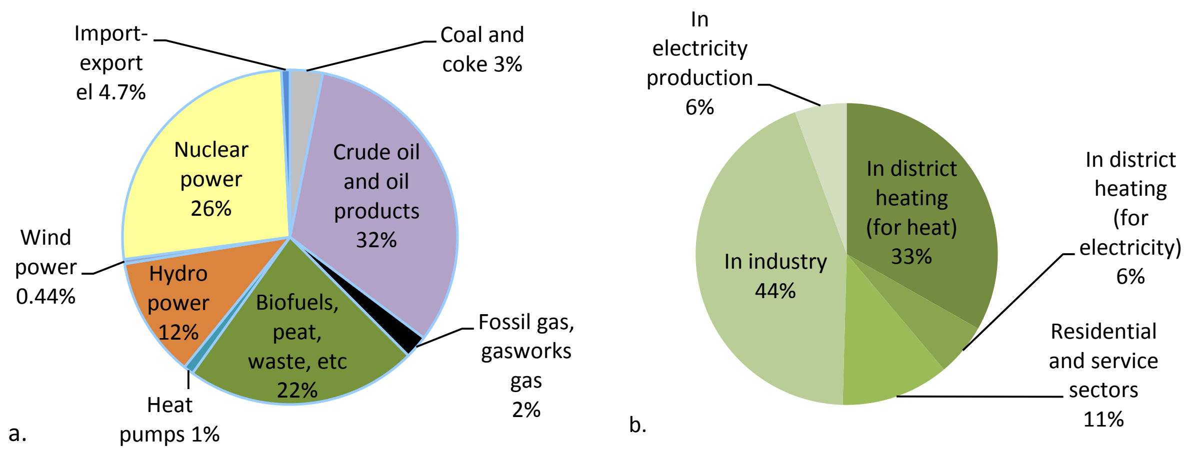


Figure 1: a) Total Swedish energy supply in 2009 and b) the use of biofuels, peat, etc. for energy purposes in 2008 (SEA, 2009)

[2] The liquid effluent created during pulping. It consists of spent digestant (caustic, sulfite or sulfate) and substances released from the wood (i.e. lignin).

1.4 Swedish forestry and the Swedish model

Swedish forestry follows a rational forestry model that includes maintenance measures during the rotation period such as cleaning, thinning, and regeneration felling. The emphasis is put on high replantation and regrowth. The Swedish government and the forest industry market the ‘Swedish model’ as a sustainable forestry model with both high production and sound environment (Örlander, 2010), being at the forefront of national and international certification schemes (KSLA, 2009).

More than half of Sweden is covered by forest. That is more than 22 million hectares of forest land and about 2,9 billion m^3fo of biomass (SFA, 2011a). About 39% is pine, 42% spruce and 12% birch. Most productive forest land is found in the northern part of Norrland[3] and decreases southward in the country. The relationship is reversed in terms of growing stock (Figure 2.a-b in Appendix I). In 2010 the average standing volume for the whole country was 131 m^3fo per hectare (SFA, 2011a). The annual volume increment varies both between tree species and different regions in the country (Figure 2 c-d in Appendix I).

Final felling was carried out on approximately 170 000 hectares in 2009, 356 000 hectares were thinned and 376 000 hectares were cleaned. About 80 million m3fo were felled, representing 85% of the annual growth. The average area reported for regeneration felling was 4,2 hectares (SFA, 2011f).

The ownership of productive forest land was in 2009 distributed as follows: private individuals (50%), private owned companies (26%), state (including state owned companies) and other public owners (18%), and other private owners (e.g. the Swedish Church) (6%) (SFA, 2011f). Ownership structure varies in different regions. In Norrland private companies own the largest share of forest land, while private individuals are the dominating form of ownership in Svealand and Götaland (Figure 1 in Appendix I).

1.4.1 Nature conservation

The legal framework contains various means for protecting forest in Sweden. *General conservation consideration* should be taken during all forest management measures according to 30§ Forestry Act and include establishment of buffer zones along watercourses, limitation of clear-felling in sensitive areas and protecting stumps and groupings of trees. Areas with high biodiversity values can be treated more strictly as *protected forest areas*, either as national parks, nature reserves, habitat protection areas or nature conservation agreements (KSLA, 2009). About 3,4% of Sweden’s productive forest land area is formally protected (SFA, 2011i). Another 4,3% are voluntarily protected areas that private owners set aside without economic compensation. These areas have to make up at least 0,5 hectares of contiguous productive forest land and shall contain high nature or cultural values or be important for recreation or outdoor life (SFA, 2011h).

Voluntarily protected areas are based on the overall forest policy ‘freedom under responsibility’, which encourages private forest owners to take measures for sustainable forestry (SFA, 2011h). Another incentive to voluntarily protect forest is the requirements under the international certification standard FSC (Forest Stewardship Council). In order to become certified forest owners have to set aside 5% productive forest land from being managed (FSC, 2010b). About half of all productive forest land in Sweden was FSC-certified in 2009 (FSC, 2010a). Nature

[3] In tables and texts regarding statistics Sweden is divided in different regions depending. See APPENDIX I.

conservationists supported by researchers in biology and nature conservation however, have long demanded that 20% of all productive forest land in Sweden needs to be protected in order to maintain viable populations of remaining forest species (Karlsson, 2011; Protect the Forest, 2009).

In 2010 the 10th meeting of the Conference of the Parties (COP10) to the Convention on Biological Diversity was held in Nagoya, Japan. This year was also declared the International Year of Biodiversity by the United Nations. The 193 parties that gathered in Nagoya adopted a new global vision for how to save biological diversity until 2020. One of the goals agreed upon, to reach the vision, was to protect 17% of land and water areas from exploitation. (ME, 2010)

Freedom under responsibility - in practice

The Swedish Forest Agency and the Swedish Environment Protection Agency (EPA) recently presented a comprehensive report on the poor environmental state in Swedish forests. It is a compilation of the Polytax[4] data showing the percentage of nature consideration taken at regeneration felling (according to the regulations in the Forestry Act). In 2009 more than 35% of all felling operations *did not* reach the requirements for nature conservation. This category has increased steadily during the last decade; meanwhile the percentage of logged area with more consideration than required has decreased by the same rate (Figure 2). The data further shows that logging on privately owned land (private individuals and companies) more often fail to fulfil the requirements compared to land owned by public actors (state, municipalities, county councils). At the regional level Svealand and Southern Norrland have largest percentage of logged area not reaching the requirements (see Figure 1-2 in Appendix III). (SFA & EPA, 2011)

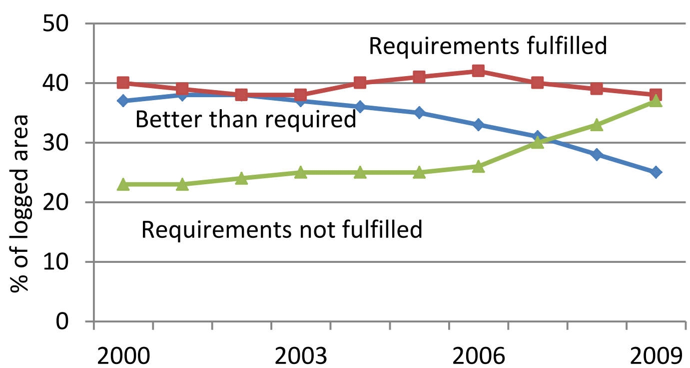


Figure 2: Compliance with environmental requirements of Swedish forest law in connection with regeneration felling during 2009. Development over time (modified from SFA, 2010c)

According to the Environmental Objectives Council's assessment the objective Sustainable Forests will be very difficult, or not possible, to achieve by 2020, even if further action is taken. The Council cannot see any clear trend in the state of the environment (EOC, 2011). In addition, the prospects of achieving several other environmental quality objectives are negatively affected by many forestry measures. Forest roads are continuously being drawn across valuable wetlands (*Thriving wetlands*), on-going loss of biodiversity in most managed forests (*A Rich Diversity of Plant and Animal Life*), forest transports, use of forest fuels and energy production have acidifying impact (*Only Natural Acidification*), and nutrient leaching affect streams, water-courses and marine waters (*Flourishing Lakes and Streams and A Balanced Marine Environment*) (EPA, 2011).

[4] The Swedish Forest Agency does annual inventories on a selection of sites notified for regeneration felling in order to measure the degree of nature consideration taken in Swedish forestry. The selected sites are inventoried before being logged and present cultural and nature values are documented. One year after felling the sites are inventoried again and the forestry measures are evaluated (SFA, 2011e).

1.5 Forest fuels

The residues of tops and branches (slash) created after logging have historically not had any real industrial use and have been left at the clear-cut to decompose naturally. The proportionally high biomass content in tops and branches (20%) and the large quantities that arise after felling have made slash an interesting source of biomass for energy. The residues are generally burned in power plants and the heat is distributed in district heating systems (FRIS, 2009).

Stumps alone contain about 20% of the biomass of a coniferous tree (FRIS, 2009), which means that there is great potential to increase the forest fuel production. Stump extraction is furthermore expected to reduce the need for additional site preparation, to enable earlier replantation, to increase the revenues for forest owners and contribute to reduce the presence of the forest pathogen *Heterobasidion*. Stump extraction signifies an intensification of conventional forest management (including only stems or aboveground biomass harvesting) (Walmsley & Godbold, 2010).

1.5.1 Laws, recommendations and practice

There is no special legislation on forest fuels, instead the extraction of forest residues is characterised as part of a normal rationalisation of forestry and the Forestry Act applies in the same way as for other forestry measures (SFA, 2009). The Forestry Act clearly states that the promotion of biological diversity shall always be given priority when there is a choice of methods to be used. However, the conservation requirements must not be so far-reaching that they make on-going forestry activities significantly more difficult (SFA, 2011d). The Swedish Forest Agency has developed recommendations on what nature consideration measures that should be taken when removing forest residues. In Appendix II shortened excerpts of the recommendations on which stands that are suitable and not suitable for removal of forest residues, as well as ash recycling are presented.

Slash

The Swedish Forest Agency recommends that 20% of the slash should be left on the site, preferably in sun exposed locations. Only slash from the most common tree species should be removed and the thickest tops should be left, especially from pine, oak and aspen. Enough residues should be spared so that forwarders can transport the wood material from the site to the road without inflicting risk of soil damage. This is especially important if also stumps are extracted (SFA, 2011f). The recommendations further state that the slash should be left to dry on the clear-cut so that most of the needles fall off and their nutrient content is kept within the ecosystem.

Stumps

Stumps are normally not extracted until 0,5-1,5 years after logging (Persson, 2010). In that way the highly nutrient rich fine roots are decomposed and more nutrients are kept in the soil. It is also easier to break the fine roots when the stump is lifted (ibid.). The most common extraction method is to use an excavator that cuts the fine roots and then pulls up the stump, leaving a hole in the ground. The method is largely unchanged since the 1970’s when stump removal was practised during a period of time. However, several alternatives are underway and within a few years new methods and more advanced machines are likely to be widely available (Hofsten, 2010). After being extracted the stumps are left at the clear-cut to dry for about one year to get cleaner material and better heating value (Jirjis & Anerud, 2010). Finally forwarders gather the stumps and transport them to a storage place by the road (Persson, 2010) for further transport to a terminal or directly to the heating plant. The practice of refining differs between actors and involves chipping at site, bundling and chipping at a terminal or directly at receiving industry (Thorsén & Björheden, 2011).

So far, stump harvesting is only recommended at final felling, not at thinning, and is restricted to 10% of the potential harvest area. The Swedish Forest Agency further exempt hard-wood from stump harvesting because of their relatively larger ecological importance and scarcity on a national level (SFA, 2009). If logging refers to an area of 0,5 hectare or more a notification to the Swedish Forestry Agency is required six weeks before harvesting and the registration is valid for five years. Consultation obligation under 12 Chapter 6 § Environmental Code occurs in cases where stump removal can be considered to substantially alter the natural environment (SFA, 2009). Knowledge of how stump extraction affects growing stands is still considered inadequate.

During the summer of 2011 the Forest Stewardship Council (FSC) adopted new directives stating that forest owners who want to extract stumps are required to develop a joint plan showing how those activities will contribute to new knowledge about stump extraction. The plan should also have suggestions on how forestry in other ways could strengthen nature values, or compensate any negative effects, including research to improve the knowledge about Continuous Cover forestry[5] (FSC, 2011).

Ash recycling

The purpose of ash recycling is primarily to counter the acidifying effects of biomass harvesting and return some of the lost nutrients to the soil (SFA, 2008a). In parts of southern Sweden where the acidifying load is considerably higher than in northern Sweden, it is extra motivated to recycle ash (SFA, 2010e).

In the regulations to 30§ Forestry Act the following is stated: "when tree parts other than stem-wood are removed from the forest, measures should be taken before, during, or after the removal so that damage on the long-term nutrient balance of the forest soil does not occur." A benchmark for ash recycling is when the total removal of other tree parts than the stem during the rotation period equal to more than 0,5 ton of ashes per ha. Ash recycling is a measure that requires consultation (SFA, 2008a). Only ash from burned forest residues is allowed and it must be pre-treated, hardened and crushed according to strict procedures in order not to dissolve too quickly or affect the soil negatively (Lundqvist, 2009).

1.5.2 Current harvesting rates

Total annual harvesting of slash and stumps from clear-cuts, thinning and cleaning, corresponded to approximately 143 TWh in 2010, about 7,5 TWh of slash were used for fuel (SEA, 2011a). The only available statistics at hand for more detailed information of the area corresponding to these figures is the notifications of regeneration felling submitted to the Swedish Forest Agency. All planned extraction of slash and stumps have to be specified in terms of surface area and its

5 Continuous Cover Forestry (CCF) has been described as a completely different approach to forest management in which the entire forest ecosystem is valued and not just the trees. The CCF system still involves stand management and timber production but priority is given to high diversity and multi-functionality of the forest. Large clear-cuts are avoided and instead a forest canopy is maintained during the regeneration phase (Mason et al., 1999). This also means smaller fluctuations of carbon fluxes and that the forest is consistently a net sink of carbon (Grelle, 2010).

proportion of spruce and pine (SFA 2011d). The notification has to be sent in six weeks before harvesting and is valid for five years.

The increasing area covered in the notifications indicates a growing interest in forest residues within the forestry sector. During 2010 harvesting of slash was notified to take place on more than 154 000 hectares, which is more than half of the total area notified for regeneration felling (Figure 3a). Stump harvesting was reported on about 7 500 hectares and has increased rapidly in recent years (SFA, 2010a).

Largest area for extraction of slash was notified in Götaland. The pattern for stump removal is not coherent with these figures. In Southern Norrland 1688 hectares were reported, closely followed by Götaland (1584 hectares) and Northern Norrland (1249 hectares), whereas only 488 hectares were notified in Svealand (Figure 3b). There is no statistics on how much of this that is actually harvested.

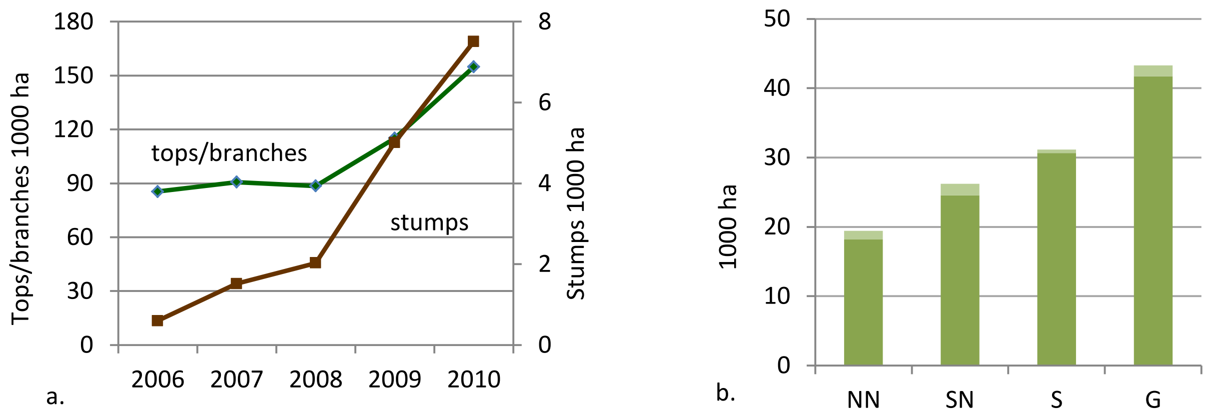
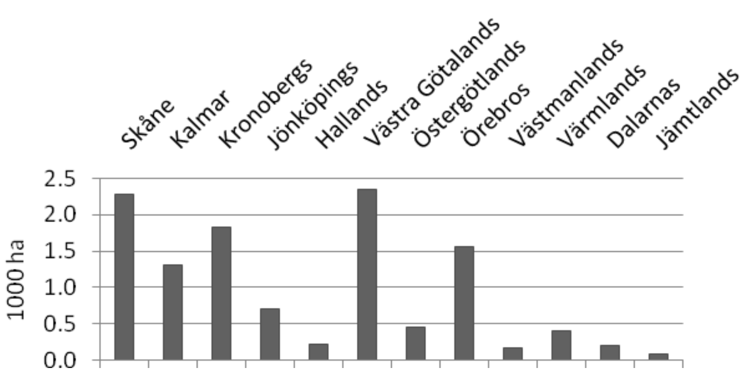


Figure 3: Notified area for extraction of forest residues per 14§ and 16§ of Forestry Act; a) for the whole country during the time period 2006-2010; b) by region, 2009. NN: Northern Norrland; SN: Southern Norrland; S: Svealand; G: Götaland. Tops/branches = bottom bar; stumps = top bar. (SFA 2010b; SFA 2010d)



Ash recycling is still a very marginal activity. It is almost non-existing in the northern regions and varies between southern regions (Figure 4).

Figure 4: Area over which ash has been recycled during 2009, per region (SFA, 2010e)

1.5.3 Potential production

There is a widespread perception among researchers, authorities and forestry sector representatives that Swedish forest fuel production has great potential to increase. The Oil Commission (2006) stated a clear ambition to substantially increase the Swedish biofuel production doubling the levels (to 228 TWh) in a long-term perspective (by 2050). Since then several investigations have estimated the future potential, with varying conclusions depending on what levels of nature consideration and expected effects of climate change that have been adopted.

In 2008 the Swedish Forest Agency presented a report where current and future development of the wood balance was analysed according to four different scenarios, all assuming effects of a changing climate, but with different intensity in forest management and ambitions in terms of nature conservation (SFA, 2008b).

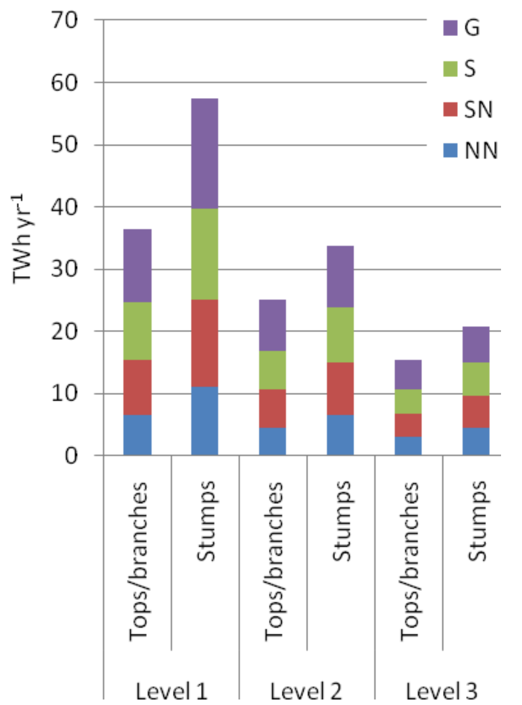


Figure 5: Annual potential extraction of forest fuels at regeneration felling by region, 2010-2019 (TWh year-1) (SFA, 2008b) G: Götaland; S: Svealand; SN: Southern Norrland; NN: Northern Norrland.

The *Reference scenario* follows current forestry management practices and adopted environmental policy in 2010, where the first interim target under the Environmental Objective *Sustainable Forests* is met. The potential supply of slash and stumps is analysed for three levels of ecological restrictions. In Level 1 no restrictions are applied, and all available forest residues that falls out after each logging operation is extracted. Level 2 means ecological constraints according to the Swedish Forest Agency's recommendations for extraction of slash and ash recycling (see Appendix II), and in Level 3 both ecological and technical/economic constraints are applied with an extraction intensity corresponding to levels in 2008 (SFA, 2008b).

According to these estimations the potential amount of slash at regeneration felling within the coming ten years (2010-2019) range between 3,2-7,4 million Ton of Dry Matter (TDM) per year, and the amount of stumps between 4,2-11,7 million TDM per year, the lower values correspond to Level 3 and the higher values to Level 1. Hence, stump extraction would increase from today's barely detectable levels to levels far higher than corresponding extraction of slash (Figure 5). If extraction at thinning is included another 1,7-3,9 million TDM of slash and 1,8-5,7 million TDM of stumps would be available, which is about one third of the total supply.

Largest proportion of forest fuel supply is expected from Götaland (G) (30%), followed by Svealand (S) (25%), Southern Norrland (SN) (24%) and Northern Norrland (NN) (20%). The same proportions apply for extraction at thinning and cleaning (SFA, 2008b).

The Swedish Energy Agency has formulated a vision for future forest fuel supply: In 2020 the Swedish forest shall deliver another 20-30 TWh per year, and by 2050 the amount should have doubled to 230 TWh (SEA, 2011b). By then Sweden shall also have efficient harvesting and logistical systems for slash, stumps and small dimension trees (SEA, 2011a).

On-going research

The Swedish climate goals involve high expectations on the supply of biomass from Swedish forests. Since forest fuel extraction until recently has been almost non-existent on an industrial scale, available technology has not advanced in decades, and many logistical challenges are yet to be solved. The knowledge about environmental effects as well as effects on production capacity has also been insufficient. Research programmes with shifting focus and scale have therefore been initiated

Sustainable supply and refinement of biofuels is a comprehensive programme administrated by the Swedish Energy Agency and focuses on increased and efficient use of domestic and renewable fuels. The first phase ended in 2010 and was followed by a second phase (2011-2015) which includes three separate areas: supply, transformation and sustainability (SEA, 2011c). *Future Forests* is a multi-disciplinary research programme supported by the Foundation for Strategic Environmental Research (MISTRA), the Swedish Forest Industry, the Swedish University of Agricultural Sciences (SLU), Umeå University, and the Forestry Research Institute of Sweden. Phase one runs from 2009 to 2012 and takes on the challenge to make forests meet all our varied needs. *Stump harvest and environmental effects* is a major research programme that focuses on positive and negative impact of stump harvesting, with the aim to provide better recommendations on what kind of environments and stumps that should be excluded to achieve a sustainable stump harvesting. It was initiated in 2007 by SLU and the Swedish Energy Agency, with contributions from the Forest Industry, and was finalised in 2010 (Persson, 2009).

Even though these and many other research initiatives have contributed to a much more profound understanding of the expected ecosystem effects from extensive extraction of forest residues, it is repeatedly stated that there are still many “black holes” to be covered, especially concerning stump removal.

1.5.4 Environmental effects

Research on the environmental effects of stump and slash removal has increased substantially during the last years and several reviews and synthesis reports have been presented [e.g. Walmsley& Godbold, 2010; de Jong *et al.*, 2012; SLU, 2010; Egnell, 2009; SEA, 2007; SEA, 2006]. The results and conclusions are not unequivocal though, and all reports underline the need for further research within basically all areas connected to forest residues. Some of the most commonly mentioned effects of forest residue extraction are presented briefly below.

Loss of biodiversity

More than half of all redlisted species in Sweden live off the forest in some way, in old trees, dead wood and deciduous trees. The greatest threat to forest dwelling species is the loss and fragmentation of forests with high nature values. The situation is most serious in southern Sweden, but the rapid disappearance of old-growth forests in the North has major impact on forest communities. The increasing trend to fertilise forest land and use exotic tree species is predicted to have further negative effects on forest biodiversity. (SSIC, 2010)

The removal of forest residues directly affects numerous species for which tops, branches and stumps are important substrates and habitats. Out of the 7000 wood-living species in Sweden about 50% are estimated to use small diameter wood, including tops and branches (SEA, 2006). Stumps represent the largest coarse woody debris component in managed forests and typically host vast numbers of valuable fungi, mosses, bryophytes and insects (Walmsley & Godbold, 2010). A study by Hjältén *et al*. (2010) showed that low stumps created at final felling support as many species and individuals of saproxylic beetles as other dead wood. Considering the fact that stumps constitute 80% of the remaining dead wood on clear-cuts, increased stump removal could have negative effects on their diversity. Vasaitis (2010) points out that an indirect effect of stump removal could be a reduced risk of root-rot in new upcoming forest, with possibly positive effects on biodiversity.

Rudolphi & Gustavsson (2005) state that slash represents a habitat with no real equivalent in natural conifer dominated forests. Forest residues further give shelter and shade to soil-living organisms from the harsh environment created after a clear-cut (FRIS, 2011a). There is also a risk that the residues attract many insects that need dead wood to lay eggs, which consequently will be transported away from the forest and burned if the residues are removed before the eggs are hatched (ibid.). However in a report by the Swedish Energy Agency (2006) this is not seen as a major threat to biodiversity since the insects that live off logging residues from conifer trees are considered common and generalists (SEA, 2006).

Soil damages and leaching

Extraction of forest residues primarily means additional activity of heavy machines. Harvesters, forwarders, excavators and site preparation methods (i.e. harrowing) expose the soil to heavy loads, track formations and stirring (Egnell, 2009). It has been shown that the proportion of land affected by tracks is significantly greater on clear-cuts where stumps have been extracted (Mjöfors & Strömgren, 2010).

The severity of the impact is determined by several interacting external and site-specific parameters. Wet areas have low bearing capacity and logging on such sites is restricted, the same applies to slopes with steep inclination. Logging usually increases the water table because of decreased transpiration and causes the clear-cut to quickly turn wet. The slash is therefore commonly placed in the tracks for the machines to drive on in order to reinforce the soil and reduce soil damages (SFA, 2008a). As tops and branches are increasingly removed from logging sites less material is left that can be used as protective mats. Stumps and thicker roots have armouring qualities in themselves, which are lost when stumps are extracted (Walmsley & Godbold, 2010).

The type of soil damages that can follow an extraction of forest residues range from erosion, compaction of the pore systems, changed conditions for roots and plant growth, unintentional ditching of the site, to leaching of humus, nutrients and heavy metals, where methyl-mercury is the most precarious form (SFA, 2011g; Egnell, 2009; Walmsley & Godbold, 2010). The methods currently available for stump extraction could also affect seedling survival and the success of natural regeneration negatively because of the holes created in the ground (Egnell, 2009), with possible consequences for future productivity (Walmsley & Godbold, 2010). However, if appropriate precautionary measures are taken many damages can be reduced or even avoided (ibid.).

The amount of inorganic nitrogen (nitrate and ammonium) in the forest soil is small compared to the storage of organic nitrogen in living biomass due to the fast uptake of inorganic soil nitrogen in a growing forest. Logging abruptly reduces the nitrogen assimilation by living biomass, and simultaneously increases the amount of inorganic nitrogen in the soil. It takes several years before vegetation has covered enough ground to assimilate most of the inorganic nitrogen produced at decomposition. This leads to an increased risk of nitrogen leaching (de Jong *et al.*, 2012). In areas where nitrogen deposition is high (primarily in south-western Sweden) removal of biomass from the forest could help to reduce the long-term storage of nitrogen in the soil and hence reduce the risk of eutrophication of streams and soils (Hellsten *et al.*, 2008), soil acidification and loss of mycorrhiza (Gundersen, 1991).

Palviainen *et al*. (2010) suggest that since stumps serve as long-term carbon and nitrogen pools stump harvesting could potentially reduce the leaching of nitrogen. However, the high C:N ratio (300-500) of stumps and coarse roots causes wood fungi and other decomposers to import large amounts of nitrogen from the surroundings in order to decompose these substrates. This indicates that stumps are long-term nitrogen sinks (Persson, 2010).

Nutrient depletion and acidification

Harvesting large amounts of biomass generally causes the soil surface to acidify. The removal of base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) from the ecosystem result in a reduced degree of base saturation and pH (Hellsten *et al*., 2009). Furthermore, Ca, Mg and K, and also Phosphorous (P) are important tree nutrients and loss of them can lead to shortages. The risk of nutrient depletion increases when more biomass than only stems are harvested (SFA, 2008a). The severity and degree of the impact depend on several parameters: how much biomass that is left on the site, if and how it is spread out and how the vegetation manages to assimilate the remaining nutrients (de Jong *et al*., 2012).

Many studies have been done on the effects of whole-tree harvesting on the ecosystem’s nutrient budget (comparing the inflow of nutrients by deposition and weathering with the nutrient outflow by leaching and harvesting) [i.e. Hyvönen *et al*., 1999 and Hellsten *et al*., 2008]. Several studies have shown a negative nutrient balance in the ecosystem when forest residues are removed. Especially slash affects the balance since the concentrations of nutrients and acid-buffering elements are highest in crown foliage (SFA, 2006). Stumps and thicker roots have basically the same nutrient content as stems (Hellsten *et al*., 2009) and as long as fine roots[6] are left in the ground it’s been suggested that stump removal does not affect the nutrient balance as much as slash (de Jong *et al*., 2011). However the mechanical disturbance of the soil following stump extraction increases the risk of nutrient loss through leaching (Egnell, 2009). To prevent net loss of nutrients and acidification after removal of forest residues compensation is often needed, especially in spruce forests (Akselsson, 2005)

1.5.5 Greenhouse gas emissions and climate change mitigation

One of the most commonly expressed benefits of forest residues is their potential to replace fossil fuels, both from energy and climate perspectives. The combustion of biofuels is often seen as climate neutral since the biomass would have decomposed naturally if not removed and burned, resulting in the same amount of CO_2 emitted to the atmosphere. Provided that the harvested site

[6] Primary roots usually smaller than 2 mm diameter that have the function of water and nutrient uptake.

is regenerated properly the emitted amount of CO_2 will eventually be taken up by new vegetation. However, to determine the climate change mitigation potential of a specific biofuel the greenhouse gas (GHG) emissions during the complete chain, from production to utilisation, have to be analysed. It is also necessary to consider the full chain of the replaced energy system. (Gustavsson, 2011)

Affected carbon balance in the forest

Final felling is generally followed by a large instantaneous release of carbon dioxide (CO_2) as the respiration by soil organisms is no longer outweighed by photosynthesising trees (Lindroth *et al*., 2008). It is complicated to separate the additional impact of the extraction of forest residues from the impact of the felling procedure. However, a direct effect of removing biomass from the ecosystem is reduced availability of decomposable organic carbon and hence reduced emissions of CO_2 through respiration (Eriksson *et al*., 2007). The storage of carbon in forest soils is enormous (Olsson, 2010a). The mechanical disturbance from excavators and forwarders often affects the soil profoundly, which can trigger and increase decomposition of soil-bound carbon with subsequent carbon emissions (Walmsley & Godbold, 2010). The emission rates vary greatly with soil type and land use methods; for example, a drained peat-land has substantially higher carbon emissions than a dry and nutrient poor land (Holmgren *et al*., 2007).

On the other hand stirring the soil could possibly improve the establishment of a new stand, which would favour the long-term carbon binding. Heavy track formations reduce the CO_2 emissions but can on the same time lead to increased surface runoff and disturb plant growth. As tracks often make the soil waterlogged the production and emission of the highly effective greenhouse gases methane (CH_4) and nitrous oxide (N_2O) can be triggered (Mjöfors & Strömgren, 2010). As winters become increasingly warmer and wetter, periods of frost in the ground will become rarer which enhances the risk of severe track formations (Egnell, 2009) with subsequent greenhouse gas production and emission.

During the following 5-20 years after felling the clear-cut will be a net source of carbon to the atmosphere. Depending on the outcome of plant establishment and re-growth it can take 15-40 years before the carbon uptake balances the emissions and the stand becomes a net sink of carbon (Örlander, 2010; Grelle, 2010).

The supply chain

Most operations within the logistic system of forest residues require use of fossil fuels and hence emit greenhouse gases (GHG). Type of resource used (slash or stumps), how the forest residues are recovered and refined (employed technology), how far they are transported (geographical location) and what mode of transportation (truck, train and ship) that is used, determine the carbon efficiency of the harvested biomass.

Holmgren *et al*. (2007) conducted a comparative study of GHG emissions from a number of solid biofuels in order to investigate to what extent biofuels can be considered to be climate neutral. Except for the production system's impact on soil carbon storage and the land use methods (especially use of drained peat-lands), factors such as the use of fertilisers (both direct and indirect), combustion technology, refining of the fuel (i.e. pelletisation) and storage (especially of comminuted fuels) contribute to the total GHG emissions. Moreover, harvesting machines, transportation and waste handling involve great emissions (Holmgren *et al*., 2007).

In a study by Gustavsson *et al*. (2011) costs, primary energy and CO_2 benefits of various refining systems for using slash locally, nationally or internationally were analysed. It showed that the potential replacement of fossil fuels per hectare of harvest area was greater with a bundle[7] system than with a chip[8] system. Even though the bundle system used more primary energy and emitted more CO_2 per unit biomass delivered, its costs and dry-matter losses were lower, allowing for more biomass to be extracted per hectare (Gustavsson *et al*., 2011).

In a case study by Lindholm *et al*. (2010) it was shown that supply systems of forest residues in southern Sweden required less primary energy input than similar systems in the North, due to lower moisture content of residues, higher load factor, shorter transportation distances and less transport via terminals. Energy requirements and emissions from seven different procurement chains of both slash and stumps were calculated using Life Cycle Analysis (LCA). The most energy efficient recovery systems of forest residues were the ones handling loose residues that were chipped at the roadside. Bundle systems of both slash and stumps required more energy. However, it was also concluded that available technologies are immature and with developing technique there is potential to improve the efficiency when handling forest residues (Lindholm *et al*., 2010).

Many studies have identified transportation as the dominating primary energy user in many forest fuel systems (Lindholm *et al*., 2010). This suggests a difference in mitigation potential of forest fuel chains between northern and southern Sweden. However, in the study by Gustavsson *et al*. (2011) the transport system was of minor importance for the CO_2 emission balance. The factor with greatest impact was the type of fossil fuel replaced. The contradicting results by Gustavsson *et al*. and Lindholm *et al*. exemplify the complexity of making general conclusions on the climate change mitigation potential of different forest fuel practices since most studies differ with respect to setup, study categories, analysed parameters, geographical area, substituted fossil fuel and so on.

Substitution of fossil fuels and time perspective

The amount of greenhouse gases (GHG) emitted per generated energy unit[9] (kg GHG TJ^{-1}) is higher for forest fuels compared to most fossil fuels. When forest fuels are burned the emissions of GHG are instantaneous, whereas if the same amount of biomass is left on the clear-cut to decompose naturally[10] the emissions occur over several years or decades (Holmgren *et al*., 2007). Palviainen *et al*. (2010) studied carbon dynamics during decomposition of stumps in Finland, and found that 78% of the initial carbon in conifer stumps was lost in 40 years. It is therefore crucial to consider the temporal aspect when analysing the climate change mitigation potential of forest fuels.

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[7] The residues are compressed into logshaped bundles on the clear-cut site, which are then forwarded and transported to a central facility where they are chipped.

[8] The loose residues are collected and forwarded to the roadside where they are chipped, the chips are then transported.

[9] The emission factor for wood is 112 000 kg GHG TJ^{-1}, for fossil gas 56 000 kg GHG TJ^{-1}, for crude oil 73 300 kg GHG TJ^{-1} and an average of about 96 000 kg GHG TJ^{-1} for different types of coal (IPCC, 2006).

[10] The decomposition rate for stumps is assumed to be about 4,6% per year (Melin *et al*., 2009), for slash 7,4% per year and 17% per year for needles (Palviainen *et al*., 2004).

Melin *et al*. (2010) evaluated "whether, from a carbon balance perspective and over short and long-terms, stumps are more important as a source of energy that replaces fossil fuels, or as a carbon sink." They used historical data from the Swedish National Forest Inventory (NFI) to estimate the energy potential of stumps from pine, spruce and birch. They concluded that in a short-term perspective (0–20 years) the net carbon emissions from bioenergy combustion are slightly higher than from burning fossil fuels. To reduce emissions within the next ten years the best alternative seems to be to leave stumps in the ground. However, in a long-term perspective (>96 years), using stumps as bioenergy would result in reduced GHG emissions. The study does not consider emissions from the soil organic carbon pool caused by the substantial influence during harvest. (Melin *et al*., 2010)

Similar results are presented by Sathre and Gustavsson (2011) in their study of "climate impact from the recovery, transport and combustion of forest residues (slash and stumps), versus the climate impact that would have occurred if the residues were left in the forest and fossil fuels used instead." They found that over a 240-year period the cumulative radiative forcing[11] (CRF) is greatly reduced if forest fuels are used instead of fossil fuels. The factors with greatest effect on CRF were the type of fossil fuel replaced and biomass productivity. If forest fuels are used instead of coal there will be an almost instantaneous reduction of CRF, whereas substitution of oil and fossil gas would reduce the CRF first after 10-25 years. Decay rate of the forest residues when left in the forest and use of fossil energy in the supply chain had less significance for the CRF (Sathre and Gustavsson, 2011).

[11] A proxy for surface temperature change and hence disruption to physical, ecological and social systems. Radiative forcing (Wm^{-2}) is a measure of the greenhouse gas induced imbalance between incoming and outgoing radiation in the earth system (Sathre & Gustavsson, 2011).

Part II – Potential energy from forest fuels

2.1 Introduction

The stem only represents about 60% of the total biomass of coniferous trees. The remaining 40% are distributed in the branches/needles/top (20%) and stump/roots (20%) (FRIS, 2009). If this biomass would be harvested on a large scale the share of bioenergy of the total national energy supply could increase significantly and reduce the use of fossil fuels.

The conditions for forest production differ across the country, mainly due to climate factors. Forest growth, site index and standing volume per hectare are generally higher in the South of Sweden compared to northern forests. These regional differences are important to consider when calculating and discussing the potential forest fuel production.

2.1.1 Objective

The objective of this part of the study was to estimate how the potential to produce forest fuels (tops, branches and stumps) differs between forest sites in the South and the North of Sweden, and how much fossil fuels the generated bioenergy would replace, in a long-term perspective. Logistical constraints are not considered in the calculations.

2.2 Method

2.2.1 Observation sites

Data from 16 productive forest sites, provided by the Swedish Forest Agency, were used to calculate the forest fuel potential at different scenarios of biomass extraction. The 16 sites are *Observation sites* (from here on referred to as Obs-sites), study plots of forested areas where continuous measurements of several parameters such as soil water, deposition, needle chemistry, tree vitality, growth, and meteorology, are performed. The measurements are managed by the Swedish Forest Agency, except for the deposition and soil water chemistry measurements which are managed by IVL Swedish Environmental Research Institute. The environmental monitoring of forest plots has been conducted since the 1980's. The background to the initiative was the intensified acidification of Swedish forests and soils in the 1960's and 1970's. During 1995-1997 more than 220 Obs-sites were laid out across the country, more densely in the South than in the North because of higher deposition of air pollution in the South (Hildingsson, 2006). The analyses enable a clarification of the impact of air pollution on forests and on the interaction between different forest areas (SFA, 2011c).

All Obs-sites are positioned within a homogeneous forest area with as little disturbing activity (i.e. roads, gaps within the stand, stand borders) as possible, located far from urban areas and/or sources of pollution (Wijk, 2011). Each site is composed of a net area in which most measurements are done. Growth measurements are undertaken by cross callipering all trees at breast height (1,3 m), as well as the measurement of 10 height trees, within a sub area of 30×30 meters (0,09 ha). Destructive samples (i.e. needles, soil, and stem drilling for age determination) are collected in a buffer zone that surrounds the net area (Figure 6). See Hildingsson (2006) for an in depth description of the measurement design.

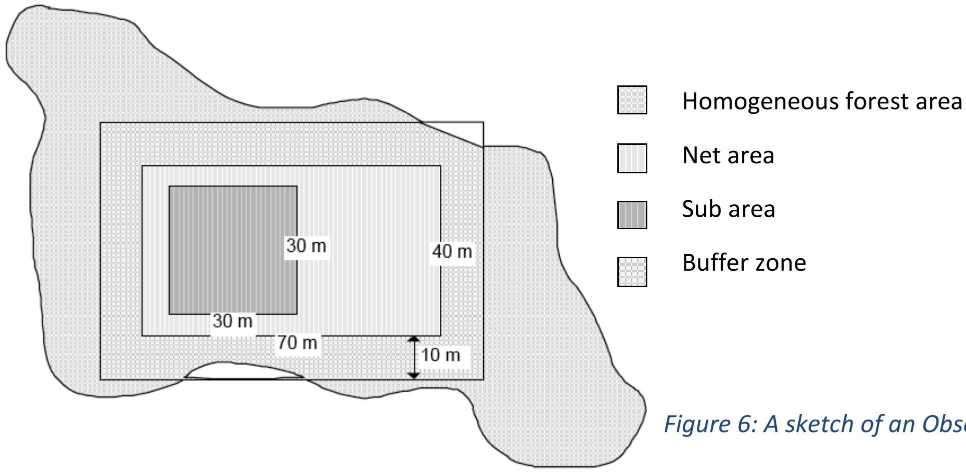

Figure 6: A sketch of an Observation site (Anon, 1995)

2.2.2 Selection of study sites

The study sites were chosen on the basis of a few criteria, as follows:

- Geographical location: 8 sites in the in the north-eastern parts (Västernorrland) and 8 in the south-western parts of Sweden (Halland/Kronoberg)
- Tree species composition (with a minimum of 80% domination of spruce)
- Spatial distribution (as short distance between the sites as possible)

Site characteristics are listed in Table 2 and the sites' geographical position is seen in Figure 7.

Table 2: General data for the 16 study sites, obtained from the Obs-database. The top 8 sites are located in the North of Sweden and the following 8 sites in the South. Coordination system: RT90. All sites have a minimum of 80% spruce domination.

Site nr	Coord Y	Coord X	Site name	County*	Meters above sea level	Year of establish ment	Site index (H_{100})	Soil texture
2270	6993700	1581550	Djupbäcken	Y	285	1995	G20	-
7103	6897721	1547496	Brännbacken	X	320	1996	G24	Sandy fine till
7201	6907600	1527650	Storulvsjön	Y	410	1995	G20	Sandy fine till
7203	7029000	1612300	Uberg	Y	100	1996	G24	Sandy fine till
7207	7036300	1649300	Utamlandsjö	Y	125	1997	G22	-
7302	6997250	1547300	Nymyran	Z	300	1995	G21	Sandy fine till
7401	7077050	1677950	Öreälven	AC	125	1995	G20	Coarse silt
7405	7107880	1556650	Granliden	AC	390	1996	G16	-
5604	6337500	1365950	Mellby	F	175		G26	Sandy fine till
5703	6302850	1374050	Angelstad	G	150	1996	G32	Sandy fine till
5708	6272020	1360260	Fälleshult	G	135	1995	G34	-
6302	6317550	1312150	Borgared	N	90	1997	G30	Sandy fine till
6305	6322450	1352200	Olshult	N	160	1995	G30	Sandy fine till
6313	6295700	1317200	Fastarp	N	140	1995	G30	-
6315	6312150	1331300	Ryssbol	N	145	1996	G30	-
6501	6367450	1337600	Bullsäng	P	195	1997	G30	Sandy fine till

*County letter: Y= Västernorrlands, X= Gävleborgs, Z= Jämtlands, AC= Västerbottens, F= Jönköpings, G= Kronobergs, N= Hallands, P= former Älvsborgs

2.2.3 Area of study

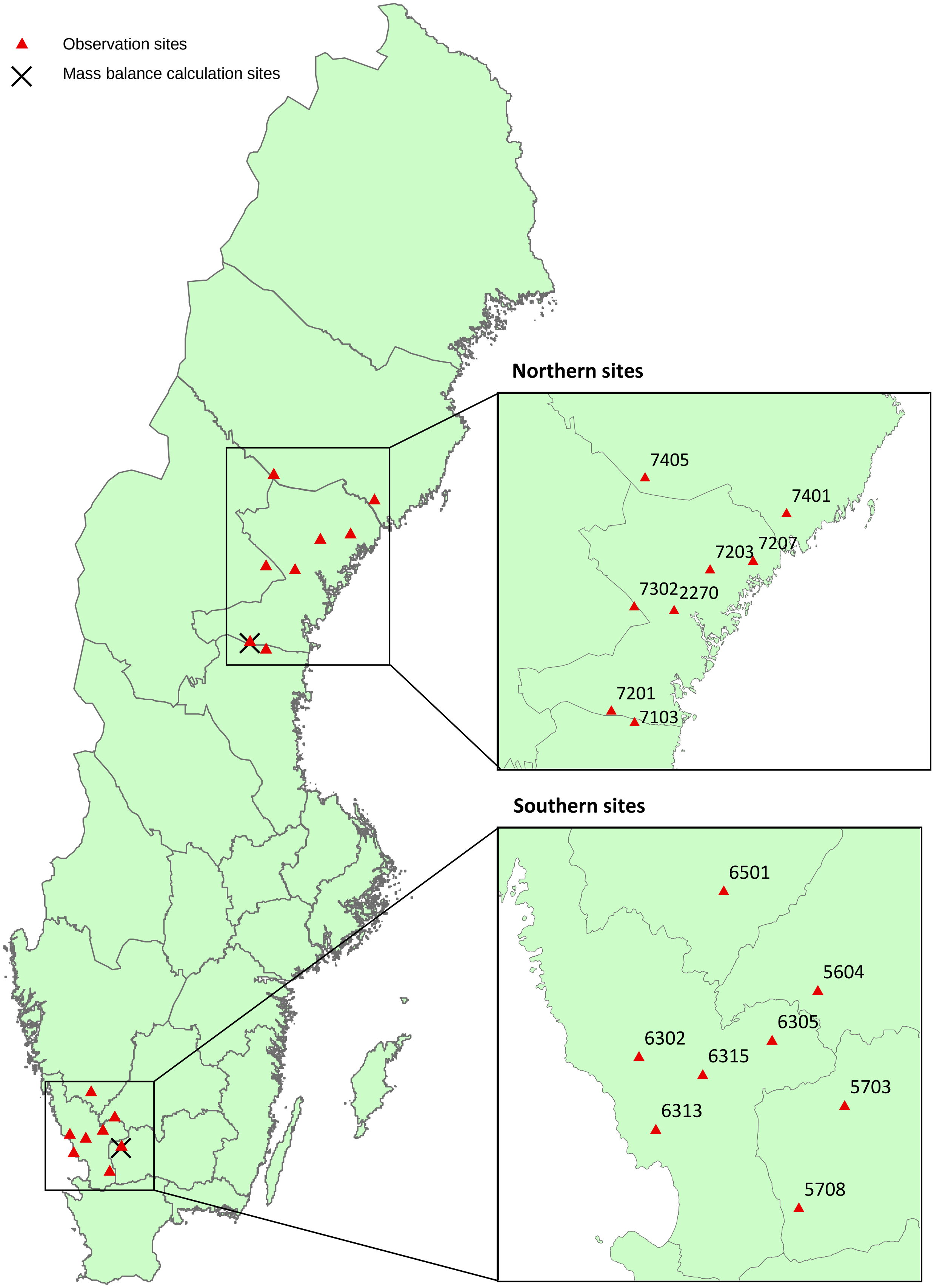

Figure 7: Geographical position of study sites

2.2.4 Calculating standing biomass

Each site's volume (ε 8 cm dbh), the total biomass of each tree species and all separate tree parts at the time of felling, were calculated by using the software application *StandWise* (Version 1.3) developed in the Heureka research programme. It is created and managed by the Swedish University of Agricultural Sciences (SLU). More information about the software setup is available at http://www.slu.se/heureka, from where it can also be downloaded.

A forest stand subject to forestry is normally felled long before it stops growing. Different climate conditions across the country result in different growth rates of forests, and thus different ages of felling. The felling age in southern Sweden normally varies between 70-90 years and between 90-120 years in the north (SFA, 2011b). In this study approximate felling ages were set to 80 years for the southern sites and 100 years for the northern sites.

Settings in StandWise

All sites were treated as separate projects with a sub area of 0,09 hectares. Mean diameter, tree species, tree type and coordinates of each tree, as well as the measured height trees were specified based on the measurements from the Obs-site inventory in 2004. Among the site characteristics only data of mean age, altitude, county and site index were available. Where data was unavailable common values for forested sites in Sweden were used (Lateral water: seldom/never; Soil moisture: Mesic/moist; Bottom layer: Mesic moss type) or set as Unknown (Vegetation type) (Figure 8).

In the *Production Model* settings, default values were used, except for the *Initial Height Source* and *Initial Age Source*, which were set to *From database* meaning that information of height and age was collected from the real data for each stand. The biomass at the time of final felling was simulated by applying the function *Planning Horizon* which uses the given site parameters in order to forecast the biomass development in periods of five years.

2.2.5 Harvesting scenarios

Two separate scenarios of forest fuel extraction were set up and compared. Scenario 1 corresponds to the most intense harvesting, where 80% of all tops and branches (including green needles) and 50% of all stumps are removed at each site. In Scenario 2 60% tops and branches and only 30% stumps are removed (Table 3). The scenarios for tops and branches were based on SKA-VB08 (SFA, 2008b).

Table 3: Scenarios of harvesting intensity of forest fuels

Scenario	Tops/ Branches	Stumps
1	80%	50%
2	60%	30%

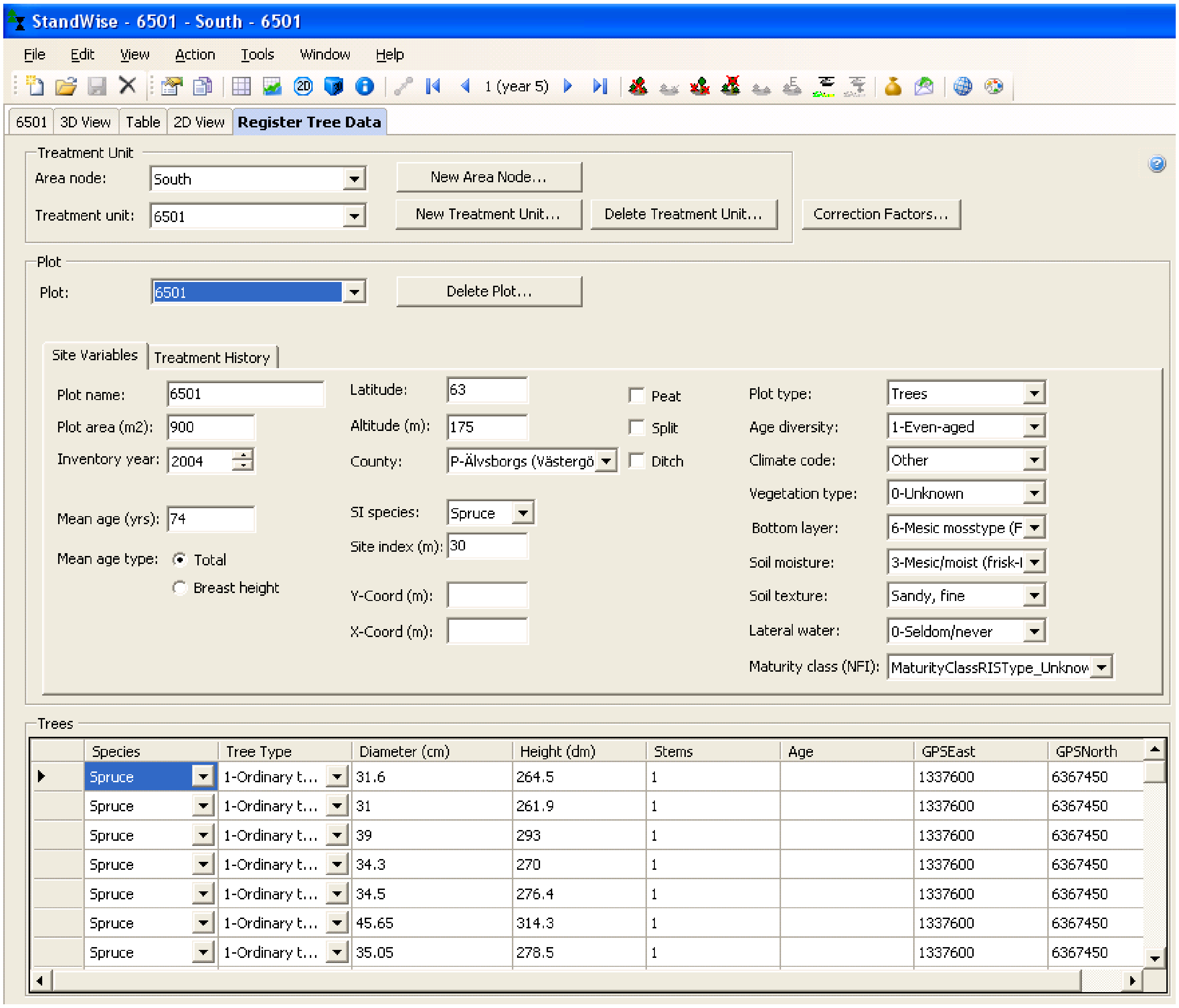

Figure 8: Input data for a specific site in StandWise, Heureka. The list of trees is not complete.

2.2.6 Calculating generated bioenergy and replaced amount of fossil fuels

The biomass (ton per hectare) of each tree part (stems excluded) at each harvesting scenario and at each site was converted into the corresponding energy yield by multiplying it by 4,7, the *Lower heating value* for biomass with 50% moisture content (given in MWh per Ton Dry Matter) (Egnell, 2009).

Finally the amount of fossil fuels the gained energy would replace was calculated using the following calorific values: Heating oil: 11,8 kWh kg^{-1}; Anthracite: 9,2 kWh kg^{-1} and Fossil gas 10,6 kWh kg^{-1} (Biomass Energy Centre).

2.3 Results

The standing biomass of tops, branches and stumps per hectare and site, as well as the mean value per hectare of all sites in each region at the time of felling, are shown in Figure 9. The southern region has about 60% more available biomass of forest residues per hectare (165 tons ha^{-1}) compared to the northern region (102 tons ha^{-1}). The northern sites have a greater internal variation than the southern sites, but the difference in biomass of forest residues per hectare between the regions is statistically significant (Unpaired T-test (6); T-value: 25,5; p-value: $4{,}5\times10^{-4}$).

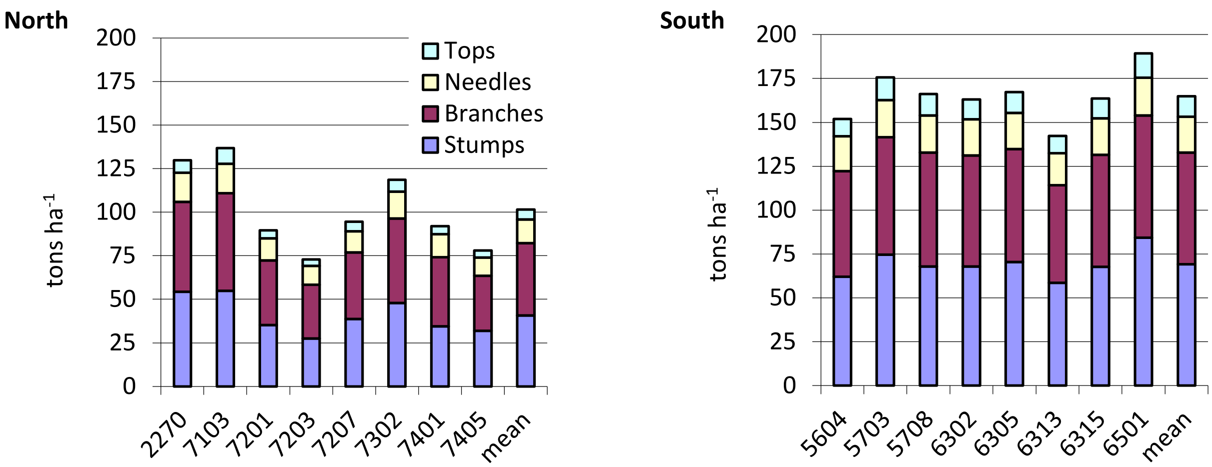

Figure 9: Biomass of forest fuels at the time of felling (100 years for northern sites; 80 years for southern sites).

In the North the production of slash is about 50% higher than the production of stumps. The corresponding figure in the South is 38%. The South further produces 70% more stump biomass than the North, and about 57% more slash (Figure 10).

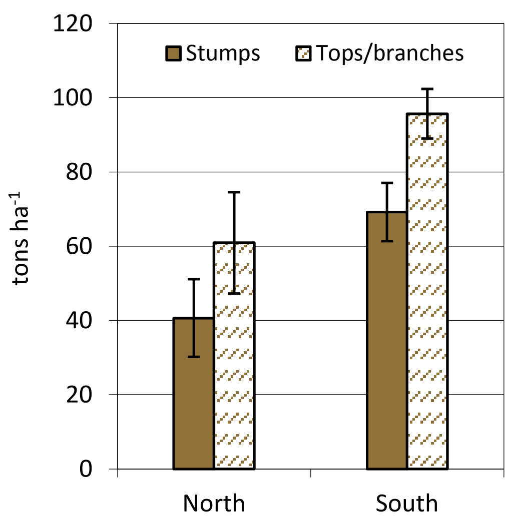

Figure 10: The available forest residues in the North compared to the South (mean value of all sites in each region). Needles are included in Tops/branches. The error bars show one standard deviation.

The energy potential from both stumps and tops/branches for both regions in the two harvesting scenarios is shown in Figure 11. The most intensive harvesting scenario where 80% of the tops/branches and 50% of the stumps are removed (S1) gave about 40% higher energy yield per hectare than the lower scenario of 60% tops/branches and 30% stumps (S2), for both the southern and northern regions.

The potential energy yield is 60% larger per hectare in the South compared to the North, for each scenario. The lower harvesting scenario in the South gives higher yield than the most intense scenario (S1) in the North (Table 4).

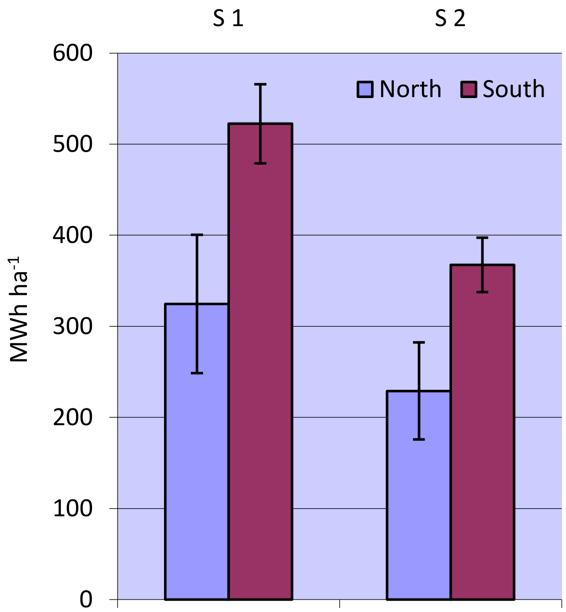

Table 4: Energy yield from forest fuels, per region and harvesting scenario (S) (MWh ha^{-1})

	S 1	Stdev	S 2	Stdev
North	324,5	75,9	229,1	53,3
South	522,4	43,5	367,4	29,8

Figure 11: The amount of energy that can be generated from forest residues, per region and harvesting scenario (S). (50% moisture content, steam energy excluded). The error bars show one standard deviation.

The amount of fossil fuels that could be replaced by the harvested forest fuels (per hectare) in Scenario 1 and 2 from each region is shown in Table 5.

Table 5: Amount of fossil fuels replaced by forest fuels (10^{3} kg ha^{-1})

	S 1		S 2	
	North	**South**	**North**	**South**
Heating oil	27.5	44.3	19.4	31.1
Anthracite (coal)	35.3	56.8	24.9	39.9
Fossil gas	30.6	49.3	21.6	34.7

2.4 Discussion

2.4.1 Methodological uncertainties and limitations

Greatest methodological uncertainty is associated with the input data obtained from the Obs-database. There are some systematic errors reported during the data collection procedure, regarding area estimation of the inventoried plots (Wijk, 2011), as well as repeated cases of unclear or missing data of the number of trees present in each site. This would suggest that the calculated potential energy yield from forest residues in these plots is underestimated. However, when comparing the regions' mean volume per hectare (m^3fo) with values from the Swedish National Forest Inventory (Official Statistics of Sweden and the Swedish University of Agricultural Sciences, 2010) for corresponding regions and age classes (80 years in the South and 100 years in the North) the former tend to be higher. This would lead to an opposite conclusion, that the calculated energy yield per hectare is overestimated in this study.

The majority of the Obs-sites have not previously been managed which contribute to high growth rates and volumes (Hildingsson, 2006). This needs to be taken into consideration if data and calculations are compared with results from similar studies.

The high domination of spruce at all sites is another factor that might lead to overestimated values of harvested forest residues since spruce trees generally have higher proportion of branches and needles than for example pine trees (Akselsson *et al*., 2007).

The limited number of sites (eight sites per region) influences the validity of the statistical analyses of the differences between the regions. However, it was not possible to find more sites that corresponded to the set criteria.

Furthermore the Obs-database did not provide all data required in StandWise, and values of the Climate code, Vegetation type, Bottom layer and Soil moisture were assumed and set equal for all sites. For a more detailed discussion of the uncertainties in StandWise the reader is referred to the administrators of the application.

2.5 Conclusions

The limited number of forest sites included in the study makes it impossible to draw any general conclusions at a large scale. However, the relative difference in the amount of produced forest residues between the regions indicates that the prerequisites for forest fuel production differ substantially between forest sites depending on their geographical location.

The results showed that a spruce stand in the North of Sweden provide 30% less forest residues (tons ha^{-1}) than a similar stand in the South, which corresponds to 60% less energy yield (MWh ha^{-1}).

Part III - Influence of forest fuel extraction on the nutrient balance

3.1 Introduction

The nutrient balance in the forest soil is determined by the net input (deposition and weathering) and the net output (leaching and harvesting) from the system. Deposition, stand and soil properties and harvesting intensity are the most important factors that influence the balance. As trees grow they take up base cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) and release hydrogen ions (H^{+}) in a process that naturally acidifies the forest soil. When the trees die and decompose the vital base cations are returned to the soil and both the pH-level and the nutrient balance is restored. When biomass is removed from the forest ecosystem the balance of nutrient flows in the soil is disrupted. Different tree parts contain different nutrient concentrations and highest concentration is found in the needles (SFA, 2006). The impact on the nutrient balance is therefore likely to be greater when harvesting slash than when only stems or stumps are harvested (FRIS, 2011b), and leads to both acidification and nutrient depletion.

The growth of forests is considered to be limited by N, especially forests in the northern half of Sweden, and N loss through leaching is generally low. However, the N-deposition varies across the country, with quite high loads along the south-western coast and significantly lower levels in Norrland (Akselsson, 2005). This affects the prerequisites to maintain a proper nutrient balance in the ecosystem after harvesting forest residues. The weathering of minerals adds base cations and P to a soil system. The weathering rate at a specific site determines its buffering capacity against acidification and the risk of nutrient depletion. Most P is found in apatite, a mineral that easily weathers and releases phosphate ions (PO_4). The PO_4-ions are quickly transferred to other compounds and depending on the soil-pH they are more or less available for plant roots. At low pH-values insoluble iron and aluminium phosphates are formed, and at higher pH mainly calcium phosphates. The acid organic compounds produced by plant roots and micro-organisms have the ability to bind the iron and aluminium ions into chelates, resulting in more free phosphate ions. Easily degradable organic material could therefore be said to favour plants' access to P (Lundmark, 1986)

3.1.1 Objective

The aim was to study the effect on the nutrient balance in the soil after slash and stumps are removed at a forest site in the North of Sweden compared to a site in the South, and how the impact varies with different harvesting scenarios.

3.2 Method

Out of the 16 Obs-sites (see Part II) two sites (7201 and 5703) were selected, one in the North and one in the South of Sweden. They are part of SWETHRO Throughfall Monitoring Network (*Krondroppsnätet)*, a collection of forest sites where continuous measurements on deposition (both over open field and in the forest), soil solution chemistry and air pollution are made (Pihl-Karlsson *et al*., 2011). SWETHRO is managed by IVL Swedish Environmental Research Institute and jointly financed by Air Quality Management Associations, County Administrative Boards and the Swedish Environment Agency. General site data is presented in Table 6 and for the exact positions of the two sites see Figure 7. In order to facilitate the reading and understanding of the calculations, the sites are from here on referred to as **North** (7201) and **South** (5703).

Table 6: General site data obtained from the Obs-database.

	North	South
Site number	7201	5703
Dominating tree species	Norway spruce (100%)	Norway spruce (96%)
Humus form	Mor	Mor
Soil parent material	Sandy fine till	Sandy fine till
Texture	Fine sand /coarse silt/fine silt	Medium-grained sand
Soil type	Iron podsol	Iron humus podsol
Texture class	Sandy loamy (Deep soil depth, uneven elluviation layer)	Sandy loamy
Precipitation[12] (mm)	488 KD	611 KD
Runoff[13] (mm)	350	650
Temperature[14]	4	6

3.2.1 Mass balance model

In order to calculate the nutrient balance in the forest ecosystem knowledge of four main processes is required:
- Weathering in the soil
- Deposition from the air
- Leaching with running water, and
- Nutrient removal by biomass harvest

A simple mass balance model was thereafter used according to Akselsson, 2005:
Cations and Phosphorous: Deposition + Weathering - Leaching – Net uptake
Nitrogen: Deposition + Fixation - Leaching – Net uptake

A negative net balance indicates that the soil is being depleted, whereas a positive net balance means that nutrients are accumulating in the soil.

3.2.2 Harvesting scenarios

Four scenarios with different intensity of biomass removal were set up and the nutrient balance was calculated for each of them. In addition to Scenario 1 and 2 (identical with Part II) Scenario 3 and 0 were included. In Scenario 3 only stems are harvested and in Scenario 0 no biomass is removed at all. Needles are included in Tops/Branches (Table 7).

Table 7: The four harvesting scenarios used in the nutrient budget calculations

Scenario	Tops/ Branches	Stumps	Stems
1	80%	50%	100%
2	60%	30%	100%
3	0	0	100%
0	0	0	0

[12]Average annual values for the period 2006-2009 from throughfall deposition measurements, available in *Krondroppsnätet* (IVL, 2011b).
[13]Approximate annual values (SMHI, 2009a)
[14] Average annual temperature for the period 1961-1990 (SMHI, 2009b)

3.2.3 Input data

Weathering

The weathering rate of base cations and phosphorous was calculated using the steady-state soil chemistry model PROFILE[15] (Sverdrup & Warfvinge, 1993). Calculations of weathering are based on a transition state theory and a number of geochemical properties of the soil system. The soil is divided into four layers for which i.e. soil moisture, mineral surface area and mineralogy are specified.

Site-specific data were used for most parameters and are presented in Tables 8-11 with brief descriptions of the applied methodology and relevant references. In cases where such data were unavailable, standard values were calculated according to the procedure in Warfvinge & Sverdrup (1995). The mineral composition was calculated according to the UPPSALA model. It is a normative back-calculation model that reconstructs the mineralogy from total analysis based on simple survey data. When no more adequate ions are available for the formation of a mineral, the content of that mineral is set to zero (Sverdrup et al., 2006). The methodology is outlined in Sverdrup & Stjernquist (2002) and based on the input data in Table 8a. The variation in mineral content between the different soil layers were adjusted for by using specific modification factors according to Warfvinge & Sverdrup (1995).

The soil oxide content was estimated to be the same as the closest measurement point supplied by the Swedish Geological Survey (SGU) (Lax & Selenius, 2005.) This distance was 667 m and 1582 m for North and South respectively (Table 8b).

Table 8: Soil mineralogy; a) Total content of the individual mineral in layer 4 (at 0,45 m depth) (% of weight); b) Oxide content in the soil (% of weight)

a.	North	South
K-Feldspar	18,4	19,4
Plagioclase	13,3	35,9
Apatite	0,6	0,5
Hornblende	8,7	6,5
Chlorite	3,4	0,0
Epidote	1,0	1,4
Muscovite	1,2	1,3
Quartz	42,7	35,2
Vermiculite	0,0	0,0

b.	North	South
CaO	2,0	2,3
K_2O	2,6	2,9
Na_2O	1,6	3,6
P_2O_5	0,3	0,2
Al_2O_3	16,0	12,1
SiO_3	69,5	75,0
MgO	1,8	0,6

The exposed mineral surface area can be estimated when the texture class is known (Table 9a). The two sites (classified as sandy-loamy in Table 6) were assigned of a certain area according to the procedure in Warfvinge & Sverdrup (1995). The surface area decreases upwards in the profile with the same rate as the density decreases. To account for this the following adjustments were made: Layer (L) 4 = 1, L3 = 0,85, L2 = 0,7, L1 = 0,2 (Akselsson, 2011a).

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[15] The PROFILE model can be freely downloaded at [www2,chemeng.lth.se/models/]

The root zone for spruce was estimated to be 0,45 m according to measurements made by Sverdrup *et al*. (2006). Measurements of each layer thickness were available in the Obs-database and are shown in Table 9b. Moisture content in the soil is highly variable throughout the year, but the steady state approach requires one specific number. A commonly assumed value in Sweden was used (Alveteg *et al*, 2002) (Table 9c).

Table 9: a) Exposed mineral surface area (106 m^2 m^{-3}); b) Soil layer depth (m); c) Soil moisture content (m^3m^{-3})

a. Layer	North	South
1	0,14	0,14
2	0,49	0,49
3	0,59	0,59
4	0,7	0,7

b. Layer	North	South
1	0,02 (Of+Oh)	0,09 (Of+Oh)
2	0,03 (E)	0,08 (Eh)
3	0,30 (B)	0,27 (Bsh+B)
4	0,10 (C)	0,01 (BC)

c. Layer	North	South
1	0,25	0,25
2 - 4	0,20	0,20

Of: Layer of decomposition; Oh: Layer of humus substances; Eh: eluviation layer with humus enrichment; E: eluviation layer; Bsh: Layer of humus in illuviation layer; B: illuviation layer; BC: transition between the illuviation layer and the unaffected base; C: unaffected base

Vegetation input

The vegetation input data comprise Net uptake, which is the amount of nutrients removed at harvest (presented in Table 13), Litterfall, Canopy exchange and Net mineralization. Both Canopy exchange and Net mineralization were set to zero. The former is normally obtained by taking the difference between wet + dry deposition, and throughfall deposition (Alveteg *et al*., 2002). However, since values for total deposition were used and because the calculations of nutrient content in needles were based on needles still attached to the tree, all nutrients were accounted for without involving canopy exchange (ibid.).

Table 10: Litterfall (kEq $ha^{-1}yr^{-1}$)

	North	South
Ca	0,18	0,64
Mg	0,04	0,15
K	0,05	0,18
N	0,39	1,35

The nutrient values in litterfall (Table 10) were obtained by using a fixed relationship between net uptake in stems and litterfall, according to Warfvinge & Sverdrup (1995a). Litterfall/net uptake = 3,1 for Ca, Mg and K; and 5,4 for N. The amount of litterfall is the same in all scenarios since the biomass of stems is fixed.

Deposition input

Atmospheric deposition affects the soil chemistry and thus the nutrient budget in the forest soil. The south-western parts of Sweden are submitted to high loads of air pollution brought in by continental winds, whereas northern and central parts of the country receive less. The deposition is affected by the amount and composition of the precipitation, and the air's content of different substances (IVL, 2011a).

Much of the deposited NH_4 is taken up by the trees and throughfall deposition can thus not be used as a measure of total deposition. Total deposition was calculated following Alveteg *et al*. (2002) pp. 15. Wet deposition of NH_4-N, and wet and throughfall deposition of SO_4-S used in the calculations was obtained from SWETHRO (IVL, 2011b; IVL, 2011c) (Table 11a).

Table 11: Deposition data used in the PROFILE-model (kEq $ha^{-1}yr^{-1}$)

a.	North	South
NH_4-N	0,074	0,391

b.	North	South
SO_4-S	0,042	0,139
Cl	0,109	1,229
NO_3-N	0,019	0,219
Na	0,093	1,028

c.	North	South
Ca	0,082	0,215
Mg	0,043	0,267
K	0,037	0,078

The interaction between SO_4-S, NO_3-N, Na and Cl and the trees is considered to be very low. Throughfall deposition in itself is a good measure of wet and dry deposition (Alveteg *et al*., 2002). Data was obtained from forest measurements available in SWETHRO (IVL, 2011c) and is shown in Table 11b. Average values for the period 2006-2009 (hydrological years) were used.

Also for Ca, Mg and K there is internal circulation and total deposition has to be estimated. The interaction of these three substances with the trees is considerable and they thus have a direct impact on the forest. Dry deposition data was accounted for following the outline in Alveteg et al. (2002) (Table 11c). Wet deposition data was obtained from Open field measurements available in SWETHRO (IVL, 2011b). Average values for the period 2006-2009 (hydrological years) were used.

Deposition

The deposition values used in the mass balance calculations were for Ca, Mg and K the same as in Table 11a. The deposition of N was obtained by summarising the deposition (in kg ha^{-1} $year^{-1}$) of NH_3-N and NO_3-N (Table 15). Total deposition (wet and dry) of P was set to be 0,20 kg ha^{-1} $year^{-1}$ both in the North and in the South, according to estimations in Akselsson et al. (2008).

Fixation

An important inflow of nitrogen into the ecosystem is the plants' fixation of N from the atmosphere. Standard values of the fixation rate were used for both sites and set to 1,5 kg ha^{-1} $year^{-1}$, according to results from a study in northern Sweden by DeLuca *et al*. (2002) referred to in Akselsson *et al*. (2008).

Leaching

Flowing water through the soil profile causes leaching of chemicals, and the leaching rate is determined by the soil solution concentration and runoff. The runoff at each site was obtained from SMHI and amounted to 0,25 and 0,47 m^3 m^{-2} $year^{-1}$ at North and South respectively (SMHI, 2009a). The fixed relationship 1 litre s^{-1} km^{-2} = 31,5 mm $year^{-1}$ was used to convert the given unit mm $year^{-1}$ into m^3 m^{-2} $year^{-1}$ (SMHI, 2002).

The leaching of Ca, Mg and K was calculated using: $L = Q \times [C_i]$, as outlined in Sverdrup *et al*. (2006). L = leaching in kg ha^{-1} $year^{-1}$, Q = runoff in m^3 m^{-2} $year^{-1}$, and $[C_i]$ = annual average soil solution concentration in kEq m^{-3}.

Table 12: Soil solution concentration [Ci] (mekv l^{-1})

	North	South
Ca	0,043	0.040
Mg	0.020	0.057
K	0.0047	0.0051

The calculated soil solution concentration input data is presented in Table 12. Average annual soil solution concentration (median values) is based on the period 2006-2009. Data was obtained from the Obs-database.

An average value for P leaching of 0,04 kg ha^{-1} $year^{-1}$, as given in Akselsson *et al*. (2008), was used for both sites.

Nitrogen

Total N-leaching is the sum of ammonium (NH_4-N), nitrate (NO_3-N) and organic nitrogen (N_{Org}-N). The leaching of NH_4 is generally marginal and a fixed value of 0,39 kg ha^{-1} $year^{-1}$ was used, based on measurements performed in the central and northern parts of Sweden. It was applied to both the southern and northern sites.

NO_3 and N_{Org} however are empirically related to runoff in different ways. NO_3 is not adsorbed by the colloids in the soil but move freely with drainage water and is easily leached from the soil (Brady & Weil, 2002). Furthermore, the deposition of N varies between regions, with a direct impact on the soil solution concentration, and thus on the amount of N leached from the system. The leaching rate was therefore calculated for each site and N-form separately.

The leaching rate of NO_3, N_{Org} and total N for the northern site was calculated according to Akselsson & Westling (2005). N leaching in southern Sweden was calculated using the same method as in northern Sweden. Although the increased leaching of N in the clear-cut phase in southern Sweden, caused by elevated N deposition, was accounted for. After clear-felling a forest stand both runoff and N concentrations in soil water increase since there is no longer any trees that retain the precipitation water and the nitrogen. In this study the clear-cut phase was assumed to be five years. Results from a study in southern Sweden suggest that the runoff from a forested site is 70% of that from a clear-cut (Agestam *et al*., 2002). Thus, the runoff was increased correspondingly when calculating leaching from clear-cuts. Total N-concentration in soil solution after a clear-cut was calculated using Akselsson & Westling (2005).

The annual soil solution concentration of organic N was set to 0,38 mg l^{-1} $year^{-1}$ based on seasonal median values from the West Sea, obtained from Löfgren & Westling (2002). Deposition data for NO_3 and NH_4 at each site is obtained from the Obs-database (Table 11a-b). The average N-leaching for the whole rotation period (set to 80 years) was calculated based on the estimated clear-cut leaching (5 years) and the leaching from the remaining 75 years.

Net uptake

Net uptake is the amount of nutrients removed at harvest. It was calculated by multiplying the nutrient concentration in stems, tops and branches (obtained from Egnell *et al*., 1998), needles (obtained from Obs-database, Table 13c) and in stumps (obtained from Hellsten *et al*., 2009) for spruce and pine, with the harvested biomass (ton ha^{-1}) of each tree species and tree part

(Table 13a-b). These values were thereafter divided by the stand age for each region (100 years for the North and 80 years for the South) to get the net uptake of each nutrient. This was done for each scenario and the values were finally transformed into kEq ha^{-1} year^{-1} (Table 14).

Table 13: a-b) Biomass removed at all scenarios (S) for each tree species and region (ton ha^{-1}); c) Nutrient content in needles in the North and South (mg g^{-1})

a. **Northern sites**	**S 1 Spruce**	**S 2 Spruce**	**S 3 Spruce**	**S 0 Spruce**
Tops/branches	33,4	25,1	0	0
Needles	10,1	7,6	0	0
Stumps	17,6	10,5	0	0
Stems	91,5	91,5	91,5	0
Total	152,6	134,7	91,5	0

b. **Southern sites**	**S 1 Spruce**	**S 1 Pine**	**S 2 Spruce**	**S 2 Pine**	**S3 Spruce**	**S3 Pine**	**S0**
Tops/branches	62,1	1,7	46,5	1,3	0	0	0
Needles	16,8	0,25	12,6	0,2	0	0	0
Stumps	36,1	1,2	21,7	0,7	0	0	0
Stems	245,4	11,3	245,4	11,3	245,4	11,3	0
Total	360,4	14,5	326,2	13,5	245,4	11,3	0

c.	**North**	**South**
Ca	4.48	2.16
Mg	1.21	1.59
K	5.32	4.22
N	12.62	13.26

3.3 Results

3.3.1 Cations

All harvesting scenarios (S 1-3) at both sites have a negative balance for Ca and it is also the nutrient that shows the largest losses. Mg has a negative net balance when forest residues are harvested in the northern site (Scenario 1 and 2), but a positive balance in Scenario 3 (only stems). In the South the balance of Mg is negative in all scenarios where biomass is removed. K shows positive values for all scenarios in the North, whereas the net balance is negative when forest residues are harvested in the South. The net balance for each site and scenario is shown in Table 14 and illustrated in Figure 12.

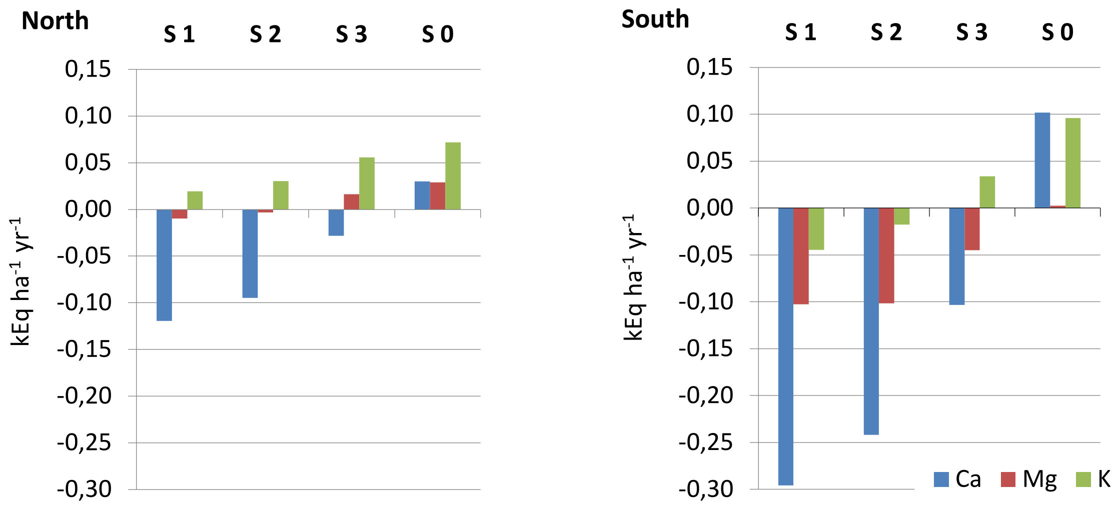

Figure 12: Net balance of cations in the soil at each site and for each harvesting scenario (S).

Figure 13 shows the differences in the net balance of base cations between all scenarios. The loss of Ca is 1,3 and 1,2 times higher in S1 (80% slash; 50% stumps) compared to S2 (60% slash; 30% stumps), for the North and South respectively. Between Scenario 2 and Scenario 3 the differences in the Ca balance are even greater. The Mg-balance shows greatest variety in the South. There is no difference between the scenarios where forest residues are harvested (S1-2), but only half as much Mg is lost if only stems are removed (S3). In the North the impact on the Mg-balance is much lower, both in absolute and relative terms, and even shows a positive value in S3. The loss of K from the southern site is 2,5 times higher in S1 than in S2, and the K-balance becomes positive in S3. In the North K is accumulated in the system at all harvesting intensities.

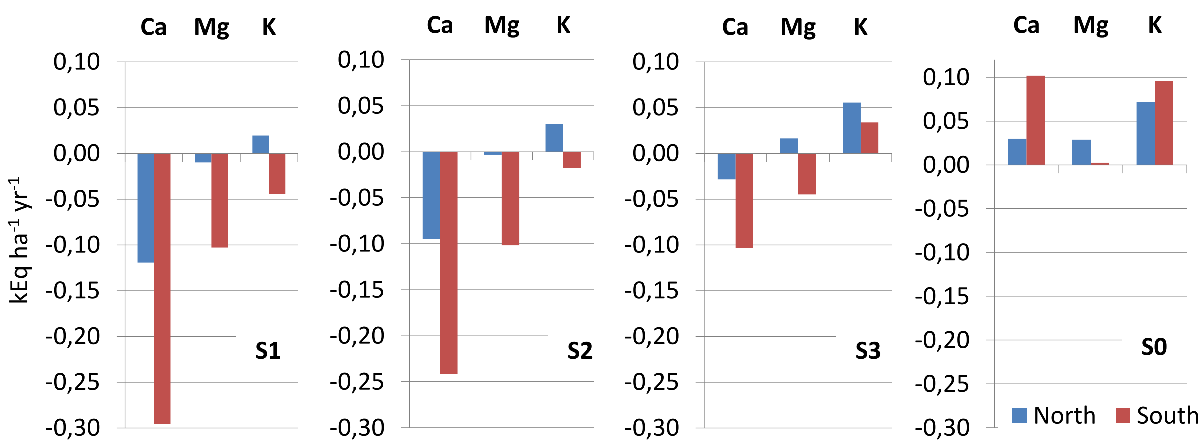

Figure 13: Comparison of the Net balance of cations in the soil between the sites for each scenario (S).

Figure 14 shows the relative contribution of each process to the final net balance of Ca, Mg and K in Scenario 1. The weathering rates are similar across the country, Mg in the South being an exception. Quite a lot Ca and Mg are lost through leaching both in the South and in the North even if the losses are much greater in the South. Harvesting is the most important process for Ca and K, whereas Mg is added mostly through deposition, at least in the South.

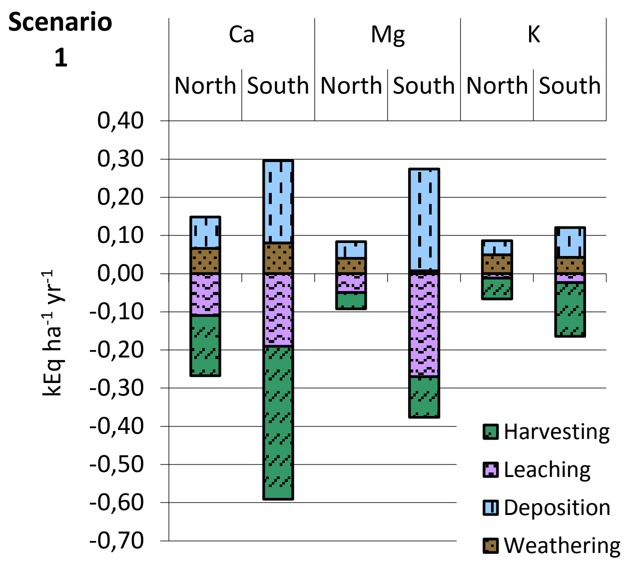

Figure 14: The contributions of each process to the final net balance of base cations when harvesting 80% slash and 50% stumps (Scenario 1)

Table 14: Calculations of the mass balances of Ca, Mg, K (kEq $ha^{-1}year^{-1}$) at all scenarios (S)

	North				South			
Weathering	**S 1**	**S 2**	**S 3**	**S 0**	**S 1**	**S 2**	**S 3**	**S 0**
Ca	0,066	0,064	0,059	0,058	0,080	0,081	0,077	0,077
Mg	0,040	0,039	0,037	0,036	0,007	0,006	0,006	0,006
K	0,049	0,050	0,048	0,047	0,042	0,047	0,042	0,042
Deposition								
Ca	0,082				0,215			
Mg	0,043				0,267			
K	0,037				0,078			
Leaching								
Ca	-0,110				-0,191			
Mg	-0,050				-0,270			
K	-0,012				-0,024			
Net uptake	**S 1**	**S 2**	**S 3**	**S 0**	**S 1**	**S 2**	**S 3**	**S 0**
Ca	-0,157	-0,131	-0,059	0	-0,400	-0,347	-0,205	0
Mg	-0,043	-0,035	-0,014	0	-0,106	-0,104	-0,047	0
K	-0,054	-0,044	-0,017	0	-0,140	-0,119	-0,059	0
	North				South			
Net balance	**S 1**	**S 2**	**S 3**	**S 0**	**S 1**	**S 2**	**S 3**	**S 0**
Ca	-0,119	-0,095	-0,028	0,030	-0,296	-0,242	-0,103	0,102
Mg	-0,010	-0,003	0,016	0,029	-0,103	-0,102	-0,047	0,002
K	0,020	0,030	0,056	0,072	-0,045	-0,018	0,034	0,096

3.3.2 Phosphorous and Nitrogen

In the North the net balance of P shows a small negative value in Scenario 1, and then turns positive in the following scenarios. About 5 times more P is maintained in the ecosystem if only stems are harvested (S3) compared to S2 (60% slash; 30% stumps). The loss of P from the southern site is substantially larger and the P-balance is only positive if no biomass at all is harvested (S0). The P-balance in S0 is very similar in the North and the South (Figure 15a).

Regarding the N-balance, the results show an inverse relationship between the sites compared to the P-balance. The loss of N is greater in the North than in the South, in all harvesting scenarios. If no residues are extracted the N-balance is positive at both sites but about 7 (S3) and 4,8 (S0) times higher in the South (Figure 15b).

Since both deposition and leaching have fixed values for all scenarios the processes that influence the variation in the final net balance of P are harvesting and weathering. The relative importance of harvesting (Net uptake) compared to weathering is greater at the southern site, whereas the difference is minor in the North (Figure 16a). The N-deposition in the South is almost equal to the amount of N lost during the most intensive harvesting scenario (S1). The northern site loses 2,5-3,5 times less N at harvest (S1-S3) compared to the South, but the small amounts of N added through deposition (6,5 times less than in the South) still leads to greater net loss in the North (Figure 16b). The data of all processes contributing to the net balance are presented in Table 15.

Table 15: Calculations of the mass balances of Phosphorous and Nitrogen (kg ha^{-1}year^{-1}) for all scenarios (S)

	North				South			
Weathering	**S 1**	**S 2**	**S 3**	**S 0**	**S 1**	**S 2**	**S 3**	**S 0**
P	0,341	0,330	0,295	0,279	0,279	0,248	0,279	0,264
Fixation								
N	1,5				1,5			
Deposition								
P	0,2				0,2			
N	1,298				8,539			
Leaching								
P	-0,04				-0,04			
N	-1,186				-2,304			
Net uptake	**S 1**	**S 2**	**S 3**	**S 0**	**S 1**	**S 2**	**S 3**	**S 0**
P	-0,524	-0,423	-0,128	0	-1,335	-1,187	-0,444	0
N	-4,232	-3,400	-1,010	0	-8,599	-9,062	-3,500	0
	North				South			
Net balance	**S 1**	**S 2**	**S 3**	**S 0**	**S 1**	**S 2**	**S 3**	**S 0**
P	-0,023	0,063	0,326	0,439	-0,896	-0,779	-0,005	0,424
N	-2,620	-1,788	0,602	1,612	-0,865	-1,327	4,235	7,735

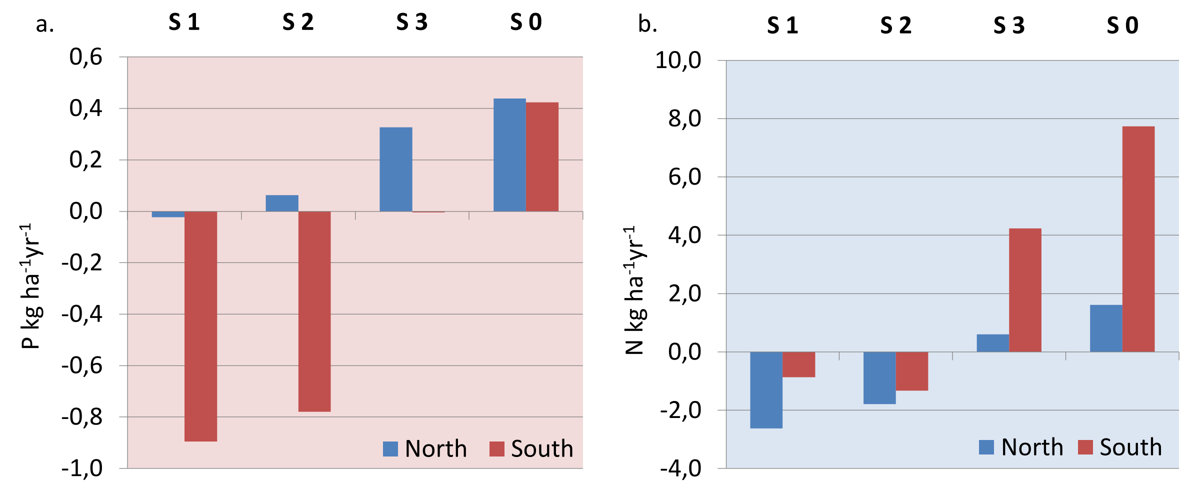

Figure 15: Nutrient balance of a) Phosphorous and b) Nitrogen at each scenario (S), for North and South respectively. Note the different scales of the Y-axis.

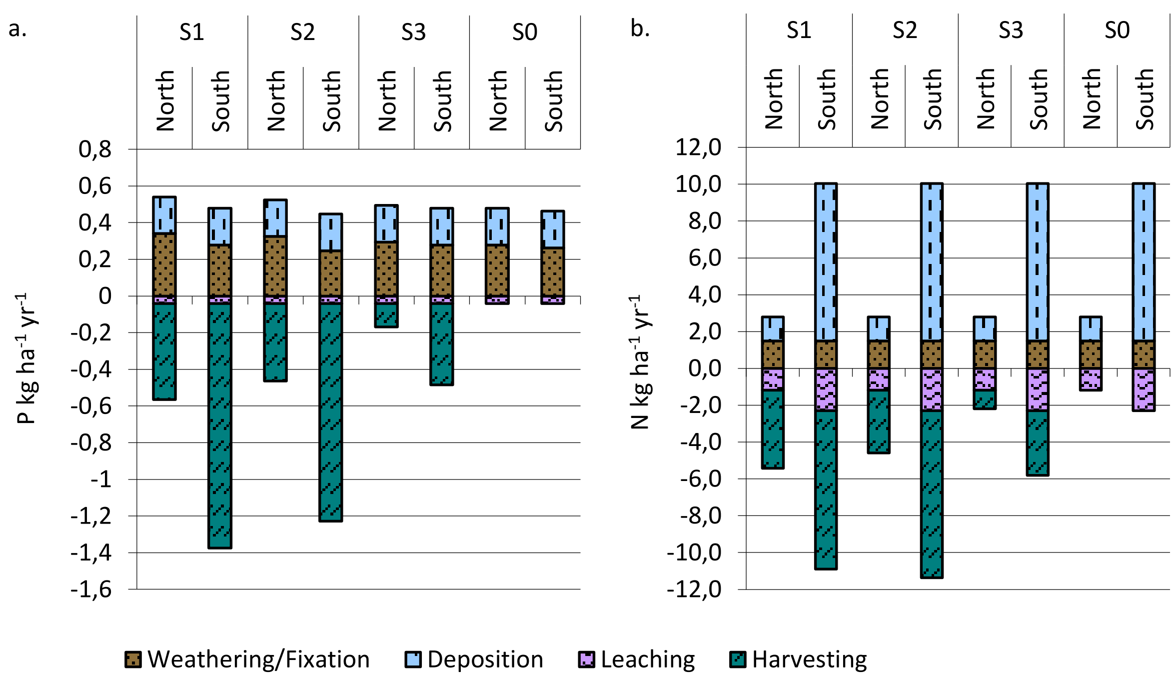

Figure 16: The contribution of each process to the final net balances of a) Phosphorous and b) Nitrogen at each scenario (S), for South and North respectively. Note the different scales of the Y-axis.

3.4 Discussion

3.4.1 Methodological uncertainties and limitations

The selected sites are highly spruce dominated (>80%) but sites with higher share of or totally dominated by pine are also subject to forest fuel extraction. It has been shown that the loss of base cations is higher in a spruce forest compared to a pine forest after harvesting. This has to do with several factors: the concentration of base cations is higher in spruce trees than in pine, spruce has higher growth rate, a spruce forest has more branches and needles, pine trees have deeper root systems which increases their access to weathered base cations in the soil (Akselsson *et al.*, 2007). The calculated net balances can therefore not be used as proxies for nutrient losses on a large scale where mixed forests are included.

Only two sites are included in the calculations, one from each geographical region, which eliminates the possibility to get statistically trustworthy results, especially considering the existing variations between sites. However, the results do give an indication of how the harvesting of forest residues affects the sustainability of a forest ecosystem, in the North compared to the South of Sweden.

Furthermore, all input parameters are uncertain to varying degrees. The runoff data used to calculate leaching is based on all land use classes, which could lead to an overestimation of runoff on forest land (Akselsson, 2005). Fixed values for leaching are used, assuming constant flows in the soil even though these are known to vary over time.

The deposition data for P is an average value and does not consider geographical variations. For the southern site this is however less important since the relative contribution of deposition to the final net balance is small compared to harvesting. The N-fixation is also set to be equal across the country even though it's been shown that the N-fixation of bryophytes is limited at certain N-deposition loads, and less N made available for vascular plants (Gundale *et al*., 2011).

Regarding the calculations of Net uptake the main uncertainties are the nutrient concentrations in the different tree parts and the lack of geographical variation of the values in branches, tops and stems (average values obtained from Egnell *et al*., 1998).

The uncertainties concerning weathering are mainly associated with the PROFILE model. The accuracy of the model is briefly mentioned in a study by Sverdrup *et al.* (2006) and depends on the input data accuracy. In the study the accuracy of the output data was assessed to be ± 5, but during practical and realistic conditions they estimate it to be within ± 15-25%. A more extensive discussion about validation and uncertainties is available in Sverdrup & Warfvinge (1995). However, the uncertainty estimations are uncertain in themselves, since validation of weathering rates is difficult.

The PROFILE model has been criticized for assuming that the soil solution in the root area has the same composition as elsewhere in the soil, not taking into account that the pH around roots varies, caused by their secretions, nor the fact that mycorrhiza and ground vegetation can affect the weathering (Högberg & Jensén, 1994). The main reason why the definition of soil characteristics has yet to include distance to roots is a lack of in depth understanding of for example the rhizosphere and of mycorrhiza (Akselsson, 2011b). Another related uncertainty factor in the model is the assumption that all P is considered to derive from apatite, when in fact the soil also contains phosphates bound to iron and aluminium. The low weathering of these compounds would suggest an overestimation of the weathering rate used in the model (Akselsson *et al*., 2008).

3.5 Conclusions

Harvesting forest residues to the levels in either Scenario 1 (80% slash; 50% stumps) or 2 (60% slash; 30% stumps), result in net losses of Ca, Mg and K in the South, and of Ca and Mg in the North. If only stems are harvested the effect on the nutrient balances across the country is more varied, whereas zero harvest shows a net gain for all base cations at both sites.

Harvesting forest residues has greatest effects on the levels of Ca and K, which is because the concentrations of these substances are significantly higher in tops, branches and needles compared to stems and stumps. Ca has highest concentration in trees, which together with its high leaching propensity, explain the comparatively high losses of Ca in all harvesting scenarios.

The concentration of Mg is much lower in all tree parts than Ca and K, and the Mg-balance is therefore not as affected by the harvesting intensity of forest residues.

The fact that the P-loss is much greater in the South (Scenario 1-2) than in the North is mainly because of the larger biomass extraction in the South. Under these conditions P could become limiting in the South in a long-term perspective.

The greater N-loss in the North compared to the South in S1 and S2 is mainly due to the much lower N-deposition at the former site. The large differences in the net balances in Scenario 3 and 0 compared to S1 and S2 indicate that the harvesting of forest fuels could potentially reduce the risk of N-leaching in the South. The northern site on the other hand shows more negative net balance at S1 and S2 and less accumulation in S3 and S0, indicating that these soils could become N limiting in a long-term perspective.

Part IV – An interview study with actors from Swedish forestry

4.1 Introduction

Forest fuels is a comprehensive and complex issue. It is connected to several areas of society, it affects a broad range of actors and it involves political decisions about how to organise our societies in the future. It is also an issue combined with strong opinions, competing interests, national policies and of global importance. There is on-going research in several fields that concern forest fuels, but in order to better understand and be able to identify the conflicts and problems related to the extraction of forest residues it is necessary to collect views and perceptions from those involved, representing different actors and different parts of the country. This is crucial in the understanding and planning of future harvesting of forest fuels.

4.1.1 Objective

The overall aim of the interview study was to investigate how actors that work practically within or close to Swedish forestry perceive the consequences of extracting forest residues and the prerequisites to meet the increasing demand for forest fuels – from an environmental, economic and political perspective – in the North compared to the South of Sweden. I have set out to answer the following questions:

- What are the benefits of forest fuels?
- What is the current situation of forest fuel extraction and what are the prerequisites to meet the production goals?
- What is the environmental impact of forest fuel extraction?
- What is the practice of, attitudes towards and difficulties with nutrient compensation?
- What are the challenges with an increasing demand for forest fuels?
- What are the needed measures to achieve a sustainable extraction of forest residues?
- What role might forest fuels play in the future?

4.2 Method

During March and April 2011 I carried out seventeen qualitative interviews with representatives from five actors within the Swedish forestry sector. As a first step I identified the main actor groups that have practical experience or knowledge of Swedish forestry: the Swedish Forest Agency, the forest industry, forest owner associations (as representatives for individual forest owners), forest researchers and nature conservationists. The geographical location served as a base criterion in the selection process, and only actors active in northern and southern Sweden were chosen to participate (Table 16).

4.2.1 Presentation of the actors

Swedish Forest Agency (SFA) - The national authority in charge of forest related issues. Its primary mission is to “promote the kind of management of Sweden's forests that enables the objectives of forest policy to be attained”, where production and environmental goals are given equal importance. The authority is placed under the Ministry of Rural Affairs and its goals and financial framework is outlined in yearly directions from the government. The work is to a great deal field-based (inventories, site visits and contact with forest owners), and mostly carried out by the local districts, which are geographically divided into five regions. The organisation has about 1000 employees and a total of 100 offices. SFA cooperates with representatives from both the forest industries and the environmental sector.

SCA - The largest private forest owner in Europe, with a total area of 2.6 million hectares of forest land located in northern Sweden. SCA holds a leading position globally in a variety of wood based business sectors, such as personal care products, tissue, packaging and forest products. Within the forest products sector SCA provides i.e. magazine paper, pulp, wood components for building construction, solid-wood products and biofuel. In 1999 SCA's forestry was certified under the international certification system FSC.

Holmen - One of Sweden's largest forest owners with more than one million hectares of productive forest land (5% of the total Swedish forest land). Two thirds of this land is located in south-western and central Norrland. The company has three main functions: forest management; wood procurement for their own paper and sawmills; and wood purchase from private forest owners, forest owner associations and sawmills. The extraction of biofuels from Holmen's own forest is increasing and plans to take growth stimulation measures to significantly increase the volume of biofuels are underway. Holmen's forestry is certified under the FSC and PEFC standards.

The primary objective of the forest owner associations is to promote the profitability of their members' forestry. **Skogsägarna Norrskog** has about 13 000 members, owning more than one million hectares of forest land, mostly located in the central parts of Norrland. The subsidiary company Såtab manages biofuels. **Norra Skogsägarna** has 16 000 members in Central and Northern Norrland, owning more than 1,2 million hectares of forest land. They are one of the largest providers of biofuels in Norrland and produce about 600-700 GWh of biofuels per year, out of which 40% are forest fuels. With approximately 51 000 forest owners as members **Södra** holds more than half of all privately owned forest in southern Sweden. They are responsible for about a fifth of the market for biomass in southern Sweden.

The Swedish University of Agricultural Sciences (SLU) has several departments that conduct research on a wide range of areas related to forestry and forest ecology. They study different production systems for forest fuels and the consequences an increased exploitation of the forest will have on soil, water, climate, biodiversity, etc. The SLU representatives present in this study work within the Department of Forest Resource Management in Umeå and the Southern Swedish Forest Research Center in Alnarp.

The actor labelled **Umeå University** in this study is a senior lecturer in Human Ecology and Sustainable forestry at the Department of Ecology and Environmental Sciences at Umeå University. The **Nature conservationist** is a forest activist since 15 years and with 10 years' experience of professional forest and clear-cut inventorying.

4.2.2 Selection of representatives

The selection of representatives did not follow a uniform procedure, instead contact with each interviewee was established in a variety of ways. Within the Swedish Forest Agency the districts of Halland, Växjö and Jönköping, and Västernorrland, Umeå and Skellefteå were chosen to represent southern and northern Sweden respectively. All employees in each district were contacted by email, presenting the purpose of the study and asking for people within their district with specific knowledge and experience of forest fuels. The suggested persons were then contacted directly and asked to participate in the study.

A similar procedure was followed in the case of forest owner associations and the forest companies. Three out of four existing associations were selected: Södra, Skogsägarna Norrskog and Norra Skogsägarna. The forest companies SCA and Holmen Skog were chosen because they are the dominating forest actors in Norrland. All actors were contacted by email with a request to be put in contact with people in their organisation especially responsible for forest fuels.

The researchers and senior lecturer were selected either on the basis of their activity (published articles and reports on the topic) or after having been referred to by other researchers or actors. Geographical position was not a very important selection criterion for this group but because of logistical constraints the possibilities to meet researchers from different universities and/or research institutes were limited. The nature conservationist was contacted because of extensive experience of forest conservation work.

The forest sector has always been and still is largely male dominated, and the representation of women within Swedish forestry today is only eleven per cent (Nybäck, 2011). The low figures are reflected in the present study, where one interviewee out of 17 is female (5,9%).

Table 16: The interviewed representatives and corresponding code used in the analysis

	Northern Sweden	Code	Southern Sweden	Code
Swedish Forest Agency	Southern Västernorrland Northern Västernorrland Northern Västernorrland Västerbotten	*SFA1* *SFA2a* *SFA2b* *SFA3*	Halland Växjö	*SFA4* *SFA5*
Forest companies	SCA Holmen	*SCA* *Holmen*		
Forest owner associations	Skogsägarna Norrskog Norra Skogsägarna	*Norrskog* *Norra*	Södra	*Södra*
Researchers	SLU* SLU* Umeå University**	*SLU1* *SLU2* *UU*	SLU*** SLU***	*SLU3* *SLU4*
Nature conservationist	Västernorrland	*NC*		

*Dep. of Forest Research Management; **Dep. of Ecology and Environmental Sciences;
***Dep. of Southern Swedish Forest Research Centre

4.2.3 Interview structure and analysis

The interviews were carried out in a semi-structured manner, similar questions were asked to all interviewees, but still giving them quite some freedom to direct the focus of the talk (compare Dalen, 2008). New aspects and questions arose during the course of the study and were then added to the interview set-up. The interview design changed somewhat depending on actor, and on the type of information that each actor was expected to have. However, certain topics were made sure to be covered before ending the interview. Some of the interviewees had asked to see the questions beforehand, but the majority of the participants were unprepared for the interview questions. The interviews lasted in general one hour, with a few exceptions lasting up to 1,5 hours, and all interviews were recorded. The majority of the interviews took place in the offices of the representatives, except the interviews with *NC* and *SFA2a*, which took place at public libraries. All interviews were carried out in Swedish.

The initial part of the interviews can be described as a type of *information investigation* (according to Esaiasson *et al*., 2007), where the interviewees were asked to give insight to prevailing conditions in Swedish forests, such as current scope and practices of forest fuel extraction, environmental effects and the degree of nature consideration taken during forest management. The subsequent and dominating part is best characterised as a *respondent investigation* (ibid.), with the aim to capture and identify as many angles and perspectives as possible that concern the *study issues*. After having transcribed the interviews in their totality the data was divided into categories which form the chapter headlines in the analysis. The categories are basically the same as the topics of the interview questions.

Validity

My personal position and interest in certain issues have most certainly influenced which answers that have been selected over others. To compensate for this, I have attempted to reproduce the original formulations as much as possible, which is also the reason behind the numerous citations.

The representatives were asked to answer questions that involved the performance (e.g. environmental and legal) of their company/organisation, which can be seen as a factor that undermines the validity of their answers. As an example, it can be considered likely that a company's poor environmental performance is toned down by its representative. Another important aspect to consider when weighing the validity of the responses is that many questions required the interviewees to give personal opinions, while still representing their company/organisation. That kind of dual role could restrict the representatives from providing answers free of company loyalty. The same is true for representatives of the Swedish Forest Agency.

4.2.4 Methodological uncertainties and limitations

This study is not claiming to present all actors within the forest sector, nor does it try to cover all existing topics that relate to forest fuels. It should be viewed upon as an attempt to summarise some, out of a wide range of important aspects of forest fuels that need to be discussed further. Some apparent shortcomings concerning representativeness do exist and need to be pointed out:

- Unequal geographical distribution in all actor groups, with more representatives from northern compared to southern Sweden.
- Overrepresentation of the forest industry compared to actors from civil society and the environmental movement.

Time constraints, closely connected to logistical aspects, are the main reasons for these shortcomings.

It would further have been interesting to include politicians and decision makers responsible for current targets for forest fuels and the regulations of Swedish forestry, to broaden the discussion; however that will have to be a task for future studies.

4.3 Results and analysis

4.3.1 Benefits of forest fuels

The common view among most actors is that forest residues have a great potential to contribute to the mitigation of climate change. The Swedish Forest Agency, supported by researchers, is of the opinion that when the substitution effect [see Part I] is included in the greenhouse gas emissions calculations, forest residues have an overall climate benefit (*SFA3*). *SFA4* even believes that Sweden has potential to become carbon neutral on its forestry. *Södra* states that the huge biomass reserve stumps represent should be used to replace oil, otherwise "we might have to import biomass to a larger extent, which only implies additional transports." *Södra* continues by pointing out that forest residues have very low energy input, for slash it is about 5% diesel in and 100% energy output.

Most actors share *SLU3*'s conviction that: "even if we would reach the EU-objective of 20% increased energy efficiency to 2020, there will be an energy shortage in Europe." According to *SLU3* forest biomass makes up 50% of all renewable energy in Europe. *SLU1* predicts that the supply of raw materials will be a bottleneck for many European countries when trying to reach their renewable energy goals. *Holmen* takes the situation in Great Britain as an example: "To replace 10% of their current use of coal they would need about 50 million cubic metres of wood fuels per year, an enormous volume which corresponds to half of what is annually felled in Sweden." *SLU2* predicts that the price on forest fuels will increase, especially since the other EU-countries have not the same bio-resources as Sweden, and *SLU2* sees a great potential for extraction. In this global context Sweden is considered to have very favourable conditions, and *SCA* underlines that: "we already use 32% biofuels in the Swedish energy mix, which is world-leading."

SLU4 comments that the forestry sector of course has picked up the argument that forest fuels have climate benefits. Extracting forest residues is seen as a win-win situation, positive both for the climate and for the business. However, *SLU4* doesn't believe that it is possible to combine climate benefits and biodiversity, saying that: "these things don't go together." *SLU1* points out that even though all energy systems have negative consequences one must look at forest fuels in a greater perspective, that Sweden has access to this renewable resource while striving to replace fossil fuels.

4.3.2 Current situation of forest fuel extraction

Northern Sweden

Slash

SFA2b provides statistics of forest fuel removal in southern Norrland during 2008-2010, which show a positive and increasing trend among private companies. In 2010 slash was to be removed on more than 50% of the areas notified for regeneration felling. On forest land owned by private individuals the reported extraction of slash has stayed on a constant 20% of the areas notified for regeneration felling (*SFA2b*).

All SFA-representatives in Norrland describe the attitude among private forest owners towards slash removal as quite reluctant, even though, as *SFA2a* puts it, “the harvest of slash has become part of the general assortment that the buyers offer forest owners.” According to *SFA2b* private owners primarily worry about possible negative growth effects from removing the nutrient rich slash. *Norra* is often asked about the risks of soil damages when slash is removed and experiences that many forest owners hold a general scepticism against new things, even though some members show great interest in forest residues. *Norra* also mentions that even among officials at Norra Skogsägarna there are some that don’t regard forest residues as a valuable assortment, who think that especially stumps generate too much work and too small revenues. But *Norra* believes that, “When people see that it works well and they get money for it they will become less afraid.” *Norrskog* on the other hand has met very few forest owners that are against slash removal.

SFA3 points out how the low economical profit made from slash reduces the propensity among private owners to take the risk of removing slash. *SFA3* estimates the compensation to be roughly 1500 SEK per hectare and is more or less the same all over Norrland. *Norrskog* describes that they remove slash on sites with 100% spruce, or with a 10-15% mix of pine. The association has chosen to offer its members a fixed price for their slash (30 SEK per cubic metre), even for material that is not of sufficiently good quality or where the distance to the customer is too far to give a revenue. “The association takes that business risk in order to start up harvesting of slash over a large geographical area”(*Norrskog*).

Holmen states that slash harvesting is still marginal within the company. It could potentially quadruple if there was a market for it, but the margins are so tight that forest residues hardly generate any revenue at all. According to *Holmen* almost all forest fuels are taken care of locally, not much is transported southward since there are several larger boilers along the coast and a few inland that request forest fuels.

Stumps

Stump extraction in Norrland is still very limited and according to *SFA3* it has to do with “high costs, problems with contamination and a lagging technology.” As an example of the additional costs involved *SFA3* mentions the need for another machine-team to be able to extract stumps since that can’t be done straight after the felling. *SFA3* is convinced though, that stump harvesting will increase as the economy and technology improve.

Holmen describes the stump sector as very immature, that there are very few actors and entrepreneurs, and that the costs to extract vary a lot between different regions. “We keep testing different methods to make the process more efficient, such as using the excavator to prepare the soil” (*Holmen*). However, no other representative believes that the excavators used to extract stumps are effective enough for soil preparation, especially not at clear-cuts larger than one hectare. Holmen’s vision is to produce as much energy from stumps as they do from slash, which would mean a ten-fold increase of current activity (*Holmen*).

NC’s impression, based on extensive field experience, is that: “stump removal is increasing, and clear-cuts where stumps have been extracted are now seen in various places.” *SFA1* says that Västernorrland is the county with the highest share of notifications for stump removal, over 1000 hectares per year. *SFA1* explains that this is due to SCA's great interest in stumps, having both a big saw-mill and a paper mill that require much heat for their production. According to *SCA* however, they don't make money on forest residues yet. "The most important fuel for us is still spent liquors, a bi-product from the pulp industry"(*SCA*).

Southern Sweden

Slash

The ownership structure is quite different in southern Sweden compared to northern Sweden. 80% of the forest land is owned by private individuals. Sveaskog[16], the Church and the municipalities own the remaining 20%. All actors in southern Sweden see a clearly positive trend to harvest slash, which is explained by an improving economy. *Södra* claims that slash increases because the forest owner wants as much as possible out of the property. *Södra* estimates that about half of their 52 000 members hire them when it is time to fell. If the buyer does a good job, and if it is an object that is practically and environmentally suitable for it, the forest owner will be asked if slash should be harvested as well. *Södra* estimates the net revenue of extracting slash to be about 5000 SEK per hectare, more than three times as much as a forest owner gets in northern Sweden. *Södra* adds that some inspectors and buyers are not too happy about slash because it means a lot of extra work.

Stumps

Stump extraction is carried out in a very small scale. Södra has been working with stumps for two years now but mostly on a testing scale and the challenge is to get a reasonable profit (*Södra*). At present the company has three active machines and each machine costs about 50-70 SEK per cubic metre stump. *Södra* goes on and explains that the forest owner doesn't get any net profit from harvesting stumps. Instead they are offered free soil preparation, worth about 500-1000 SEK per hectare, which makes it possible to plant directly (*Södra*). *SFA5*'s perception is that nobody wants to invest in stumps now because it is difficult to make it profitable, but adds, "that can change quickly with the energy prices."

SFA4 says that if a site is smaller than one hectare it is not worthwhile to go in and extract stumps. Usually the entrepreneurs try to co-ordinate the stump extraction between several forest owners that have properties close to each other. *Södra* states that once at a site they remove as many stumps as possible, since it costs money to leave stumps that are extractable. However, *Södra* underlines that it is not possible to take all stumps, because there are so many restricted areas. *Södra* doesn't think they ever remove more than 80%, so leaving 20% for nature consideration, as the SFA recommendations[17] state, is not a problem. "It is only where it is plain and smooth that we can remove everything" (*Södra).*

Practical and economic prerequisites to meet the production goals

All company and association representatives, as well as most representatives from the Swedish Forest Agency, agree that a complete extraction of forest residues under current

[16] Sveaskog is Sweden's largest forest owner and leading supplier of timber, pulpwood and biofuel. Sveaskog belongs to the group of state-owned companies whose operations are subject to market conditions and requirements (Sveaskog, 2011).

[17] Swedish Forest Agency's recommendations for removal of slash and ash recycling [SFA, 2008a].

conditions is not realistic. The most important factor that drives up the costs of slash extraction in Norrland is transportation. Logging sites too distant from the end user are not relevant since the costs exceed the profits, and as *Norra* puts it: "are directly unprofitable to extract slash from." *SLU1* estimates the upper transportation distance to be about 100-150 kilometres and points out that since most customers are located in or nearby the bigger cities and along the coasts large parts of the northern inland have potentials that are difficult to extract. *Norrskog* calls for new logistical solutions, such as using the inland railway and terminals that would make most of the inland reachable.

SFA5 confirms that also in southern Sweden, the single most important factor that determines if slash is harvested is the distance to the heating plant. According to *SFA3* this means that the extraction rates will never reach critical levels, even though maximum levels might occur in some regions, as is already the case around Umeå and Mälardalen.

All companies, forest owner associations and a few SLU-researchers further claim that environmental constraints - such as inclination, soil moisture, boulders, proximity to watercourses and roads, and so on - also limit the number of clear-cuts that forest residues will be extracted on. *SLU1* doesn't see any risk that stump extraction will be carried out on more than the 5-10% of the total final felling area that has been allowed by the Swedish Forest Agency.

4.3.3 Environmental impact of forest fuel extraction

Almost all actors have strong opinions about how and to what extent the extraction of forest residues affects the environment. Many share *SFA3*'s view when stating that the environmental impact could be characterised as marginal, given that existing recommendations for nature consideration are followed and as long as it isn't done at unsuitable areas. Others oppose such a statement and believe that removing forest residues will have irreversible consequences.

Less biodiversity

NC underlines that tops and branches are important as habitats for many wood-living species: "If you look closely you will find many species, mostly fungi and insects. Also redlisted and critically endangered species can be found on thicker branches. Since the substrates are quite short-lived the species don't stay there for too long, but it might be the only dead wood around." *SLU2* on the other hand, can't see anything wrong in using this resource from a biodiversity perspective. *SFA2b* has a more modified opinion though: "if we were to extract everything everywhere the habitats would certainly be affected." But *SFA2b* adds that neither the proper technique nor enough money exist for that to happen. *SCA* claims that forest fuel extraction will not be a problem in Norrland, since "we manage to maintain all species." The situation in southern Sweden is on the other hand described to be very different since the landscape is almost exclusively dominated by farmland and only fragments remain of the broad-leaved deciduous forest that characterised the landscape 2000 years ago (*SCA*).

Concerning stump removal *NC* points out that many of the wood-living species are seen as common and generalists and that they therefore wouldn't be too affected if we remove stumps. But, *NC* states that they are only common because there are so many stumps, and adds “in fact most dead wood in our forests today are stumps and very little are wind-felled trees or high-stumps.” *NC* states that many species exist naturally in the roots and stump, for example the redlisted fungi *Asterodon ferruginosus* that grows on dead and living wood. For other species, like mosses and lichen that colonise slowly, stumps are vital refuges in the competition for substrates. Removing stumps affects a whole chain of animals, from insects, rodents and small birds to predators, not only threatened species.(*NC*)

SLU1 argues that stumps are substrates made by humans and not really natural habitats. “They are probably used mostly by trivial species which can possibly out-compete other species and even be considered to have a negative impact on biodiversity” (*SLU1*). *Södra* doesn’t see spruce stumps as a very important biotope either, and claims that no redlisted species are found in them. *Södra* further comments on the Swedish Forest Agency’s declaration that stumps can be extracted on 10% of a felling area without causing problems: “The bugs will never have far between stumps,” since 90% will be left untouched, plus the 20% that is left as general nature consideration at each site. *Södra* says that they only extract stumps on 1,5% of their total regeneration felling area, which means that 98,5% of all stumps are left in their forest.

NC says that to compensate for the removal of forest residues about 25-50 high-stumps per hectare, of thick spruce trees and with a height of at least five metres, should be left at the clearing site. However, *NC* doesn’t believe that any private forest owner would be willing to accept such revenue loss. *NC* emphasises that the extraction of forest residues must be put in its context: “We keep bargaining with biological diversity in a stage when we have transformed 90% of the landscape, changed the ecosystem completely and only have a few tree species left, like spruce, pine and lodgepole pine.” *NC* goes on saying that slash and stumps alone might not have that much impact on the environment but everything put together will be a complete disaster, and ends: “we deplete the forest with all these measures.”

Soil damages and leaching

When felling is carried out on wet soils and on soils with low bearing capacity branches are used as soil reinforcement by placing them in the tracks for the machines to drive on. If residues are increasingly removed at the time of felling the demands on the soil conditions also increase. *NC* says that even when leaving an armouring mat of branches the risk of soil damage is obvious when heavy machinery run over a wet bare ground area. The removal of slash and stumps further require extra rounds with both forwarder and excavator (*NC*). *SFA5* stresses that the severe stirring of the soil during stump extraction destroys all cultural relics present.

SLU1 believes that there is a real risk for long-term or permanent soil damages when harvesting forest residues. “We have to be very careful and make sure that we operate under optimal conditions, preferably on frozen ground. If and when we operate on sensitive soils we need to use the slash to drive on” (*SLU1*). *Norrskog* agrees and says that: “On areas with high volumes of tops and branches but with low bearing capacity the slash has to be removed when the ground is frozen, even though it means removing it green.” According to *NC* the only acceptable time to undertake forestry measures on wet soils is when the ground is frozen.

SFA3 though, notes that if logging is performed on frozen ground it is possible to enter areas with weaker soils and also prepare for removal of forest residues there. When the biomass has dried and is ready to be collected the ground is bare and the stabilising roots in the soil are weaker. *SFA3* believes that the risk of soil damages is even greater if stumps are removed as well. The excavator used to extract stumps is quite light and can easily access weaker soils, but *SFA3* points out that the severe damages arise at a later stage, when the much heavier forwarder comes to collect the stumps. *SFA3* says that driving heavy machines in the forest always result in some kind of track formations, but adds that for such formations to be defined as soil damage they should have severe long-term effects. However, *SFA3* has noted both higher frequency and increasingly indifferent attitudes towards track formations among entrepreneurs.

Even if an increase of track formations when removing forest residues is considered likely *SCA* doesn't think it is necessarily a very negative thing: "It might not look beautiful, but I don't consider it a gigantic problem," and continues, "soil compaction is not a problem either, at least not in the North, since the ground is loosened by the frost every winter." *Södra* says that stump removal doesn't look as bad as one thinks since spruce roots are shallow and the hole is evened out with the excavator. *Södra* even claims that the clear-cut will look better after stump removal compared to how it looks after only harrowing, which is the normal soil preparation method in southern Sweden. *Södra* also refers to research showing that effects on erosion are minor.

Soil disturbance, elevated ground water levels and increased runoff are common effects after felling and stump removal. If stumps are extracted in areas with less suitable conditions, such as slopes or areas with high soil moisture content, *NC* sees a great potential risk of heavy metals (especially dimethyl mercury) leaking to nearby streams. *SFA1* underlines that it only takes a little bit of incautiousness by forestry machines to cause severe damages. *Södra* however, discards the risk of dimethyl mercury leaching by claiming that stumps are not removed on wet soils.

Norrskog describes how the logged wood material normally is stored temporarily next to the clear-cut. But according to *SFA3* it is not unusual that the slash is put in ditches or on other less suitable places due to the limited storage area in the forest. If the residues are left under such conditions for a longer time there is a risk of nutrient leaching to surrounding streams (*SFA3*).

Affected carbon balance

No one seemed to have thought much about how the removal of forest residues affects the carbon balance in the forest ecosystem. *SFA3* mentions how the decomposition of soil carbon increases because of the extensive stirring of the soil due to the activity of heavy machinery, and points out that some carbon is lost as stumps are extracted.

Only the researchers had deeper understanding of the actual trade-off between burning forest residues on the one hand and leaving it in the forest and using another energy source on the other. *SLU4* emphasises the need to look at the greenhouse gas emissions during a stand's entire rotation period and not only at the phase immediately after the clear-cut. *Södra* declares that even though the clear-cut is a carbon source for 3-4 years after felling, the following 45-50 years it becomes an important carbon sink. *SCA* states that if left at the clear-cut, stumps and branches of spruce are decomposed in about five years, and concludes that with that time perspective burning forest fuels can be characterised as a free and CO_2-neutral energy source. *SFA2b* says that they don't consider soil carbon emissions at all. *Södra* refers to SLU's environmental analysis concerning stump removal that is under way, which *Södra* believes will sort out many question marks.

Nutrient depletion and acidification

Several SFA-representatives do not see any huge risks that the extraction of forest residues will cause any long-term nutrient depletion, and many argue like *SFA3*: "if research would prove differently it can easily be fixed by adding nitrogen." *SFA2b* states that the effects of removing slash on production are unclear, but the attitude within the forestry sector is that there are enough nutrients in the soil and hence no risk of growth effects. *SLU1* confirms that growth might be reduced with 2-3 years per rotation period, but only if 100% of the slash is removed, with all needles still attached, and ends, "that is unlikely to ever happen in practice."

SCA does acknowledge that there are risks with nutrient removal and mentions that both other plants and organisms at the site as well as the growth of coming forest stand could be affected. The new generation could be delayed by about one to two years. If any ecosystem services or resilience are lost is unclear, but no indications of that have been shown (*SCA*). *Södra* believes that as long as the harvest intensity of slash is restricted to one time per rotation period there will be no problems, and emphasises the fact that forest residues are used to replace oil, to heat houses and produce green electricity.

4.3.4 Nutrient compensation - practice, attitudes and difficulties

Green versus dry slash

Current SFA-recommendations state that slash should be left on the clear-cut to dry in order for the nutrient rich needles to fall off. However, both companies and associations describe an increasing trend to remove slash at the time of felling, that is, still green and attached to the branches. This is mainly for economical and logistical reasons, since it reduces the number of times heavy machinery need to be brought to the clear-cut (i.e. *Holmen, Norra, Norrskog*). Even several SFA-representatives agree with this standpoint. *SFA2b* says that generally the slash is gathered in piles and then left to dry, but as they are transported away much of the nutrients are lost anyway. Following the recommendations also means that the slash has to be collected during bare ground season leading to increased risk of severe track formations. As it is today *SFA3* sees a conflict between the risk of nutrient loss and the risk of soil damages.

SLU1 also promotes removing the slash straight after felling, still green. Even if research has shown that it might reduce growth with two to three years during a rotation period, *SLU1* points out that it also enables one to two years earlier planting. *SLU1* is convinced that more and better planting spots and hence better growth will lead to a positive net result from removing green slash.

Another aspect of the discussion about removing slash immediately after felling or leaving it to dry on the site is brought up by *Norrskog: "*Today 99% of the harvested forest residues are burned. Much of it has quite high moisture content, which means that we both transport and burn a lot of water." According to *Norrskog* this could be rationalised with quite simple measures, like letting the forest residue dry for a few more weeks, refining some of it to a more octane rich fuel while using the waste heat. *Norrskog* also mentions that there are substantial differences between sites with respect to how easily needles fall off the branches. The factors influencing the propensity for needles to detach are however not yet known. *Norrskog* believes that each geographical area should choose the system that suits them best.

Ash recycling

As stated in Part I ash recycling is encouraged in order to prevent net loss of nutrients and acidification after forest residues have been removed, however as shown in Figure 4, the practice is low across the country.

Attitudes and practice

All SFA-representatives in Norrland have experienced a widespread scepticism among forest owners towards ash recycling. It is primarily based on a fear that the production will be negatively affected, which certain studies have indicated. *SFA1* explains how fast-growing grass and shrubs benefit from the mineral nutrients in the ash and consume the available nitrogen, leaving less for the slow growing tree plants. However, *SFA1* plays down the effect since the ground vegetation eventually is decomposed and nitrogen made available for the trees again. Considering that the rotation period for a tree is between 80-100 years there is time to recover from the initial growth reduction. *SFA1* promotes a combination of ash and nitrogen spread at the same time to avoid a growth reduction. *SLU1* says that ash might at best counteract acidification but has only half of the neutralising effect of ordinary lime, and advocates nitrogen entirely over ash.

The opinions about ash recycling differ quite a lot among the SFA-representatives. *SFA4* and *SFA5*, both active in the South, believe ash recycling is a necessary measure, whereas the attitudes in the North are more diverse. *SFA3* points out that the conditions for ash recycling differ between Norrland and southern Sweden. The pressure on the soil is much higher in southern Sweden due to intensive forestry, higher forest production and high deposition, causing acidification. *SFA3* states that in Norrland problems with the soil are much less pronounced; instead the focus is on threatened biodiversity. *SFA3* doesn't agree with the compensatory approach that many promote, in which the amount of nutrients going out is strictly balanced with the amount of nutrients that has to be returned. *SFA3* calls for a new way of looking at the issue, more from a landscape perspective, thinking of how to use the existing resources in the most economical way. But, *SFA3* doesn't believe the Swedish Forest Agency will nuance the recommendations on this point. *SFA2a* was previously worried about the risks of leaching, but after having listened to lectures on ash recycling *SFA2a* considers it likely that the mineralisation is so fast that there won't be a problem. But, *SFA2a* adds that such conclusion "could be completely wrong too."

Among the represented companies and forest owner associations ash recycling is not something anyone is pushing for. *Norra* believes that it should be done on the right type of soils, not on all kind of areas where slash has been removed as stated in the SFA-recommendations. *Holmen* says that if it is proved to be necessary to maintain high growth then they will of course start. However, *Holmen* expresses a concern that the additional costs entailed might press down the margins and further mitigate the interest in forest residues. According to *Södra,* "it is quite costly and complicated and we have just not seen any reason to do it." The practice within Södra has been to let the slash dry on the clear-cut since: "we don't get paid for water" (*Södra*). If the needles fall off on the site there is no need to recycle ash, and *Södra* concludes: "If we remove more from the forest we have to bring back ashes, everybody in the forestry sector knows this."

SCA criticises the available weathering models for containing large uncertainties and leading to wrong conclusions about effects, especially in naturally poor soils. In southern Sweden they have seen positive reactions from ash recycling on base cations in the soil, which indicates a shortage. In the North however, *SCA* continues, where the soils are naturally less fertile, the main problem is nitrogen loss. This is a common opinion among a majority of the representatives in the North. *SCA* goes on saying that to bind as much carbon as possible the ashes should be spread on mires where there are only organogenic soils and a shortage of base cations. *SFA1* agrees that ash recycling would give an enormous production boost on peat-lands, but stresses that from an environmental perspective it is not a good idea since it consumes the storage of carbon and nitrogen in the peat layer.

Access to ash

The supply of ash is another highly relevant factor which affects the level of activity. *SFA5* describes how Kronoberg County has quite a long experience in taking care of ashes: "An entrepreneur and former SFA-employee contacted the biggest local energy plant and concluded that they had problems getting rid of their ashes. The original objective was to mix ashes with lime to counter acidification. Today it is an established business and we have no trouble getting hold of ash producers. It is much cheaper for them to spread their ash in the forest than paying landfill fees."

Norrskog declares that there are no ash producers in Norrland that provide a quality approved ash since, "the large thermal power plants mix everything, forest residues, peat, recycled wood, waste and so on." *Norrskog* doesn't see any tendency that this would change, especially since the current plants will be used even in 20 years. *SFA1* points out that the quality demands exclude ash from large parts of Västernorrland, because of too high caesium concentrations due to the heavy fallout after the Tjernobyl accident in 1986, and also from Jämtland, where the bedrock is naturally arsenic rich.

SFA3 says that all bigger ash producers in Norrland follow the discussions closely since they know that all of a sudden things can change dramatically. *SFA3* also mentions increasing landfill charges as an example of what could make it economically interesting to find other ways of using the ash.

Lack of structure and insufficient action

Representatives from SFA, forest owner associations and companies agree that the Swedish Forest Agency doesn't really enforce their requirement for compensation when forest residues have been harvested. There is no data on the total amount of forest residues that is removed and no way of knowing where compensation is needed. *SFA3:* "Today we only recommend the forest owners to note in their forestry plan if they intend to remove slash. The responsibility to keep records is entirely placed on the owner and the buyer." *SFA3* continues: "Imagine that we in 30-40 years find that compensation is essential to avoid severe effects on forest production capacity and soil conditions, which is already our official standpoint, we would not have documents good enough to be able to do that." *SFA3* adds, "I believe we need to take action for a better system to keep track on the areas where slash has been removed."

SFA1 mentions that it can be difficult to get a permission to recycle ash if it is classified as an environmentally hazardous activity. It then has to be authorised by the municipality, a process that depends on how fast the municipality officials answer, their knowledge about the issue and so on. *Södra* is not worried about the future though: "All clear-cuts where we harvest stumps are registered and the idea is to return to them when we have started up the ash recycling properly." But *Södra* also points out that, "stumps don't contain much nutrients, they are mostly wood, and the smallest fine roots remain in the ground." *Holmen* thinks that keeping records have to be the landowner's responsibility since it is not possible to incorporate a measure that is due in 40 years' time in the felling deal.

SFA3 summarises the current situation saying that the uncertainty regarding growth effects, together with the extra costs it implies, such as more machines entering the site, make it difficult to motivate forest owners to compensate with ash: "It is necessary to understand that even though the principle of ash recycling is good the incentives to realise it are few." *SLU4* predicts that with current conditions, ash recycling will never become a big thing in northern Sweden because of logistical constraints, too little available ash and long transports, whereas in southern Sweden it will most probably increase with a growing supply of ash. However, *SLU4* adds that the forestry sector is conservative and introducing new things takes time.

4.3.5 Challenges with an increasing demand for forest fuels

The question of how well the goals for forest fuels comply with the available resources was discussed mainly from two perspectives: the potential to harvest more forest residues and the effects of an intensified competition over forest products.

Available resources

SFA2a's perception is that forest fuels sometimes are considered as the solution for the energy crisis. "It seems as though politicians think that there is so much forest only standing there, that we can use it to replace nuclear power and fossil fuels," but *SFA2a* declares, "that is not really the case, we cultivate as much forest as we possibly can, so the potential to harvest more is not immense." *SFA5* notes that, "if you summarise all actors' investments and prognosis the available forest resources will not be enough." *SFA5* says that already today there are regions in the South of Sweden where the extraction rate is too high and not sustainable in a long-term perspective.

Holmen also perceives the prognosis and plans for the future development of forest fuels as quite naive and not based on what is practically feasible. *Holmen* says that from a forest perspective there are many competing interests and, “it is not possible to promise everybody a piece of the pie because it won’t be enough.” *Holmen* goes on: “In order to produce dramatically more forest fuels we would have to take raw materials from other sectors like the pulp industry, or it might result in that fewer areas are protected, and then we have to ask ourselves what the purpose of the plans were.”

Norrskog believes that, “we take only a fraction of what we have” and states that, “slash has an enormous potential if we would extract everywhere.” *SLU1* points out that even though there are large unexploited areas in Norrland where stumps can be extracted, there are limits: “We can keep expanding for at least another 5-10 years but it has to be related to the available resources and how the demand is distributed among industries.” *SLU1* declares that the future importance of stumps will depend on how the issues of lacking technology and contamination are handled and adds, “in five years the largest volumes of forest residues will still be slash.”

UU says that forest fuels might still have a small potential but stresses that, “if we are to meet all the other important goals of the forest we cannot get carried away.” *UU* suggests that forest residues could be removed during the first thinning opportunity and from areas where growth wouldn’t be too affected. *NC* believes that forest residues can be positive if it is extracted from degraded land, but warns that removing slash and stumps while maintaining current production of pulp and timber will lead to the disappearance of many species. *NC* ends: “If we continue down this road we should at least be open about the consequences.”

NC continues by pointing out that the potential energy gain from forest residues is marginal compared to what phasing out of the energy intensive paper and pulp industries would generate. But *NC* says, “that is a much more controversial issue than forest fuels,” since it involves large companies, competitive advantages, who is to benefit from the available resources and so on, and adds, “everything leads back to the remarkable economic situation we have today.”

Unequal balance between environmental and production objectives

The question of how an increasing demand for forest residues will affect the general nature consideration is highly relevant considering that the environmental performance in Swedish forestry has been shown to be far from satisfactory. According to the Polytax measurements nature consideration was insignificant at more than 35% of all felling operations in 2009, and the status of the environmental quality objective *Sustainable forests* is regarded as very difficult to reach (see Part I).

However, the actors have very different opinions about this figure: Company and association representatives see few problems with current practice in Swedish forestry; SLU researchers and some SFA-representatives acknowledge certain problems but believe that relatively small changes in the system of control and sanctions will improve the situation; and other SFA-representatives, the nature conservationist and the researcher at Umeå University believe the current situation is alarming and that there is an urgent need for strong action on structural and political levels. These opinions are reflected in the actors' perceptions of how the demand for forest residues will affect nature.

Holmen states that the pursuit of increased production shouldn't overshadow everything else, but says that there is always a risk that something goes wrong during a forestry operation. If more actions are carried out, such as extraction of slash and stumps, the risk increases. *Holmen* underlines though, that the most common errors are that logging is performed at the wrong place or that trees with high nature values are logged, and claims that if forest residues are extracted or not is of minor importance. *Holmen* further declares that the individual forest owner will not be free to remove more dead wood just because it becomes more profitable.

Norra firmly states that: "we take proper nature consideration at all felling operations," and says that they encourage their members to use the forest well, strive for higher growth in order to bind more CO_2, get more forest and have more to spare. *Norra* stresses that: "if we or the forest owners would violate the regulations we would be charged, so there are no risks as long as we have the Forestry Act and a controlling Forest Agency." *Norra* goes on: "Just look at forestry in general; stems are left as high-stumps even though they are worth a lot. Forest owners give away lots of money to achieve the regulations of both the Forestry Act and PEFC[18] certification." *Norra* further thinks that, "we protect and leave too much in the forest," and argues that even though a high-stump is valuable to keep in the forest it is more valuable if used to substitute oil or other fossil fuel intensive materials.

On a theoretical level *Södra* acknowledges the risk that nature values might become more exposed as a consequence of an intensified extraction of forest residues but says that in Sweden it is not a problem: "Our organisation was certified 10-15 years ago and all our members and buyers know the standard now, it works very well." *Södra* claims that, "in practice it's been shown that we even take more consideration than we have to, for example we leave more timber than necessary." *Norrskog* goes along the same line and talks about how nature consideration is very well established in their organisation and doesn't think managing forest residues puts that at risk.

However, the vast majority of SFA-representatives and several researchers are concerned that increasing revenues from forest residues will put more pressure on valuable nature areas. Areas that according to *SFA3* probably should be reserved all together to achieve a proper balance between production and environment objectives, and says: "we already see problems with slash and stumps." *SFA3* describes how the interest in marginal lands, previously considered too problematic for logging is increasing, and identifies activity on weak soils and the consequent soil damages as the most important problem with forest residues. "Weak soils often have high volumes of tops and branches as well as large stumps that are easily extracted." *SFA3* explains it to be mainly because the better forest lands have already been logged and because the prices of forest materials are rising.

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[18] PEFC (Programme for the Endorsement of Forest Certification schemes) an international system for certification of forestry and forest products to promote sustainable forestry. In Sweden 36 680 forest owners and 2045 entrepreneurs are certified (Sept 2011) (PEFC, 2011).

Several SFA-representatives mention that the practice during logging operations among some entrepreneurs seems to be to take all or nothing. *SFA5* is concerned that when stumps are to be extracted everything technically possible to extract will be removed, including stumps of deciduous trees, stumps on wet soils or in areas with many cultural relics. “This creates a difficult situation which I don’t think has been thought through really” (*SFA5*).

SLU2 agrees with this view, saying that today economic factors, not biological or environmental, determine where forest residues are harvested, and stresses that if the price of forest fuels increases sharply there will have to be rules regulating where it is suitable to harvest. *SFA2a* says that as long as only pulpwood and timber are harvested it doesn’t cost extra to leave a dry spruce or other dead wood, but with forest residues it becomes interesting to remove material with less economic value but with important nature values. *SFA2a* argues that once the equipment for slash removal is present at a site there are great incentives to extract as much as possible, no matter if it is on sensitive areas. “In addition,” *SFA2a* says, “we are trained into wanting the clear-cut to be clean and free from residues and waste.”

To the arguments presented by the company and association representatives *NC* responds that current forest management has the same restrictions, but “that doesn’t stop them [the entrepreneurs] from logging the steepest slopes or the wettest areas. They are already in these areas, extracting both slash and stumps.” *NC* adds that when it comes to logging there are no technical impediments today.

4.3.6 Needed measures to achieve a sustainable extraction of forest residues

Better education and proper planning

SFA5 is convinced that the main reasons why the environmental objective is not met are the lack of proper planning before a final felling and subsequent removal of forest fuels, together with the pressed time schedules during the field operation. *SFA2a* mentions a lack of knowledge among entrepreneurs and that officials leave too little information to the drivers. *SFA2b* calls for better education among all actors in the forestry chain, such as planners, buyers, machine staff and so on.

SFA4 agrees and says that: “If only all actors involved are sufficiently educated I don’t think we have to worry about environmental risks. Here, the Swedish Forest Agency has a big responsibility, to educate forest owners so that they know what demands to make and dare to do it.” *SFA4* thinks that the responsibility lies both with the buyers/contractors to put requirements on the entrepreneurs, and with the forest owners to require of the entrepreneur that the harvest operation is well done. However, *SFA4* can see why there are lacking incentives to take proper nature consideration when extracting of forest residues; for the forest owner it might look nicer if all trees are removed, while the entrepreneur can sell more and get more money.

Norrskog also points out the importance of proper education throughout the entire production chain, but doesn’t mention nature consideration as the primary driving force: “Slash is too economically sensitive to allow any mistakes. Using many machines and creating deep track formations cost a lot of money. Stump extraction is an even more delicate task and requires that both the buyer and the entrepreneur know what they are doing" (*Norrskog*).

SFA3 on the other hand, thinks that there already exists a lot of knowledge and once again stresses that the problem is more a question of attitude. As an example *SFA3* mentions that the forest industry often presents it as inevitable that track formations occur if the ground doesn't freeze during winter. But *SFA3* counters by asking: "Is it nature's fault that soil damages occur?" and underlines that when working with biological resources one needs to accept that there is a naturally given framework. However, *SFA3* sees a clear tendency to question the framework as soon as it becomes a bit uncomfortable.

SFA3 underlines that planning has to be done during bare ground season to be able to adjust the instructions of which areas that are unsuitable for extraction of forest residues. *SFA3* concludes that as the demand for forest fuels increases so do the requirements on the entrepreneurs to know what they are doing and on the planning of the forestry operations. *SFA2a* suggests that borders should be marked both on a map and with strips to facilitate the job for those driving the machines.

SFA3 stresses that all operators have a legal obligation according to the Environmental Code to perform self-monitoring of their activities, which also should include a sustainability perspective, but adds: "Whether it is actually carried out is highly questionable." *SFA4* mentions the on-going discussion within the Swedish Forest Agency on the need for a more accurate and reliable data collection system, in addition to Polytax, in order to have a better perception of the environmental status after forest operations.

SFA2a brings up another aspect: "We have no statistics on it but we have noticed differences in the standard of felling notifications", the results of nature consideration after felling tend to be better at the companies' own forest compared to bought forest. *SFA2a* says that this leads to poor or non-existent planning, more mistakes, bigger risks of track formations and so on: "I believe it has to do with the fact that the forest owner has the final responsibility and because the certification standard puts quite high demands on companies." *Södra* confirms the fact that private forest owners often follow the buyer's suggestions on where and what to harvest and how much.

SFA5 has noted that the level of nature consideration differs between forest companies. Sveaskog has almost no remarks, which *SFA5* believes is because they have professional people that go through the site thoroughly before felling, noting exactly where and what kind of nature consideration that is required. According to *SFA5,* Sveaskog has made necessary investments to achieve that while other companies have higher demands to make a profit, and ends, "that is a clear difference."

Swedish Forest Agency's power to act

Almost all representatives recognise that the Swedish Forest Agency (SFA) lacks power to control, act against and sanction forestry. *SFA3* states that SFA's mission is to turn forest policy into reality, and says that, "we are generally positive to using as much forest residues as possible, but always considering long-term sustainability and biological diversity, keeping the balance between production and environment."

SFA5 explains that a fundamental part of SFA's work to achieve this is to educate, spread knowledge and enthuse forest owners to manage the forests properly. *SFA5* states that the regulations provide a good instrument but believes that it is necessary to reach further. *SFA3* declares that: "Since the SFA receives notifications of all planned felling operations we are also left with a choice to proceed with cases where there are doubts of a site's suitability for felling and/or for removing forest residues. According to *SFA2a* most risk assessments are done by studying maps and satellite images on the computer, but adds that a consultation is preferably preceded by a field trip to the area. But as many SFA-representatives underline, the SFA does not have enough resources to do that to the extent needed.

SFA2a believes that the SFA has quite far-reaching theoretical possibilities to protect areas with high nature values from forestry. They can redeem the area as a habitat protection area or make an interim order and stop a planned felling, however *SFA2a* admits that it is very rarely done. *SFA3* further states that the SFA also lacks resources to practice proper law enforcement and there are normally no sanctions for those who don't follow the recommendations or abide to the regulations in 30§ Forestry Act. *SFA3* notes that this puts a big share of the responsibility to achieve the environment objectives on the forest industry, which *SFA3* thinks creates a certain concern regarding the poor nature consideration taken in forestry.

Change of policies and stricter regulations

Several representatives, across the entire range of actors, want both more extensive and clearer regulations on a number of areas relating to forest residues. *SFA2a* declares that the Forestry Act is weak and requests a clarification of the law so that extraction of forest residues is properly regulated and not just mentioned in the interpretations. "As it is today we only have our recommendations to lean on," (...) "it would facilitate our work if the legislator gave us more directives in these issues" (*SFA2a*). As an example of a needed regulation *SFA2a* mentions a specification of which areas that are suitable and not suitable for forest fuel extraction. *SFA3* especially requests that the SFA-recommendations should be modified so that extraction of forest residues is only promoted when the soil is frozen, to avoid severe soil damages.

Holmen believes it is up to society to balance between interests that compete for forest values, and is certain that: "it will be clearly stated in the regulations exactly what is allowed and what is not." *SLU1* however, says that: "We cannot create rules and barriers that prevent the rise of alternatives immensely better than oil and coal, even though those alternatives are not perfect." *SLU1* mentions that there will soon be sustainability criteria for biofuels, "which is good," but asks: "should we develop that for oil and coal as well?"

UU says that: "Irrespective of political control measures the global market economy will within a few decades drive up prices on forest products to a point where the paper industry cannot compete with forest fuels. Politicians should realise this and think thoroughly about what we want with the Swedish forest. We could choose Continuous Cover forestry, high biodiversity and reindeer husbandry. We could phase out the energy intensive paper production and turn the factories into something else. The paper industry is very strong and will not give up easily but it is a fight we have to take."

SFA3 suggests measures within three areas: First of all, increased resources to be able to compensate those forest owners who set aside forest land. "Today we don't even manage to redeem the key biotopes that forest owners want to protect," (...) "we are even further from achieving what is needed to ensure biodiversity," and "still we only protect 1-2% forest land in this region [Västerbotten]." *SFA3* thinks that there is a huge lack of societal contributions. Secondly, *SFA3* points out the need for better law enforcement instruments to uphold proper general nature consideration, primarily at regeneration felling. *SFA3* mentions how the SFA always has to relate to the strong protection of ownership, which limits the possibilities to take necessary measures against forest owners. Thirdly, *SFA3* calls for a change of attitude towards responsibility, and states that 1990s' shift[19] of the national forest policy and the resulting amendments of the Forestry Act proclaiming *sector responsibility,* has not been successful.

4.3.7 Future role of forest residues

A question of land use

SCA states that even though Sweden has managed to substantially increase both the forest and crop volumes, on a global scale there are huge land areas that are mismanaged, degenerated or used as grazing land. *SCA* says that: "We have to turn these areas into productive green lands, and that will involve a great deal of fiddling with nature and compromising with other interests." *SCA* adds: "I don't believe that nature is 'good', it becomes what we make out of it. (...) The consequence of less fossil fuels is more extensive production, I can't see any other alternative." *SCA* believes that this view is strongly opposed by the environmental movement and ends, "they are very conservative."

Holmen emphasises that it will be very difficult to replace all nuclear energy, coal and oil with bioenergy and at the same time protect more forest, and thinks that something quite radical is needed to solve the problem. *Holmen* believes that, "we might have to cultivate land in fallow and even question the creation of new nature reserves." *Holmen* ends by saying that: "As I have understood it there are huge steppelands in southern Africa that are regularly being burned and then used as poor graze lands. Imagine how forest or some other energy crop could be cultivated there and possibly supply energy systems in Europe or other places."

SLU1 warns that creating a dependency on renewable energy from Brazil or from countries in Africa would only result in a new form of colonialism and in a competition for available land areas for food production. *SLU1* argues that every country has to deal with its own problems, since "that is the only way to reach a reasonable level of energy consumption." *SLU1* goes on: "I would like all biofuels to be produced locally (…) people would then see the environmental effects of their energy consumption up close. If you want to heat your house, drive your two cars and go on your annual vacation to Thailand, then this many stumps have to be extracted,

[19] The development of policies and regulations within Swedish forestry is described in Part I.

preferably in the forest closest to your house." *SLU1* concludes: "We have to realise the consequences of our consumption to bring about a change."

Unsustainable levels of energy consumption

SCA points out that, "We will soon be nine billion people on the planet, and a growing number want a better standard of living." *SCA* says that: "We [Sweden] are not yet facing any major lack of welfare or energy, however if we shut down the nuclear power plants and stop using fossil fuels we will have to find other energy sources. We obviously have to reduce our consumption of meat and goods to meet these needs but apart from that we have to start cultivating to a much larger extent, not just food like today but also to get energy, and such measures will surely affect our environment."

SLU1 states that replacing all fossil energy with renewable energy will not be possible, and says: "The fundamental problem is that we have constructed a society dependent on fossil fuels. Oil has been too cheap for too long, but now that is over and we have a painful transition ahead." *SLU1* emphasises that, "We will not be able to solve the problems using the same framework of thinking that created them," instead: "we need to cut the volumes and rethink how we plan our communities. Living at one place, working at another, shopping at a third, and leaving the kids at kinder-garden at a fourth is not sustainable." *SLU1* guesses that the strongest driving force in the transition will be the price of oil versus the price of other fuels, which is controlled partly by taxes but also by political initiatives such as EU's goals for 2020. *SLU1* states that they need to be put into practice at a national level in order for biofuels to become competitive, but underlines that energy systems are not created over night, it takes decades, and concludes, "the market has to know the deal for at least the coming 20 years, or else nobody will make necessary investments."

NC brings up the question: "how much fossil fuels do we really manage to replace?" and refers to the fact that the number of petrol cars increases faster than biodiesel is produced. *NC* further argues that the generated energy is only used to benefit the capital, to make more money, and adds: "I refuse to accept that species diversity and our living space are sacrificed for that. If we instead reduce our use of cars and transportation, we might not need to extract stumps at all." *Norrskog* agrees on the point that: "It doesn't matter how much we can increase the production and extraction from the forest if we keep using more energy. Striving to replace all fossil fuels with biofuels while the total energy use keeps increasing, I wonder how long it will last."

Holmen states: "there is no doubt that we are consuming and wasting too much," but asks, "which politician would dare to prohibit indoor temperatures over 22 degrees or introduce penalty taxes on food to avoid waste? We might end up there but it requires economic and political decisions." *Holmen* adds, "I don't know if the general Swede is ready to start using cloth diapers or taking the bike to work. It is all about sacrifices, choices for the individual and the society about how to live." *Norra* declares that the primary success factor for a society is cheap energy and says, "that is what has made our welfare and that is also what China is investing in now." *Norra* criticises the environmental movement for saying no to everything, to nuclear power, bioenergy, stump extraction, even to wind power at some places, without presenting any solutions of their own, and wonders, "so what should we live off?"

As a response *UU* asks "how much welfare do we need?" and goes on: "I think most people know that we live on a finite planet. Still, the forest companies strive for more profit and Sweden keeps trying to increase the GDP. Everybody acts rationally on their respective level, but in a global perspective it is completely unsustainable to go on like this." *UU* underlines that, "we must lift the discussion to a global level, not lose ourselves talking about recycling paper and replanting a few trees." *UU* calls for a global economic change to eventually achieve a sustainable development, a process that might take up to seven or eight generations. *UU* believes that biofuels have a role in the transition towards an equal *environmental space*[20], but emphasises that the vital measures are about saving energy and reducing nativity, especially in rich countries. *UU* concludes that, "the only way out is to adjust the forces that drive consumption to the degree of what is ecologically efficient so that we will get a net reduction of materials in the energy flows" and ends: "This is where the issue of forest residues become relevant, otherwise it is completely decoupled."

[20] Defined as "the quantity of energy, water, land, non-renewable raw materials and wood that we can use in a sustainable fashion," in the study "Towards sustainable Europe" by Spangenberg 1994; the Wuppertal Institute in co-operation with Friends of the Earth Europe.

4.4 Discussion

Benefits of forest fuels

The discussion about the climate mitigation potential of forest residues had different focus among the actors. The representatives within the forest industry and the Swedish Forest Agency did not question the climate benefit of forest residues. They pointed out that all types of energy generation processes have some level of impact on the environment, and were convinced that the most climate efficient thing to do is to extract and burn forest residues and meanwhile substitute fossil fuels. This was commonly used as an argument to promote higher extraction intensity. There was little discussion about time perspective and the fact that if we want to substantially reduce greenhouse gases within the coming years it would be better to leave the forest residues at the clear-cut. The SLU-researchers argued that the climate mitigation potential of forest fuels has to be seen in the perspective of an entire rotation period, and that it is misleading to isolate the greenhouse gas emissions during the years straight after felling. The crucial question is how much time we have to make the necessary reductions of greenhouse gases before we reach the crucial tipping-point of climate change. IPCC-researchers have estimated that with current emissions rates this could occur within the coming decade. In that case even a few years are extremely valuable.

It was further pointed out that the connection between forest fuel production and reduced use of fossil fuels is not obvious. Providing cheap bioenergy could potentially boost the energy market, resulting in an overall increase in energy use. Representatives across the whole spectra of actors were aware of this aspect but no one went deeper into strategies for how to deal with such development.

Current situation and prerequisites to meet production goals

The trend to extract slash is clearly positive all over Sweden, while stump removal is still a very marginal activity, both in Norrland and in southern Sweden. The main obstacles for a large scale harvesting of forest residues mentioned by the actors are too low profits, which makes it sensitive to transportation distance and working costs, and lacking technology for efficient stump removal. The interest in stumps is reported to be higher among companies than among associations and private forest owners. This is said to be because stump extraction requires high inputs in terms of capital and logistics. Since companies generally hold larger forest properties they can harvest more at a time, which brings down the costs per hectare. The forest owner associations use various measures to encourage their members to extract slash, such as offering a fixed price per cubic metre regardless of the distance between the site and the customer, free soil preparation, and so on. There is a certain resistance also within their organisations, mainly concerning the extra work-load it entails. Despite the marginal extraction at a landscape level, the nature conservationist reported to already have noted severe effects at individual sites, especially where stumps have been harvested.

There is a gap between the political goals of increased production of forest fuels and the practical prerequisites across the country to achieve them, which is generally overlooked in most reports of forest fuel extraction (see de Jong *et al*., 2012). Most of Norrland's inland is too far from the thermal power stations to make it profitable to extract. Low profits contribute to the sceptical attitudes towards slash and stumps among many private forest owners, both in the North and the South of Sweden. In Norrland there is also a widespread concern that slash removal will affect the growth of the coming stand negatively. There are several parameters that further favour higher extraction rate in the South compared to the North: higher demand for forest residues, the majority of the end-users live in southern Sweden, the supply chains are generally more efficient and the forests produce more biomass per hectare.

All company and association representatives, as well as most representatives from the Swedish Forest Agency, agreed that a complete extraction of forest residues never will be reached. Environmental, economic and practical constraints, together with the heterogeneity of forest ownership, were mentioned as the primary reasons for this. At the same time, everybody believes that as the economy improves and it becomes increasingly profitable to extract forest fuels, even for private forest owners holding smaller properties, the economic and practical challenges will most likely be overcome. It is just a question of how fast the demand increases. The large differences in forest ownership structure across the country could possibly result in that stump removal increases faster in Norrland (80% company owned forest land) than in southern Sweden (80% owned by private individuals.)

Nutrient compensation

The Swedish Forest Agency (SFA) actively promotes the extraction of forest residues, and to balance the loss of nutrients they recommend ash recycling. It is clear however, that ash recycling is not a priority for most actors. Non-existent ash producers and logistical constraints are important factors that reduce the incentives among entrepreneurs in Norrland to spread ash. But equally contributing to the situation is the general scepticism against the benefits of ash, mostly based on arguments that refer to the naturally nutrient poor soils in Norrland. In southern Sweden access to ash is not a problem, instead it seems to be the entrepreneurs' attitudes that decide whether it is carried out or not. Since there is no system of keeping records of the sites where forest residues have been harvested, it is very difficult to determine who will be ultimately responsible for it to happen in the future. The fact that many SFA-representatives in Norrland question the recommendations on ash recycling might contribute to the low activity among entrepreneurs.

A common conviction, especially among company and association representatives as well as SLU-researchers, is that if it turns out that removing forest residues affects growth negatively, it can easily be fixed by adding nitrogen. Fertilisation has long been a promoted measure by those who want to see an intensification of the Swedish forestry. By arguing that nitrogen is needed to compensate for the removal of forest residues it becomes a less controversial measure and much indicates that such trend is already on the way. The problems of lacking structures for knowing which areas that need compensation still exist though but are not really seen as a major problem. The effects of adding nitrogen to the forest have not been the focus of this study, however it is an area that requires more research, especially considering current trend.

Environmental impact and challenges with increasing demand for forest fuels

The main risks of forest fuel extraction discussed in the interviews were severe soil damages and subsequent leaching of heavy metals and nutrients, lost habitats with negative impact on biodiversity and reduced growth as nutrient-rich biomass is removed.

All actors confirm that as more forest residues are extracted there is a risk that nature consideration becomes less prioritised. There are several factors leading to such assumption: The high costs involved in the transportation and usage of excavators and forwarders, in combination with logistical challenges when transporting forest residues from the clear-cut, create incentives to harvest as much as possible once at the extraction-site. Forest materials, which previously had no or very low economic value suddenly become profitable, which could result in less dead-wood left in the forests and an affected biodiversity. It could also make marginal and sensitive forest areas, with weak or wet soils, interesting to harvest and lead to severe soil damages with potential leaching of e.g. heavy metals and nitrogen.

Increasing activity of heavy machines in the forest creates track formations and stirs the soil. The severity of the soil damages depend on the specific soil conditions at each site and on how much consideration that is taken by the machine-team during extraction. Several actors report about an increasing trend to enter weak soils and previously marginal areas in search for forest fuels, which probably will result in even more frequent soil damages. This issue is linked to an on-going discussion about when it is optimal to harvest the residues to avoid most severe soil damages. Some argue that slash only should be extracted when the ground is frozen. However, that would mean that slash is removed in combination with winter felling, while still green, resulting in the simultaneous removal of all nutrient rich needles. The alternative is to leave the slash on the clear-cut for a year or two until the needles have dried and fallen off. This procedure however, requires an extra round to the site with a forwarder, with additional CO_2-emissions and possibly also a risk of weaker soil structure due to decomposition of the stabilising fine roots. Another aspect of winter harvest is that areas clearly unsuitable for extraction during bare ground season (too wet or weak) become easily accessible for the driver when the ground is frozen, which increases the possibility that these areas are prepared for extraction at a later stage. The climate conditions vary across the country though, with much shorter time periods of frozen ground in the South. Milder and wetter winters are expected also in the North as an effect of climate change. This puts even higher demands on extra cautiousness during forest fuel extraction.

It is common among company and association representatives to play down the environmental risks of forest fuel extraction by referring to the existing legal framework and the SFA-recommendations. However, there is an obvious discrepancy between different actor groups regarding their perceptions of how well the regulations are followed and hence about current environmental state in Swedish forests. Forest companies and owner associations almost completely disqualify the Polytax-measurements as an indicator for nature consideration, which means that they can question the credibility of the reports showing an alarming environmental state of the forests. Nature conservationists and some representatives for the Swedish Forest Agency on the other hand describe the environmental state of Swedish forests as disastrous, especially regarding biodiversity, and that clear-felling and forest fuel extraction are already repeatedly carried out in areas highly unsuitable for forestry activities. They claim that the poor nature consideration indicates that the principle of ‘freedom under responsibility’ is a highly inconsistent mechanism to achieve the environmental objective of the Forestry Act, and they suspect a similar or worse scenario when more forest materials are extracted.

The discussion about the difficulty of combining biodiversity with increasing forest fuel production often ended in the larger discussion about the Swedish forestry model as a whole. Many actors proposed a change of conventional forestry towards a division of forest land into areas especially designated for production and others set aside completely for nature conservation. The companies and owner associations, together with quite a few of the researchers especially mentioned the potential to use measures for harder production not allowed in conventional forestry. Others mentioned the possibility to create better protection for really valuable ecosystems (e.g. old-growth forests). However, such development was by some seen as a way of surrendering to the fact that we don't manage to achieve the environmental goals, instead of changing the way we relate to the forest and what we expect it to deliver. The poor environmental state is to a large degree identified as a problem of attitude among the entrepreneurs. All SFA-representatives stress the need for better planning before a forestry activity, and emphasise the importance of entrepreneurs having proper knowledge, especially when forest fuels are extracted.

Sustainable extraction of forest residues

Almost all actors stated that the available forest material will not be enough to both produce energy and sustain the traditional forest industries (pulp and paper). This will result in an intensifying competition where those with best ability to pay get access to most forest resources. Even if new markets for conventional forestry products arise globally, most representatives agree that with the current demand for bioenergy and the expected future energy need, the strongest competitor will be the energy sector.

The increasing demand for bioenergy is predicted to challenge basically all components of current forestry and put higher pressure on the forest. The majority of the representatives, both within the forestry sector and the Swedish Forest Agency as well as SLU-researchers mentioned the importance of adequate regulations of forestry in general and of forest fuel extraction in particular. The nature conservationists criticise the existing regulations for not being sufficiently far-reaching concerning nature conservation. Most SFA-representatives don't question the regulations as such, their main critique concerns the authority's lack of resources to carry out proper law enforcement. The company and association representatives confirm the absence of sanctions in cases when the regulations have been violated, even though their opinions of to what extent that happens differ from most other representatives. Still it was common to play down the risks of extensive environmental effects of forest fuel extraction by referring to future regulations that will be created if it turns out to be needed.

The broad request for regulations and the fast development of the bioenergy sector indicate that there is an urgent need to develop guidelines and policies in this field. They must consider aspects such as regional variation in biomass production and practical conditions during extraction, the carbon emissions connected to production and consumption of forest fuels, at what harvest intensity biodiversity and the nutrient budget become severely affected and what the consequences are for the forest ecosystem. This requires in-depth knowledge about the risks and long-term effects of forest fuel removal. Numerous research projects have already been initiated to increase the understanding in this field, but all actors agreed that there are still many knowledge gaps to be filled.

However, the environment and production objectives are already given equal importance in the Forestry Act, but the present system lacks the proper mechanisms to achieve a balance. Only changing formulations of the Forestry Act without a simultaneous change at other policy levels will therefore have little effect in practice. If we set ambitious environmental goals we have to be prepared to make the efforts needed for them to be reached. The SFA-representatives call for more resources to be able to follow-up more errands and control forest sites before and after forestry operations. If general nature consideration is to be taken during all forestry activities a comprehensive approach involving multiple societal and political levels has to be implemented. Key actors within Swedish forestry, decision makers, authority officials, researchers, civil society, and the environmental movement need to be involved in the process. But the crucial question is at what point in time and to what extent society will start to regulate this.

Future role of forest residues

The dominating views of the function and values of the forest - a resource to be exploited (Sweden's green gold), the solution to Sweden's climate change mitigation efforts, or an ecosystem harbouring thousands of forest dwelling species - tend to influence and shape the prevailing forestry paradigm. The representatives hold very different views of what forest values that should be given priority over others, to what extent it is necessary to compromise between interests that compete for forest materials and also of the severity of a higher taxation of nature. Some SFA-representatives declared that these questions are fundamentally based on the notion of whether there exist any natural boundaries that need to be considered or if all boundaries are politically decided. Representatives from the forestry sector and also within SFA commonly believed that the forest should be managed hard and that the available resources should be used. Others argued that if we set objectives that challenge existing goals then we have to realise that either of them have to be reformulated. The nature conservationists questioned the current forest management model in its totality, both pointing to its negative impact on biodiversity and on its close connection to an unsustainable economic system in which growth is the most important driving force.

Another important discussion concerns the connection between social and environmental justice and energy production. Sweden imports a substantial share of the total energy supply. However, the consequences of that energy production in terms of exploited nature and human suffering, takes place elsewhere. If we are to sustain the current levels of energy consumption, but without violating the environmental space of others, it could be argued that it is only fair to sacrifice our own nature.

Nobody claims that it is possible to replace current use of fossil fuels with bioenergy, and all actors emphasised that a reduction of the overall energy consumption is the primary and most important step both in order to reduce the greenhouse gas emissions and to handle the need for new energy sources. The interesting question is what role forest fuels can play in the transition towards a sustainable society. If one puts the Swedish energy use and the global demand for energy against the available resources in the forest, how far is it possible to go? To what extent is it meaningful and justifiable to produce forest fuels? The benefits of exploiting the available nature resources (low costs, easily accessible) have to be weighed against the immediate and future consequences (e.g. extinct species, less nature conservation).

This thesis focuses exclusively on forest fuels' potential to replace *fossil fuels*, however if we are really serious about the efforts to create a sustainable society a braver approach would be to compare forest fuels with other non-fossil energy alternatives.

4.5 Areas of further interest

In the interviews several issues were raised that already have or will have influence over the future development of forest fuels. Many identified small diameter wood as an important new category for forest fuel production. According to *Norrskog* there are about 2 million hectares of forest land that need to be managed in the near future and where small-diameter wood could be harvested. However, there is a risk that zones around streams, between fields and forest edges will be harvested as well, with negative effects for biodiversity. The Swedish Forest Agency is developing recommendations for this assortment, but more research of the potentials and effects is needed.

Intensive forestry measures were another issue frequently brought up by many actors. Fertilisation is already an established practice within Swedish forestry but enhanced frequency and refined methods are promoted by the forest industry, together with the use of hybrids, clones and Lodgepole pine. Many claim that the suggested measures are necessary in order to meet the future demand for forest biomass, but very little research has been done on the possible effects of implementing them on a large scale. The question of intensive forestry is closely related to the discussion about an overall transformation of the Swedish forestry model discussed above.

Part V - Final discussion and conclusions

The conditions for forest fuel production vary across the country due to differences in forest properties, environmental conditions and socio-economic factors. In southern Sweden the forest fuel potential is about 60% higher per hectare than in the North, due to more biomass per hectare. This corresponds to 520 MWh per hectare in the South and 320 MWh per hectare in the North in the most intensive harvesting scenario (80% slash; 50% stumps). Although the potential of forest fuel harvesting per hectare is larger in the South, there are large areas of productive forest in the North.

Also the removal of nutrients is larger in the South compared to the North, at all studied harvesting scenarios, with the exception of nitrogen in Scenario 3 and 0, showing the opposite relationship. The comparison between a site in the South and a site in the North showed that 2,5 times more Ca, 10 times more Mg and more than 3 times more K are lost from the southern site than from the northern site in Scenario 1. The N loss is about 3 times greater in the North than in the South and for P the balance was around 0 in the North and almost 1 kg ha^{-1} in the South. The differences between harvesting scenarios showed that whether forest residues are removed from the forest system or not is the most influential factor determining the net balances of all studied nutrients (base cations, phosphorous and nitrogen). The effects of removing forest fuels were significantly higher in the South than in the North of Sweden, because of more biomass being removed per harvesting scenario, resulting in a higher risk of nutrient depletion in the South.

Forest residues are considered a renewable and cheap energy source with large potential to reduce Sweden's dependence on fossil fuels and the national greenhouse gas emissions. However, there is a gap between the political goals of increased production of forest fuels and the practical prerequisites across the country to achieve them, which is not thoroughly handled in planning and policy work. During current practical and economic conditions, a large-scale extraction of forest fuels is judged as impossible to achieve by actors within and close to Swedish forestry. The possible level of extraction and the limiting factors vary across the country. Whereas the biomass production described above sets the potential forest fuel production, attitudes towards increased biomass extraction, prices, infrastructure and ownerships structure determines the actual forest fuel extraction.

There is a widespread fear of growth reduction among forest owners, especially in the North. Shorter transportation distances and higher demand for bioenergy in the South of Sweden contribute to the currently higher forest fuel production compared to northern Sweden. As prices on forest residues increase the challenges of long transportation distances and low interest among forest owners will most likely become less significant. The differences in ownership structure between southern (mostly private individuals) and northern (mostly companies) Sweden could lead to faster development of primarily stump removal in the North. The practice of ash recycling is generally very low among entrepreneurs across the country. It is more common to recycle ash in the South of Sweden than in the North, which is where the need is the greatest according to nutrient budget calculations. The main reason is that there are widespread concerns about growth effects and low access to ash in the North.

There is a conflict between the climate benefit of forest fuels on the one hand and biodiversity and nature conservation on the other, as well as between a maintained nutrient balance and the risk of soil damages as forest fuels are extracted. The poor general nature consideration in Swedish forestry and the strong competition for available forest materials are important challenges that need to be tackled as the demand for forest fuels increases. Otherwise there is a risk that nature values become even less prioritised. There is a sharp discrepancy between actor groups regarding current environmental state in Swedish forests, and hence in attitude towards the severity of the effects of forest fuel extraction. Still, most actors ask for clear regulations of how and where to extract forest residues. All actors agree that the Swedish Forest Agency has limited power to conduct law enforcement. Insufficient planning before and lacking knowledge during forestry operations are identified as main reasons for low nature consideration in Swedish forestry. This requires comprehensive attention in order to achieve a sustainable extraction of forest fuels.

This study shows that a trans-disciplinary approach can improve the basis for decisions and planning concerning future forest fuel production and that the different conditions in different parts of Sweden have to be handled more thoroughly than at present. There is a need to adjust the goals and ambitions for forest fuels, so that they become more consistent with the actual conditions to produce and extract forest fuels across the country, and so that the goals of maintained biodiversity and high nature consideration are truly possible to achieve.

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Appendix I – Ownership, Regions and State of Forest

Ownership structure of productive forest land area, 2010

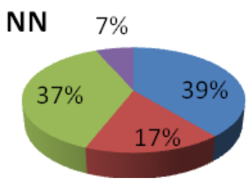
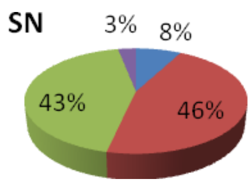


Figure 1a.



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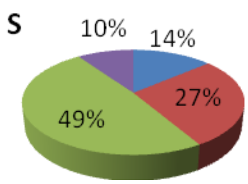

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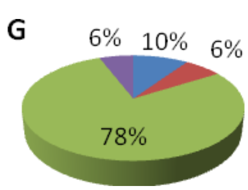
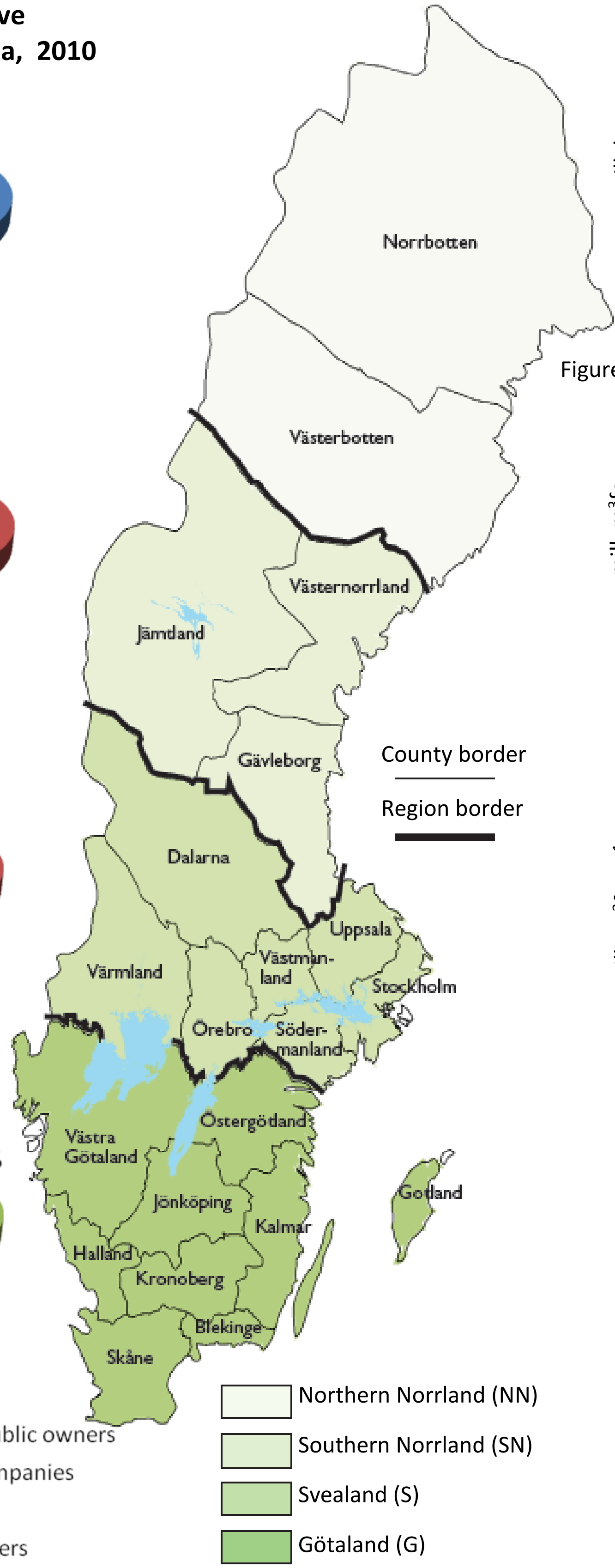


d.

- State and other public owners
- Private owned companies
- Private individuals
- Other private owners

Division of country in regions



State of forest 2005-2009

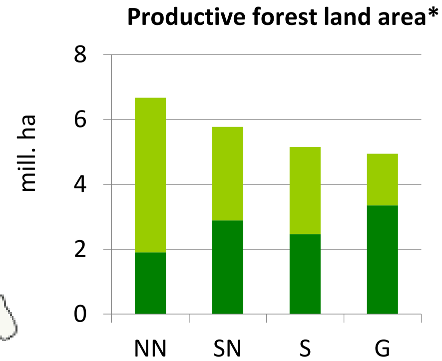
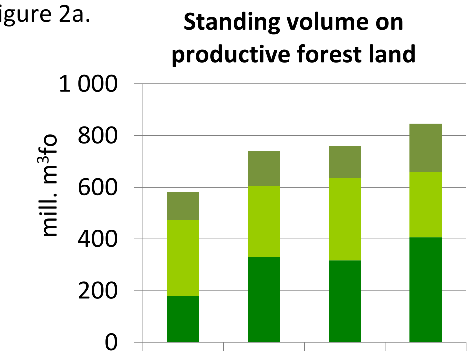


Figure 2a.



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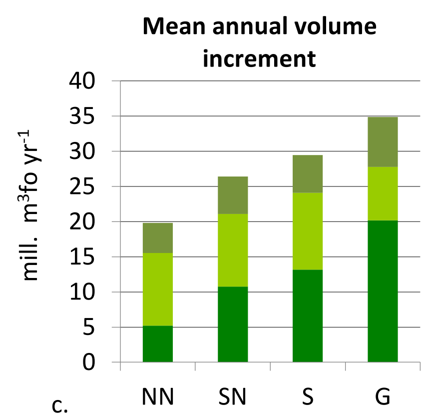

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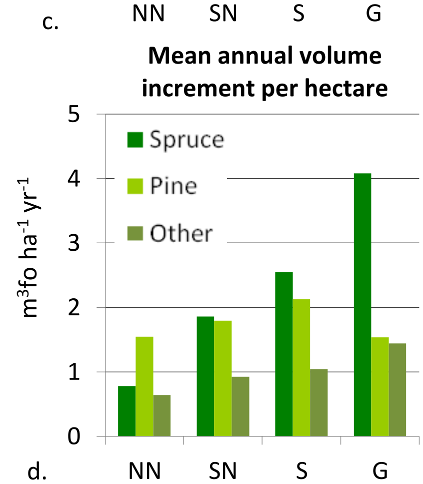

d.

*Protected land excluded

Source: STA, 2010 (Figure 1a-d); SNFI, 2010a-c (Figure 2a-d)

Appendix II – Swedish Forest Agency's recommendations

Stands suitable for extraction of forest fuels and ash recycling

<table>
<tr><th>Slash</th><th>Stumps</th></tr>
<tr><td>In areas with high N load removal of needles is positive, provided that ash is returned.</td><td rowspan="3">Unless there is high conservation value, valuable cultural environments or high social values, and where soil conditions are such that stumps can be harvested without any apparent risk of soil damage and subsequent negative effects on production or the environment.

Stands damaged by root rot, where removal of stumps may have the potential to reduce the risk of root rot in the next stand.

Spruce plantations on abandoned agricultural land, which usually have relatively low environmental values.</td></tr>
<tr><th>Ash recycling</th></tr>
<tr><td>Should take place on lands where slash are extracted substantially at some point during the rotation period. When: 1) the total removal of other tree parts than the stem during the rotation period equal to more than 0.5 ton of ashes per ha and, 2) most needles are not left evenly spread out.

Ashes should always be returned if: 1) the soils are strongly acidic, or 2) the forest is growing on peat soil.

In areas with low N load and high harvest of biomass compensation with both ash and N-fertilisers may be needed.</td></tr>
</table>

Stands not suitable for extraction of forest fuels and ash recycling

<table>
<tr><th>Slash</th><th>Stumps</th></tr>
<tr><td>Sensitive biotopes and during periods when wildlife can be damaged.

Forest with high conservation values, such as some swamp forest and key biotopes, should be avoided if conservation values are at risk of being damaged.</td><td rowspan="3">Stands with high conservation values, which could be adversely affected.

Stands related to water, to not risk a negative impact on drinking water quality.

Stands with soil moisture class moist and wet, i.e. groundwater surface < 1 m below the surface --> large risk of severe soil damage, with negative impact on surface water quality (sedimentation and increased leaching of organic and inorganic substances).

Stands on fine-grained soils, i.e. soil parent material with coarse silt/silt and finer texture (to minimise the risk of soil compaction and erosion). Exceptions can be made on flat stands not adjacent to water, and where the risk of soil compaction is small.

Stands with inclination > 15-25% (or 10-15°) (to reduce the risk of erosion).

Stands with valuable cultural environments. At large remains the precautionary principle should be applied.

Stands in areas rich on ancient remains that are likely to harbour additional relicts.

Stands with high social values.</td></tr>
<tr><th>Ash recycling</th></tr>
<tr><td>Sensitive biotopes and during periods when wildlife can be damaged.</td></tr>
</table>

Considerations within stands where forest fuels are extracted and ash recycled

<table>
<tr><th>Slash</th><th>Stumps</th></tr>
<tr><td>It is important that trees, bushes and dead wood previously spared for conservation interests are left and not damaged.

Should only cover the most common tree species in the landscape.

At least 20% of slash should be left on the clear-cut area, preferable in sun exposed locations.

Especially important to leave tops, thick branches and dead wood from broad-leaved trees and pines.

Technique, system and timing should be chosen so that driving doesn’t cause transport of sediment and organic material to streams, or damages on cultural and heritage sites, and so that mechanical damages on trees are reduced.

Measures should be taken to prevent insect damage.</td><td rowspan="3">Only stumps of conifers should be extracted, since they are a more common substrate with lower diversity of species (incl. endangered species) than hard wood stumps.

Leave 15-25% of available volume of both spruce and pine stumps, since these species cannot fully replace each other in order to maintain biodiversity.

Not stumps in moist or wet sections, or parts of stands where texture or inclination is such that risk of erosion exists.

Not stumps in or close to base roads in order to maintain buoyancy.

Leave buffer zones next to borders adjoining lakes and running water, and tree retention patches, so that the stability of these trees do not deteriorate further. In connection to ditches the risk of negative impact on water quality should be considered.

Strive to integrate soil preparation with stump removal, to reduce the number of occasions machines enter the stands and to reduce ground damage.

Not stumps on or adjacent to valuable cultural environments. Stump removal within an area with ancient remains requires permission from the County Administrative Board.

Not stumps adjacent to forests with high social values or to paths/trails in the landscape. When extracting stumps it should be considered to inform users.

Within grazing areas of reindeer stump removal should take place with least possible impact on sites with lichen.</td></tr>
<tr><th>Ash recycling</th></tr>
<tr><td>The ash product should have its origin in biofuels, be hardened and dissolve slowly so that damage on sensitive species is avoided.

Recommended Ton Dry Matter (TDM) of ash per ha: 2 on stands where SI < G23; 3 on stands where SI > G23

To avoid unwanted effects should not more than 3 TDM of ash be recycled per ha and 10 years, and a maximum of 6 TDM ash for a rotation.

The total input of heavy metals and other harmful substances during a rotation should not be more than what is removed at biomass harvest.

N-leaching and loss of added nutrients should be prevented.

An ash-free zone of 25 m should be given to sensitive areas.</td></tr>
</table>

Nature consideration according to 30§ Forestry Act

Nature consideration to be taken at all forestry measures (SFA, 2011d):
*Do not create excessively large felling areas; *Leave non-productive forest land untouched; *Avoid damaging sensitive habitats and valuable historical sites; *Be particularly careful when felling in areas rich in rare flora and fauna; *Retain some deciduous trees in coniferous forests for the entire rotation period; *Leave protective buffer zones adjacent to water, non-productive land, agricultural land and urban areas; *Always leave a number of older trees standing on felling sites, preferably in groups; *Plan felling and transport operations so as to avoid or limit damage to the land and water courses; *Plan forest roads in a way that minimises damages to the woodland and safeguards cultural heritage.

Appendix III- Nature conservation in Swedish forestry

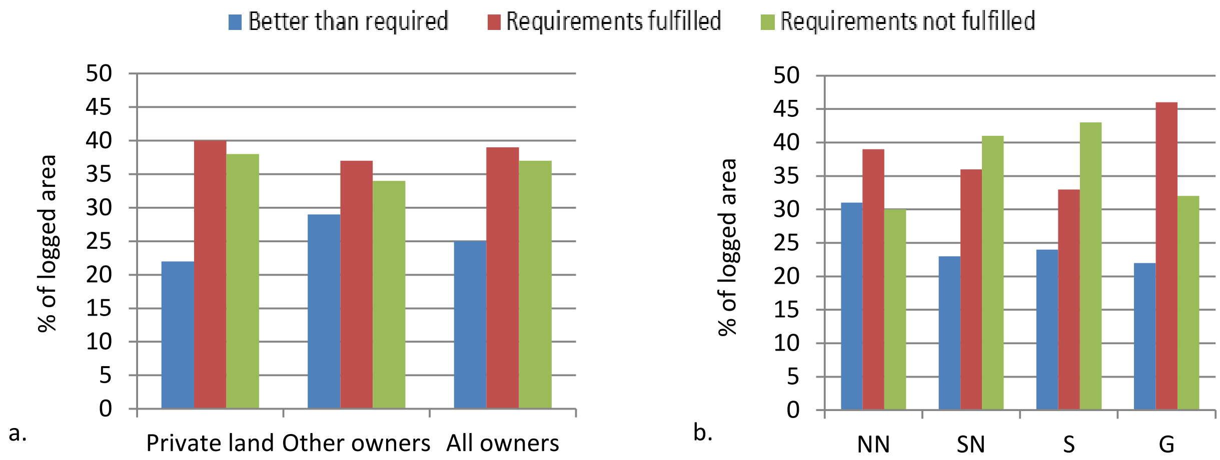

Figure 1: Compliance with environmental requirements of Swedish forest law in connection with regeneration felling during 2009: a) Per ownership category (see definitions in Appendix I); b) Per region. NN: Northern Norrland; SN: Southern Norrland; S: Svealand; G: Götaland. (SFA, 2010b)

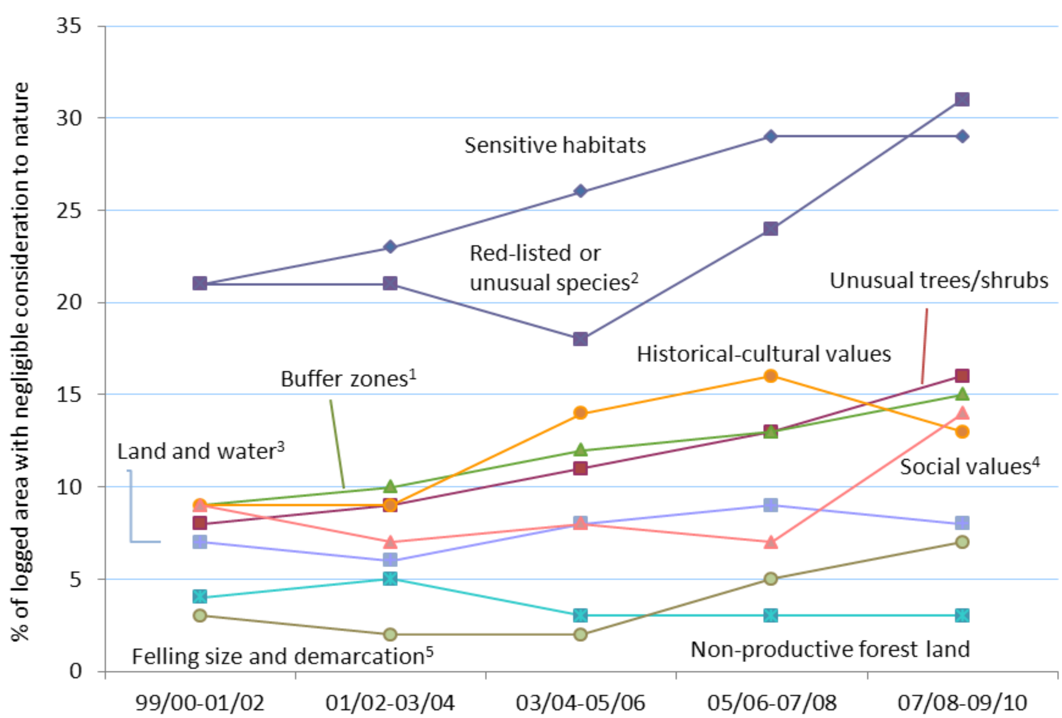

Figure 2: Percentage of logged area in which negligible environmental consideration was taken to parameters regulated in Swedish forest law. Regeneration felling (SFA, 2010c (P1 2010)).

Note. 1) Safety zones next to non-productive forest land, lakes, streams or open agriculture land. 2) Environmental consideration to redlisted or regionally uncommon plant- or animal species. 3) Damages on ground and water includes damages due to track formation, driving over streams, safety drainage and nourishment leaching. 4) The following is included in social consideration; safety zones towards buildings and that commonly used tracks are free from felling residues. 5) An adjustment of the size and form of the felling area to nature and culture values.