Stump Harvesting

Impact on Climate and Environment

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Impact on Climate and Environment

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Stump Harvesting – effects on climate and environment

Preface

In 2007, the Faculty of Natural Resources and Agricultural Sciences (NL) at the Swedish University of Agricultural Sciences (SLU) initiated the thematic programme "Theme stump harvesting". The programme was jointly financed by the Swedish Energy Agency, the NL faculty, and FSC-certified forest companies and was run for eight years, 2008 – 2015, with a total budget of approximately 12 million €. The strategic work has been led by a steering committee.

This report summarizes the findings and conclusions of the research programme but also some other research in the area. A large number of scientists from SLU, Lund University, Uppsala University, Umeå University and Skogforsk (the Forestry Research Institute of Sweden) show here how stump harvest affects the soil, plants, fungi, small animals, greenhouse gases, nitrogen leaching, mercury and forest production. The programme also analyzed how much the climate will benefit from using stumps instead of fossil fuels, how biodiversity is affected by various stump harvest intensity and if it is possible to compensate for potential declines in biodiversity among wood-inhabiting species by creating more snags.

Many individuals and organizations have contributed to the report. Forty-two scientists (see address list at the end of the report) have written the chapters, but we note that a review of the international publications that formed the basis for the chapters will reveal that many more researchers have contributed overall. We are grateful for their significant effort to fill a large number of knowledge gaps. We also want to thank the programme funders the Swedish Energy Agency, SLU and nine FSC-certified forestry companies (Sveaskog, Holmen, SCA Skog, Södra Skog, Bergvik Skog, Stora Enso Skog, the Swedish Forest Society Foundation, BillerudKorsnäs and the Church of Sweden). Several of these companies have acted as hosts for the newly established stump-harvesting trials as well the Rappe- von Schmiterlöw Foundation, Norunda Häradsallmänning and SLU. We thank the landowner hosts and their staff for all their help and cooperation.

Uppsala in April 2017

Tryggve Persson	Hans Djurberg
(Programme coordinator)	(Chairman of the steering committee)

TABLE OF CONTENTS

1. RESEARCH ON ENVIRONMENTAL EFFECTS OF STUMP HARVESTING

Tryggve Persson (SLU), Hans Djurberg (SCA), Pär Forslund (SLU) and Anna Lundborg (the Swedish Energy Agency)

The Swedish interest in stump harvesting increased dramatically after the hurricane Gudrun, which felled 75 million m^3 of trees in southern Sweden in early 2005. The interest was also a response to an increased demand of energy from a growing combined heat and power market. The consequences of stump harvesting have been studied in a research programme financed by SLU, the Swedish Energy Agency and FSC-certified forest companies.

Stump harvesting has a long story

Tree-stump harvesting has historically been performed in Scandinavia for many centuries. At the end of the 1600s, Sweden and Finland supplied the whole world market with tar from pine stumps, and during the peak of the tar burning industry (1831-1905), 20-25 million pine stumps were extracted from Västerbotten, one of the northern provinces in Sweden, corresponding to a stump-harvested area of 600 ha per year (Swedish Forest Agency 2009; Tirén 1937). During World War II 1939-1945 the need for tar increased, and as much as 30,000 Mg of tar was produced, corresponding to 4.5 million of stumps on an area of 7,000 – 9,000 ha (Anerud 2012).

At the end of the 1970s, tree stumps were tested as raw material for the pulp industry in Mackmyra situated between the cities of Gävle and Sandviken in central Sweden. As a whole, 9,200 ha of clear-cuts were stump-harvested in the provinces of Uppland and Gästrikland. The stump harvesting activity was abandoned after about 10 years, mainly because of difficulties in removing soil and stones from the stumps (Swedish Forest Agency 2009).

Tree stumps have also been harvested in Italy, the UK, north-western USA and British Columbia

(Canada). In the latter countries, the main purpose was to counteract the spread of different forms of root rot (Zabowski et al. 2008; Cleary et al. 2013), and stump removal for pulp and bioenergy has been of less importance.

Increased interest after the hurricane Gudrun

In the early 2000s, the forest industry in Finland initiated stump lifting for bioenergy purposes and was a pioneer in large-scale stump harvesting in Europe. An estimate (for 2010) is that about 20,000 ha per year are stump harvested in Finland (Juntunen and Herrala-Ylinen 2011). The Swedish interest in stump harvesting started in 2005 during the cleaning-up activities after the hurricane Gudrun, but stump extraction has at most reached 2,000 ha per year in forests certified according to the standards of the Swedish FSC (Forest Stewardship Council). The modest Swedish activity can be explained by restrictions mainly being based on concerns about the lack of knowledge of the environmental consequences of stump harvesting (Swedish FSC 2011) but not the least the low economic return. Harvesting of stumps is a relatively costly activity that takes a lot of time and requires powerful machines, and yields are relatively small. In addition, the present market is currently flooded with forest fuel. Recent winters have been mild, and heating plants have had little need for wood chips.

Research on stump harvesting effects

In order to identify and fill existing knowledge gaps on the consequences of stump harvesting for biodiversity, soils, waters and greenhouse gases, the Faculty of Natural Resources and Agricultural Sciences at the Swedish University of Agricultural Sciences (SLU), together with the Swedish Energy Agency, launched the research programme ''Stump harvesting and environmental effects'' in 2007. The programme, which consisted of 15 research projects, took place in 2008-2011 and came to an end with the international symposium "Tree Stumps for Bioenergy – Harvesting Techniques and Environmental Consequences, held at SLU in Uppsala, Sweden, on 24-26 October 2011. The symposium resulted in two special issues on stump harvesting in the journals "Scandinavian Journal of Forest Research" in 2012 and "Forest Ecology and Management" in 2013.

Figure 1.1. Some of the persons participating in the synthesis meeting at SLU, Uppsala, on 30 September 2014.

Remaining research gaps

Despite this initial programme effort, there were many critical knowledge gaps in 2011 on the stump-removal effects on soil, climate and biodiversity. Therefore, a continuation of the research programme was started and run in 2012-2015 consisting of 14 research projects with grants from The Swedish Forest Agency, SLU and a number of FSC-certified forest companies.

The aim was to evaluate the climatic impact of stump harvesting in relation to soil, water and biodiversity. The practical aim was to provide a better scientific base than before for improved guidelines on where and how stump harvesting can be made in relation to environmental goals.

The second phase of the programme has been guided by a steering committee consisting of Hans Djurberg (SCA, chairman), Karin Fällman (Sveaskog), Henrik von Hofsten (Skogforsk), Anna Lundborg (Swedish Energy Agency), Stig Larsson (SLU, 2012-2014), Pär Forslund (SLU, 2014-2017), Pär Aronsson (SLU), Jenny Stendahl (Swedish Forest Agency), Cajsa Lithell (SLU, communicator) and Tryggve Persson (SLU, programme coordinator). To reach best possible coordination, the programme members have been invited to annual programme conferences and synthesis meetings.

The latter meetings were especially important to prepare the final conference on stump harvesting held at World Trade Center in Stockholm on 26 March 2015 with about 80 participants. Many of the presentations held during this conference have been published in special issues of Forest Ecology and Management (2016) and Scandinavian Journal of Forest Research (2017).

Figure 1.2. At the final conference on 26 March 2015 about 80 persons participated representing the Ministry of Environment and Energy, Swedish Forest Agency, Swedish Energy Agency, Swedish FSC, WWF, different forest companies, Finnish TAPIO and researchers from Sweden and Finland. Here during a coffee break.

Figure 1.3. The discussion during the final conference was chaired by Gustaf Egnell, SLU. The audience seemed to agree that there are no big obstacles to increase the intensity of stump harvesting in Sweden, with the exception of a certain risk for the diversity of beetles at moderate and high harvesting intensity.

The aim of the report

The budget for the second phase of the programme was 47.4 MSEK. In addition, the Swedish Energy Agency provided grants to another ten projects concerning stump harvesting amounting at 14.7 MSEK. In all 24 research projects with a total budget of 52.1 MSEK (almost 6 000 000 €) have worked towards a common goal to reach a scientific basis to evaluate pros and cons with stump harvesting. The aim with this report is to draw attention to the research, results and conclusions arrived at during especially the latter 4-year period.

2. THE FOREST SECTOR´S NEED OF UPDATED KNOWLEDGE OF STUMP HARVESTING

Karin Fällman (Sveaskog) and Jenny Stendahl (the Swedish Forest Agency)

The need for forest biomass will increase as we move into a future of bio-based economy. The results from the research programme will have an impact on the revision of the future guidelines for stump harvesting.

The demand for fuel chips from stumps has fluctuated over time and is currently low. Most observers do agree though that the need for forest biomass will increase as we move into a future bio-based economy. The interest in stump harvest will most likely increase again, given that stumps have a high fuel value. With new future technology, productivity in stump harvest can increase and contaminations be reduced leading to better fuel quality.

Today's "rule of the game" for stump harvest derives from the knowledge gaps that were identified in the early 2000s. After the big hurricane "Gudrun" in 2005, the question about stump harvest was raised again, this time as a source of bioenergy.

Within the forest certification scheme FSC (Forest Stewardship Council) stump harvest has been a controversial issue since the mid-2000s when commercial interest for stumps awakened and has been restricted in different ways since then. Swedish FSC considered stump harvest as a "non-proven activity", and to fulfil the criteria of a "proven activity", this organization required that the knowledge of the environmental consequences must be improved, especially about how stump harvesting affects biodiversity but also climate, soil and water. The FSC-certified companies have contributed to the thematic programme, mainly as landowner hosts, in order to fulfil the requirements.

In 2009 the Swedish Forest Agency presented guidelines for stump harvest, which were later incorporated in the Forestry Act. The guidelines were based, among other things, on the environmental impact assessment study of stump harvesting that some forestry companies submitted to the Agency in October 2008.

An important basis for the guidelines was that the Swedish Forest Agency then considered that stump harvest in the coming years would affect a limited area, about 10,000 to 20,000 hectares per year, which corresponds to 5 to 10 percent of the annual clear-cut area in Sweden. The effects on biodiversity was then supposed to be limited, provided that the guidelines were followed, while the effects on the climate were expected to be positive as stumps could replace fossil fuels.

The Swedish Forest Agency, however, noted that in several areas there were gaps in knowledge, for example concerning biodiversity. It was unclear what would happen if the stump harvest activity increased and thereby affected a larger proportion of the landscape. There was a lack of any sort of threshold for how many stumps could be harvested without a clear negative impact on biodiversity. A further question mark concerned the risk of leakage of methyl mercury to downstream waters. The Swedish Forest Agency´s recommendations were based on a precautionary approach.

During 2012 and 2013, the Swedish Forest Agency did a monitoring of compliance with the guidelines (Drott and Stendahl 2016). The result of the monitoring, along with the recent scientific results of the environmental effects of stump harvesting that came up in the research programme, constitute an important input for the Swedish Forest Agency when the guidelines are to be revised.

3. TREE STUMPS FOR BIOENERGY IN SWEDEN

Anna Lundborg (Swedish Energy Agency)

It is important to receive scientific evidence of how stump harvesting affects biodiversity, greenhouse gases, soil conditions and global climate both in the short and in the long term.

In 2013, 129 TWh of bioenergy were used in Sweden, which can be compared with the total energy consumption of 375 TWh. The contribution of bioenergy has the potential to further increase. Stumps have so far been used as bioenergy at a very small scale, but their potential is much greater (up to 20-30 TWh).

Why use bioenergy?

More than 80 percent of global energy supply currently comes from coal, oil and natural gas. The use of these fossil fuels must be drastically reduced to reach the goal of limiting global warming to less than 2 °C compared to pre-industrial levels according to the Paris agreement in 2015, and renewable energy can make an important contribution.

Sweden has very good natural conditions for renewable energy. Figure 3.1 shows that hydro power is important. Wind and solar power are growing but still make a small contribution. But the figure particularly shows that bioenergy provides the largest and still growing proportion of Sweden’s renewable energy.

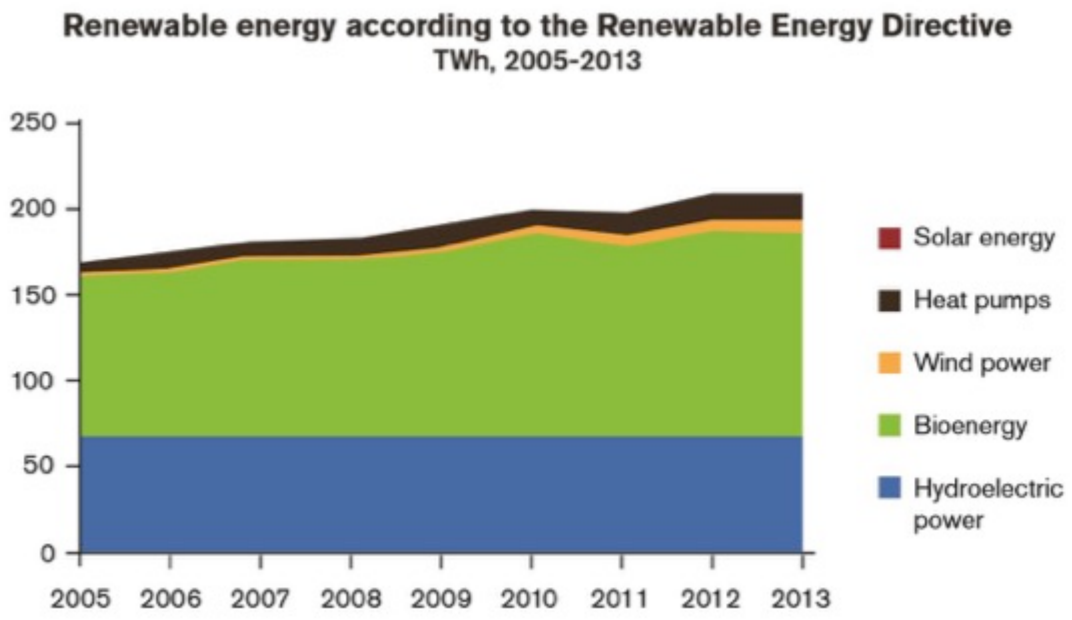

Figure 3.1. Today stumps are used for energy purposes only to a limited extent in Sweden, mainly because of the poor economy, but also due to uncertainties of the environmental impacts of stump harvesting.

In 2013, 129 TWh of bioenergy were used in Sweden, and there are realistic possibilities to further increase the supply and use by another 70-90 TWh. This can be compared with the total energy use in Sweden of 375 TWh in 2013. The energy supply was 565 TWh, and the difference between supply and use can mainly be explained by transmission and conversion losses, particularly in nuclear power generation.

Bioenergy is currently the largest energy source for heating in Sweden. In combined heat and power production (CHP), electricity can be produced simultaneously with district heating, and this is a very resource efficient way to use biomass. Biofuels can also be used to replace fossil fuels in industry and in the transport sector.

Domestic bioenergy also offers other social benefits, such as employment, security of supply, rural development and some environmental benefits in addition to climate benefits.

Thanks to bioenergy, Sweden has already reached the set EU target on renewable energy of at least 49% renewable energy by 2020. The national target is even higher, with a set target of 50% of total energy use.

Research on the environmental effects of stump harvesting

Stumps are currently used only to a limited extent for bioenergy. This is mainly explained by low prices on biomass, and stumps need higher prices to be competitive on the bioenergy market. In addition, previous uncertainties about the environmental effects of stump harvesting have also affected stumps as an energy source (Figure 3.2).

According to the Swedish Forest Agency (Report SKA VB 08), 20-30 TWh of stumps may become available after "standard environmental restrictions". Therefore, during 2008-2015 the Swedish Energy Agency funded research on the environmental impacts of stump harvest, especially in the research programme presented in this report.

The aim has been to clarify the issues relating to biodiversity, soil, water and climate effects. A general question has been how much stumps can be harvested without aggravating the work to achieve the Swedish environmental objectives, goals that are crucial to welfare, and intended to guide the Swedish efforts to safeguard the environment.

The research has been successful, and we have now a much firmer basis for Swedish guidelines on stump harvesting to meet the sustainability requirements.

The knowledge can also be used in international negotiations on sustainable bioenergy, such as in the EU, in standardization activities and in voluntary certification systems.

To secure the quality and meet processes in the EU regarding sustainable forestry and sustainable bioenergy, it is imperative that the research results are published scientifically so that they are accessible to a larger international audience. By summarizing results in a report like this an even broader dissemination is reached.

Figure 3.2. Today stumps are used for energy purposes only to a limited extent in Sweden, mainly because of the poor economy, but also due to uncertainties of the environmental impacts of stump harvesting.

EU regulations can affect the use of stumps for energy

The EU currently has sustainability criteria for bio-based gaseous and liquid fuels, and these have been incorporated into Swedish law. It is now being discussed also to introduce sustainability criteria for solid biofuels, and they may affect the possibility to use stumps as biofuel.

An important sustainability criterion is that bioenergy must have "sufficient climate benefit" compared to fossil alternatives. Emissions during collection and transportation and conversion shall be included in the calculations. For the sake of completeness, the impact on ecosystem carbon balances and fluxes of greenhouse gases can also be included, as well as the effects of land use change. Likewise, it could be needed to show how long it takes from the carbon dioxide emissions from combustion of stumps has been offset by the emissions that would otherwise have occurred when the stumps were decomposed in nature.

There is an ongoing intense debate among scientists about the principles of how the climate impact of bioenergy is to be calculated, and these discussions can affect the political positions. Therefore, it has been important to receive scientific evidence of how stump harvesting affects forest carbon balances in the short and long term.

4. STUMP HARVEST – METHODS AND MARKET SITUATION

Henrik von Hofsten (Skogforsk, the Forestry Research Institute of Sweden)

After lifting of the stumps, the stumps (including coarse roots) will be shaken and divided into 2-4 parts so that stones and soil will easier fall off. Here the sandy soil is still attached to the roots, but it will successively fall off during the storage in piles on the clear-cut.

Stump harvesting has so far mainly been carried out with a technology from the 1970´s. The stumps are lifted with large excavators and the soil is often largely disturbed. "The dream" is to produce a light-weight aggregate that cuts the root-legs and then lifts the exposed stump without damaging the surrounding soil. But this aggregate is still to be invented.

Stump harvest or stump removal has been practiced in Scandinavian forests since the Middle Ages. Up until the mid-1970s, mainly pine stumps were removed with iron-bars, spades and winches, to extract pine tar. In the early 1970s, there was a concern that the pulp industry would soon have problems with wood supplies, and attention turned to the possibilities of using stumps, primarily spruce, for pulp chips.

Figure 4.1. The Pallari 160 is a commonly used head for stump extraction in both Sweden and Finland. Two teeth grasp the stump from one side while a sharpened knife exerts pressure and cracks the stump from the other.

The stump harvesting heads developed around that time are still in use today, even if some subsequent development has taken place. Broadly speaking, these conventional heads are based on powerful grapple pliers fitted on a crawler excavator, which are used to break and pull up the stump (Figure 4.1). The method works relatively well, but requires great force, regardless of whether the force is applied vertically or laterally and usually causes significant ground damage. The great technological challenge lies in the fact that stumps and roots have evolved over hundreds of thousands of years to resist breaking forces in all directions.

The hope is that a head can be developed that cuts the roots sufficiently far out from the stump and lifts it without unnecessary soil impact. The head should also be light and easily manoeuvrable so it can be handled by a forwarder crane, and it should clean and split the stump without causing vibrations in the machine. In the past decade, some technical developments have taken place, but there is still some way to go before the ideal head sees the light of day (Figure 4.2).

In the experiments to examine the environmental effects of stump harvest described in this report, virtually only the traditional technology has been used, where great force is used to drag or break up the stumps. Soil impact, and therefore potential environmental impact, is considerable.

Figure 4.2. The TL-GROT AB stump head cuts the roots close to the stump and then lifts both the stump core and the coarse roots. Unfortunately, R&D momentum was lost before the head was fully developed, so it has not yet come into production.

After the stumps have been lifted, they are normally split into 2-4 parts to reduce their bulk and to facilitate drying and decontamination. The excavator shakes the stump parts to remove most of the contaminants before piling the stump parts on the clear-cut. The stumps often lie there for several months, sometimes over the winter, before they are accumulated and forwarded to roadside. The stump parts are then usually loaded onto a truck and driven to a heating plant for comminution and incineration. In some cases, stumps are comminuted on the landing to densify the load and thereby reduce transport costs. Furthermore, some contaminants will be removed during the process.

Unlike round-wood, the stump parts are often stored for some time before transport to the heating plants. The main reasons for this storage process are that rain, melting snow and sun cause the contaminants to drop off, and the stump wood has time to dry out. One advantage of stump wood is that it does not readily remoisten once it has dried, so stump parts, unlike logging residue, can lie on the ground for several years without any significant loss of quality and quantity. This storage property makes stumps suitable as a backup for intermittent renewable energy sources like wind power. However, the storage time on the clear-cut has been shortened, as both research and experience have indicated that the material dries and contaminants are removed just as effectively in large piles on the roadside. This leaves the clear-cut free for replanting, but one disadvantage is that roadside piles can serve as ecological traps for some insect species (see Jonsell et al., this report).

At present, stump harvest has virtually come to a standstill in Sweden. There are several reasons, but all of them ultimately come down to poor profitability. Harvesting stumps is a relatively costly activity that takes a lot of time and requires powerful machines, and the profit is relatively low. A total cost of around SEK 180 per MWh at the industry gate is not uncommon, while the price of wood chips was SEK 180-190 per MWh in June 2015.

Environmental organisations are also very sceptical, which has led to very strict restrictions on the scale of stump harvest from the Swedish FSC (Forest Stewardship Council). Another problem is that the market is currently flooded with forest fuel. Recent winters have been mild, and heating plants have had little need for wood chips. At the same time, the pulp industry has been forced to cut down on its production, so a large quantity of unused pulpwood is currently available for the heating plants. Roundwood is always cheaper to fell and handle than logging residues, stumps and small-dimension trees. Finally, there is a big supply of other 'biofuels', such as recycled wood and household waste, and these are cheap for heating plants equipped with adequate purification facilities.

However, the heating value of appropriately handled stump chips is greater than that of logging residues, and in another political or market situation the trend could quickly be reversed. It should also not be forgotten that bio-based products, based on cellulose and/or lignin, are being developed at a rapid rate today. If this development progresses from today's experimental level to full-scale production, the demand for wood from Swedish forests will once again rise.

5. WHAT IS THE CLIMATE IMPACT OF USING STUMPS FOR BIOENERGY?

Johan Stendahl (SLU, Uppsala), Torun Hammar (SLU, Uppsala), Per-Anders Hansson (SLU, Uppsala) and Carina Ortiz (Statistics Sweden, Stockholm)

To determine the climate impact of using stumps for energy, a holistic perspective is necessary. Life cycle assessments (LCA) are used to estimate greenhouse gas emissions from the entire energy system and the impact on the climate can be calculated.

Energy from stumps will immediately have a lower climate impact than fossil coal. Compared to natural gas, which has lower greenhouse gas emissions per unit of energy than coal, it will take 10-20 years before the climate impact becomes lower for stumps. Thereafter stump energy becomes increasingly favorable due to the fact that the stumps - a source of greenhouse gas emissions - have been removed from the forest.

When stumps are harvested and used for bioenergy the emissions of greenhouse gases will be influenced in several ways. Besides the emissions from the combustion, there will be emissions occurring from stump lifting, comminution and transport. The greenhouse gas emissions from the forest ecosystem will also be affected. An assessment of the climate impact of bioenergy from stumps must be based on life cycle approach, where all greenhouse gas emissions associated with the energy production are included and a comparison with alternative energy sources is made.

From stumps to energy

The procurement of stumps as forest fuel requires different energy inputs - the largest proportion is consumed during stump lifting (about 40%), followed by collection / chipping (about 33%) and transport (25%) (Lindholm et al. 2010). The total energy input is minor, though, amounting at about 4% compared to the energy contained in the harvested stumps. Residue-based forest fuel, such as stumps or branches and tops, are usually not burdened with emissions from the energy consumed during final felling, which instead is allocated to the timber production. During energy production at heating plants, the energy efficiency is slightly lower for forest fuel than for fossil fuels; about 86% compared with 88% for coal and 90% for natural gas (Gode et al. 2011). However, the energy efficiency of forest fuels (and natural gas) can be improved by flue gas condensation technology, whereby the energy in the flue gases is recovered, and efficiencies of approximately 106% and 104% can be reached (Uppenberg et al. 2001). In plants that only produce electricity, lower efficiencies are achieved compared to heat production; about 33% for forest fuels, 44% for fossil coal and 53% for natural gas (Gode et al. 2011).

What happens in the forest ecosystem?

Stump harvesting involves the removal of a source of greenhouse gas emissions from the forests, since the harvested stumps otherwise would have decomposed and released their stored carbon as carbon dioxide. However, the decomposition of stumps is a slow process and the carbon in the stumps remains in the ecosystem longer than for example the carbon in branches and tops. In addition, soil disturbance may lead to increased turnover of soil carbon, but results from field trials show that this effect is limited and transient (Mjöfors et al. 2015; Pumpanen et al. 2004).

Calculation of climate impact

When calculating the climate impact of energy systems you need to make a life cycle analysis (LCA), where all greenhouse gas emissions throughout the entire production chain are included. For stump energy systems you need to include emissions from harvesting, collection, chipping, transport, combustion, and changes in forest carbon balance. In a managed forest landscape the LCA calculations are done for a stump scenario and a "reference scenario" without stump harvesting, where the stumps are left to decay in the forest and another source of energy is used. The reference scenario is necessary to analyze the consequences of introducing stump harvesting for energy purpose. One important difference between the two scenarios is that the emissions from the combustion of stumps in the stump scenario occur instantly, while emissions from the decaying stumps in the reference scenario are distributed over time (see above). During combustion the release of carbon dioxide from the stumps thus occurs in advance, and the difference between the two scenarios will decrease over time as the stumps that are left in the forest decay. By applying a time-dependent LCA, which estimates the annual emissions over time, the variations in net emissions are captured.

Using ecosystem models (the Heureka and Q models) that describe development of the forest carbon stocks combined with LCA methodology, the climate impact was estimated for energy systems based on stumps of spruce for three regions (Ortiz et al. 2016; Hammar et al. 2015). This report presents results from southern Sweden (Jönköping County).

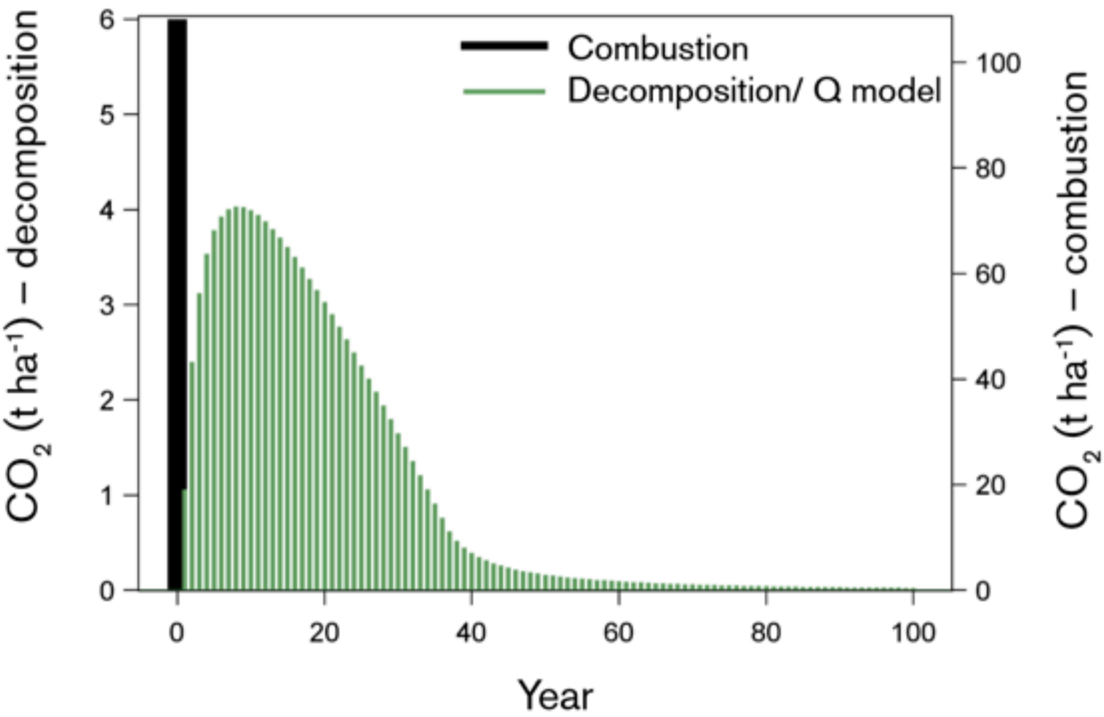

Figure 5.1. Combustion of stumps means that the CO_2 emissions from stumps occur earlier than in the case when they are left in the forest to decompose. The graph gives an example from a spruce forest in southern Sweden. Note the difference in scales of the Y-axes.

Results

The decomposition rate of stumps according to the Q model is initially low but increases significantly after about 5-10 years (Figure 5.1). The climate impact of stump energy from a single harvest reaches a maximum after 10-15 years, but then declines sharply (Figure 5.2, "Climate impact of a single harvest of stumps"). The declining effect on the temperature is because the emissions from stump combustion are compensated for by the emissions that would have occurred if the stumps had been left to decompose in the forest.

Initially the climate impact of natural gas is slightly lower than for stump energy, but from about 12 years onwards the climate impact of the stumps is lower. However, when stumps replace fossil coal an immediate climate benefit is achieved.

During continuous supply of stumps (every year) from a forest landscape, the pattern is similar although the climate impact from stump energy becomes larger relative to the fossil systems (Figure 5.2, "Climate impact of continuous supply of stumps"). However, unlike the fossil alternatives the climate effect of stump energy levels out, which means that the climate benefit increases steadily over time. The time before stump energy becomes more advantageous than natural gas is slightly longer, about 22 years, compared to the single harvest case. When stumps replace fossil coal, an immediate climate benefit is achieved, as well.

The results also show that the climate impact per extracted amount of energy is slightly higher in northern compared to southern Sweden (Ortiz et al. 2016), which prolongs the time before climate benefit is achieved compared with natural gas by 2-4 years. Further, in northern Sweden a larger area is needed to produce the same amount of fuel.

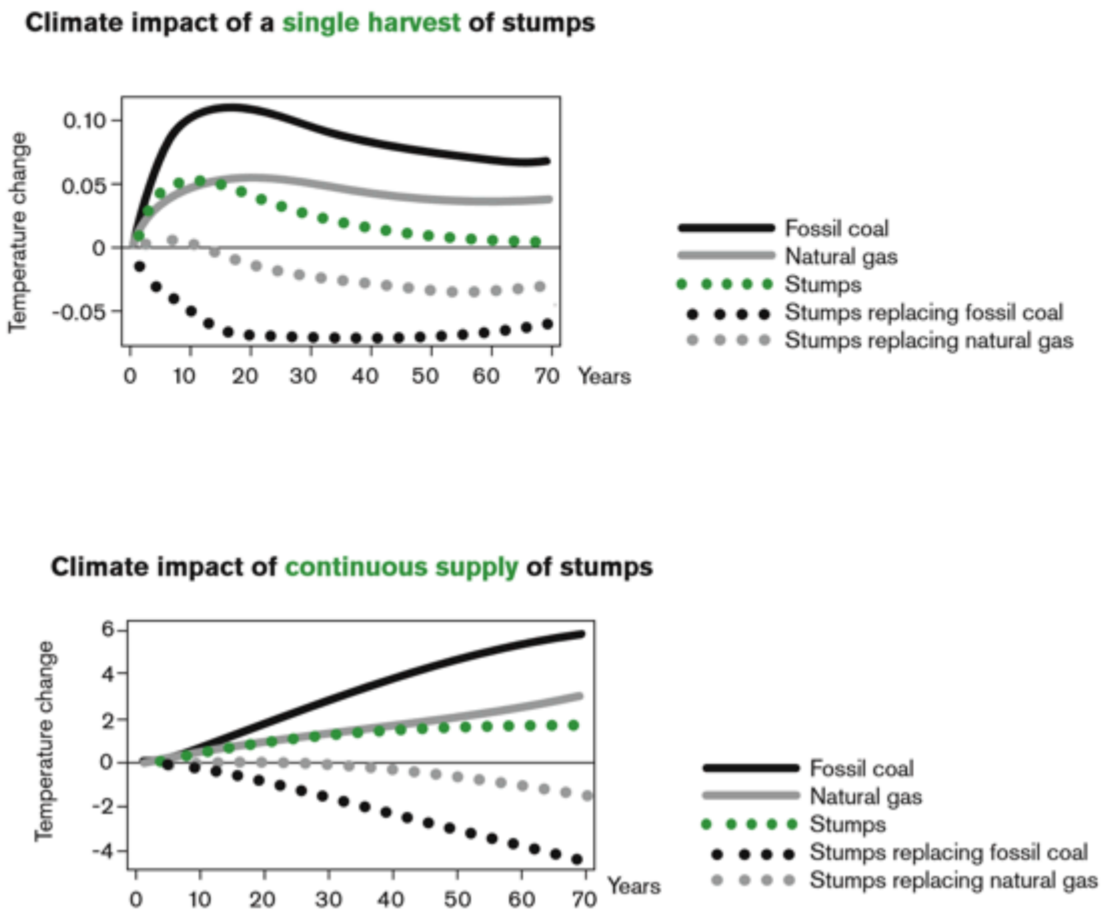

Figure 5.2. The impact on the global average temperature of bioenergy from a single harvest of stumps (upper diagram) and for continuous supply (lower diagram) compared to fossil coal and natural gas in southern Sweden [unit: femto (10^{-15}) Kelvin degrees per MJ]. Where the stump energy curves fall below the curves of the fossil alternatives, stump energy is more beneficial from a climate perspective. The substitution curves correspond to the net impact of bioenergy when replacing fossil fuels.

Conclusions

Utilizing stumps from production forests for energy provides a climate benefit when substituting fossil fuels, also within a shorter time horizon of approximately two to three decades. The climate impact of stump energy declines substantially over time, taking into account that the stumps otherwise would have been left in the forest to decompose. Regional differences in climate impact for the same amount of produced energy are small. The temporal variation in climate impact is large, which highlights the importance of using assessments based on time-dependent LCA methodology.

Facts

Greenhouse gases emitted into the atmosphere will gradually decay or be assimilated into the oceans and land ecosystems. Remaining greenhouse gases will influence the climate by altering the radiation balance (measured by radiative forcing) and as a consequence a larger amount of energy is retained and heats the atmosphere. Based on the annual radiative forcing, the effect on the global atmospheric temperature can be estimated (Ericsson et al. 2013) using functions based on atmospheric circulation models. Due to the inertia of the atmosphere there will be a time lag in the effect on the temperature. In this study, the absolute change of the atmospheric temperature was used as climate metrics.

6. STUMP HARVEST EXPERIMENTS IN SWEDEN

Monika Strömgren (SLU, Uppsala), Bengt A Olsson (SLU, Uppsala), Achim Grelle (SLU, Uppsala) and Anders Lindroth (Lund University)

A site for studies using the eddy-covariance technology from towers. The "breath" of the entire ecosystem, i.e., the uptake of carbon dioxide by photosynthesis and the loss by respiration is recorded with high time resolution.

Most of what we know today about environmental impact of stump harvesting in Sweden comes from four large experimental series with a total of 33 field experiments. In addition to those, there are four single site experiments. The earliest experiments are from the late 1970s. In this report, most results are presented in the following chapters. However, some results from the newest experiments established in 2013-2015 are presented in this chapter.

Field experiments are invaluable in order to examine environmental effects of various forest management practices. By studying these we can investigate the consequences of a certain method and validate our models, hypotheses and concerns. During the 1970s there was considerable interest in stump harvesting, which even resulted in two series of stump harvest experiments that were established by Lars Kardell and Bo Leijon, both at SLU, in the late 1970s and early 1980s. Despite a lack of interest for stump harvest during the following decades, the experiments have been maintained. When the interest increased again in the beginning of the new century, these series could be used to examine the environmental implications of stump harvest after 30 years. At this time, there was also a need for new field experiments, more adapted to the issues and methods used today and to be able to examine the effects during the first years after stump harvest. Therefore, three experiments were established in 2007-2009 in the sites Stadra and Norunda in central Sweden and Fågelfors in southern Sweden to examine the impact on the carbon dioxide balance during the first years after stump harvesting. Some years later (2013-2014), two new experimental series were established to investigate if the results from the earlier experiments could be generalized for Swedish forests and forestry.

One of the new series was initiated by Bengt Olsson and Monika Strömgren at SLU. This series comprised 14 experiments all over Sweden. The aim with the series was to follow effects of stump harvest and site preparation on trees and soil during a long period. The experiment series is included in Silva Boreal (see fact box) which guarantees that the experiments are documented, data are archived, and that the experimental plots can be located in the future.

The other experimental series, established by Achim Grelle, SLU, consists of five experimental sites. Each experiment includes a fairly large area, making it possible to monitor large-scale processes. Two of these experiments are using the same sites as the experiments within the Strömgren-Olsson series.

The location of experiments in the series is shown on the map in Figure 6.1.

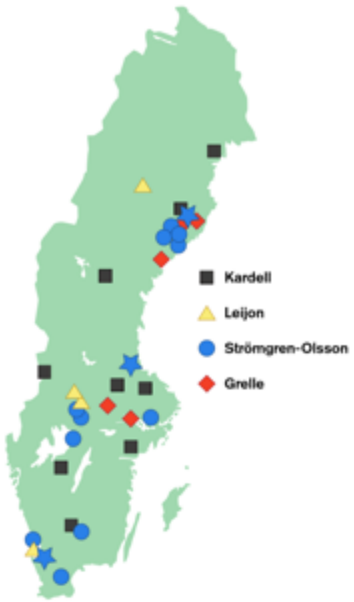

Figure 6.1. Four series of stump harvest experiments established by Lars Kardell, Bo Leijon, Bengt Olsson/Monika Strömgren and Achim Grelle. Blue stars refer to the main experiment in the Strömgren-Olsson experimental series.

Kardell´s series of experiments

During 1978-1979, professor Lars Kardell at SLU established a series of experiments with the main objective of investigating how the ground vegetation, berry production and tree production will be affected by stump harvest (Kardell 2010). These experiments have also been used to examine effects on carbon stocks in soil and biomass (Jurevics et al. 2016).

Experimental sites: 9
Treatments: 4 (control, slash harvest, stump harvest, stump and slash harvest)

Experimental design: Treatment in 40 × 40 m plots replicated in two blocks per site.
Other facts: All treatments were subjected to mechanical site preparation before planting.

Leijon's series of experiments

Bo Leijon at SLU established a series of experiments during 1981-1983 in order to examine the long-term effects on tree growth. The experiments have also been used to examine how carbon stocks in soil and biomass are affected by the different treatments (see Strömgren et al. 2013).

Experimental sites: 4
Treatments: 3 (control, stump harvest, stump and slash harvest)
Experimental design: Treatment in 35 × 35 m plots replicated in four blocks per site.
Other facts: All treatments were subjected to manual patch scarification before planting.

Strömgren – Olsson's series of experiments

During 2013-2014, fourteen site preparation and stump harvest experiments were established by Bengt Olsson and Monika Strömgren, both at SLU. The aim with the series was to monitor the effects of site preparation and stump harvest on carbon and nutrient stocks in soil and biomass, but also to study the effects on establishment of tree seedlings, biomass production, vegetation development, and soil acid-base ratio. During the first years, basic documentation about the experiments was performed, and the effects on seedling establishment and greenhouse gas emissions (carbon dioxide, methane and nitrous oxide) from the soil were monitored (see Strömgren et al. 2016, 2017).

Experimental sites: 14 (3 main sites and 11 basic sites)
Treatments: 4 for the main sites (control, patch scarification/mounding, disc trenching, stump harvest, see Figure 6.2) and 3 in the remaining sites (control, patch scarification/mounding or disc trenching, stump harvest).
Experimental design: Treatment in 30 × 30 m to 40 × 40 m plots replicated in four blocks at each main site and three blocks in the remaining 11 experiments.
Other facts: Slash harvest was carried out on all plots before treatment. At most stump-harvested treatments complementary scarification was made if necessary, i.e. in places where stump harvest did not result in a sufficient amount of planting spots. This was done at the same time as the stump extraction with an excavator. However, at two sites, the stump-harvested treatments were subjected to ordinary disc trenching at a later date. No site preparation was carried out on the control treatment.

Figure 6.2. The main experiments in the Strömgren-Olsson series of site preparation and stump harvest experiments include four different treatments: a control without site preparation (upper left), stump harvesting (upper right), mounding (lower left) and disc trenching (lower right).

Grelle´s series of experiments

During 2014-2015, a series of five stump-harvest experiments was established by Achim Grelle at SLU, in order to examine how the carbon dioxide balance is affected by stump harvest. The studies were carried out with eddy-covariance technology from towers. Hence, the "breath" of the entire ecosystem, that is the uptake of carbon dioxide by photosynthesis and the loss by respiration, can be monitored with a very high time resolution. The measurement technique requires that the treatments cover at least a radius of 50 m around each tower.

Experimental sites: 5
Treatments: 2 (control, stump harvest)

Experimental design: The two treatments have been placed in separate parts of the site with similar conditions.
Other facts: Slash harvest was performed on all plots before treatment. The control was subjected to site preparation (patch scarification/mounding or disc trenching). On stump harvested plots, complementary site preparation has been performed if necessary at the same time as stump extraction (1 site) or by mechanical site preparation on a later occasion (4 sites).

Other stump harvest experiments

Stadra: Plot experiment established nearby Nora, central Sweden, in 2007. The experiment consists of two treatments (stump harvesting and mounding) in 50 × 50 m plots replicated in three blocks. In addition to the study of emissions of carbon dioxide from the soil during the first few years, the carbon dioxide balance at the stump harvest treatment was also monitored by eddy-covariance technology from a tower (see Strömgren et al. 2012; Grelle et al. 2012).

Karlsheda: Plot experiment in Småland (southern Sweden), where the effects on carbon dioxide emission from the soil were examined for one month after stump harvesting (3 plots) and compared with untreated control plots (2 plots). The experiment was part of a project work by the SLU student Björn Holmström (2008, see also Strömgren et al. 2012).

Fågelfors: Plot experiment in Småland (southern Sweden), which was established in 2009 by Monika Strömgren, SLU. It consists of three treatments (patch scarification, disc trenching and stump harvesting) replicated in three blocks. Carbon dioxide emissions from the soil-surface were followed for two years after treatment (see Strömgren and Mjöfors 2012)

Norunda: Stump harvest experiment established on a clear-cut in Uppland in 2009 by professor Anders Lindroth at Lund University. The clear-cut was divided into four areas, whereof two were subjected to stump harvest. Patch scarification was implemented on the entire clear-cut. Continuous measurements of the fluxes of carbon dioxide, methane and nitrous oxide have been monitored via towers from each area of the clear-cut (see Sundqvist et al. 2014).

Short-term results from the Strömgren-Olsson series

Stump harvesting results in disturbed soil surfaces and an intermixing of topsoil and subsoil materials. In a study of 14 clear-cut sites all over Sweden, Strömgren et al. (2017) found that, on average, 70% of the soil surface area was disturbed by stump harvesting and following scarification (Figure 6.3). Harrowing, which is a standard site preparation method in Sweden, and mounding had significantly lower levels of soil-surface disturbance with 54% and 40%, respectively. The study also showed that some soil disturbance had occurred also in "intact" control plots, where 10% of the soil was disturbed particularly by ruts after stem-only harvesting.

The same stump harvesting and site preparation study (Strömgren et al. 2017) showed that plots with stump removal or site preparation had 12% lower carbon dioxide emissions in the first year after treatment compared to the undisturbed soil, whilst by the second year there were no differences. See also Chapter 8.

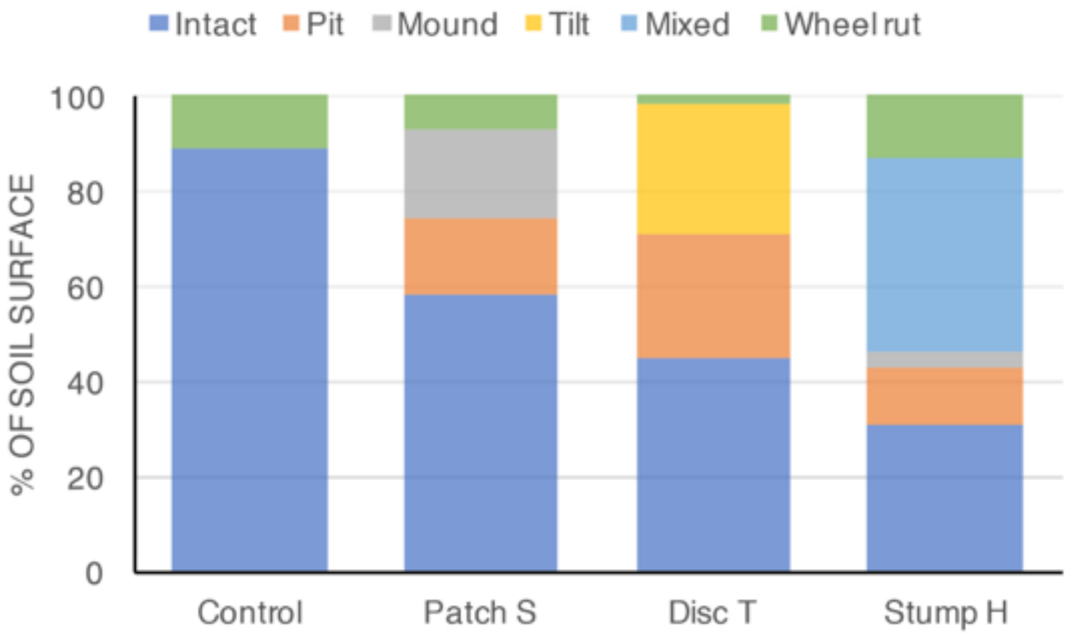

Figure 6.3. Average coverage of soil disturbance types (% of total soil surface) in each of the treatments: undisturbed (Control), patch scarification (PatchS), disc trenching (DiscT), and stump harvesting (StumpH). The average includes data from all 14 experiment sites. Graph from Strömgren et al. (2017).

SilvaBoreal

SilvaBoreal is a Swedish database of forest field experiments. It is owned by SLU and maintained by the Unit for Field-based Forest Research. Its primary purpose is to increase the availability of the information related to the field experiments and demonstration areas in Sweden.

Web: www.silvaboreal.com

7. ARE SOIL CARBON STOCKS AFFECTED BY STUMP HARVESTING?

Bengt A Olsson (SLU, Uppsala), Monika Strömgren (SLU, Uppsala), Riitta Hyvönen (SLU, Uppsala), Achim Grelle (SLU, Uppsala), Michael Freeman (SLU, Uppsala), Gustaf Egnell (SLU, Umeå) and Tryggve Persson (SLU, Uppsala)

Burning of fossil fuels means that carbon dioxide is emitted from both the fossil fuels and the decomposing stumps remaining in the forest. The great advantage of replacing fossil fuels with stump bioenergy is that the carbon stored in fossil fuels will be maintained and not emitted as CO_2.

Harvesting of stumps and coarse roots means an immediate loss of carbon from the soil carbon pool, but the difference in carbon stocks between stump-harvested sites and those where stumps are retained diminish gradually as retained stumps and roots decompose. Model studies indicate that stump harvesting could lead to some carbon reduction in the soil, but most empirical studies on well-drained upland soils have not been able to show any effect on soil carbon stocks in the long term (35 years). However, there is evidence that stump harvesting leads to reallocation of carbon from the humus layer to deeper soil layers.

Forest soil carbon is tied up in dead organic matter and is the result of two processes that balance each other - on one hand, the supply of organic material from growing vegetation and trees including dead foliage, roots, woody litter and fungal hyphae and on the other hand decomposition. The entire stock of carbon is in the form of organic compounds at varying degree of decay and age - from fresh litter to century-old humic residues. Forest soil nitrogen (N) stocks mostly consist of nitrogen organically bound to that carbon.

Seen in a global perspective, the organic soil carbon stocks are very large, and a loss of the entire soil carbon to the atmosphere would mean a significant increase in atmospheric carbon dioxide levels. However, a continuous turnover of soil carbon is necessary to release the nutrients that are bound in organic matter, which is essential for forest production and thus the supply of new carbon into the soil.

The advantage of using biofuels such as stumps and other residues from forestry operations, instead of fossil fuels, is that these crop residues emit carbon dioxide even if they are left in the forest. The difference is that carbon dioxide is instantaneously emitted when burnt but slowly emitted from logging residues in nature. The expected effect is that soil carbon and N stocks slightly decrease after the harvest of logging residues and stumps, simply because the more organic substance we harvest, the less remains. It has been shown with models that when stump harvest is introduced in a landscape with forests of different age classes, the total carbon stocks in the soil is slightly reduced at first, but the decline stops with time and a new equilibrium is reached (Eliasson et al. 2013)

Many models have calculated the effect of stump harvesting on carbon stocks based on the assumption that the supply of dead organic matter to the soil decreases after the stump harvest, but that the decomposition rate of soil organic matter is unaffected. On the other hand, it has been suspected that the mixing and disturbance of the soil profile that occurs at stump harvesting or mechanical site preparation could increase the decomposition rate. If there really is such an effect, it would be expected that soil disturbance from stump harvesting leads to a greater reduction in carbon stocks than earlier models have predicted. Such an effect would reduce the value of the stumps as biofuel in a climate perspective.

Many field trials

Several projects involved in the present research programme have investigated the effect of stump harvesting on soil carbon stocks, and there are also results from previous studies that have provided some answers. The studies can be divided by type and age of trial. New field experiments have been established since 2012 in 14 different locations in Sweden with the aim to compare the impact of stump harvest with that of mechanical site preparation (a common practice in Sweden) at different climatic conditions. We have also investigated two series of field experiments featuring stump and forest residue harvesting in different combinations that started in the late 1970s and early 1980s. There are also studies of stump harvesting conducted at a commercial scale. In central Finland, stump harvesting began in a large scale in the early 2000s, and survey studies on these sites have given us insight into the effects after a decade.

The reference situation is important

The question posed in the headline - what is the impact of stump harvesting on soil carbon stocks - can only be answered by a comparison with a reference case. The most realistic comparison given current forestry practices in the managed forest landscape of the Nordic countries is clear-felling, where stems and forest residues (slash), but not stumps are harvested, and where mechanical site preparation in any form is implemented. Since slash constitutes a physical impediment when stumps are harvested, slash is normally harvested together with stumps. Thus, a scenario where stumps are harvested but not the slash is not realistic today, but has been studied in some field trials.

New field experiment

When disregarding carbon in stumps and roots, we have not seen any immediate impact of harvesting stumps on soil carbon stocks (i.e., in the soil organic matter and fine litter) in recently established experiments. However, a short-term effect on this carbon stock is not anticipated, but stump harvesting can result in a reallocation of the soil carbon with a reduction of carbon stocks near the soil surface and increasing stocks in deeper soil layers. In the new experiments, there was a tendency of lower carbon concentration in the humus layer and higher concentration in the mineral soil following stump harvesting, but the difference was not statistically significant (Figure 7.1).

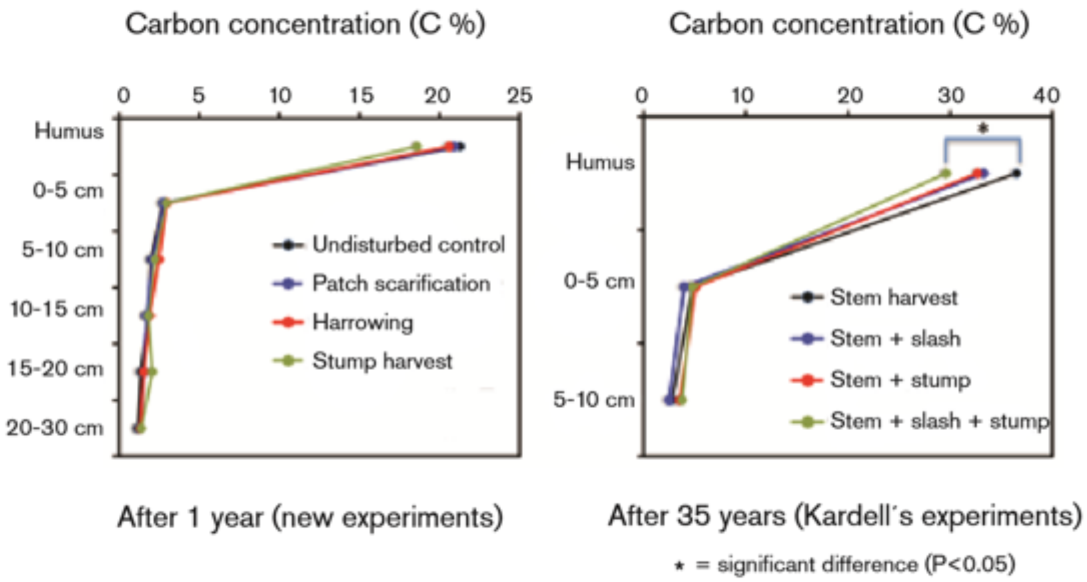

Figure 7.1. Soil carbon concentration (% C of dry weight) of about 1 (left) and 35 (right) years after different forms of site preparation and biomass harvest. Data taken from two different series of field trials with different treatments in Sweden. In the new experiments, where slash was harvested in all treatments, stump harvesting was compared with different site preparation methods. In the older series of trials established in the late 1970s by Lars Kardell, the effect of different combinations of harvesting slash and stumps were compared. Mechanical site preparation was performed in all treatments. The only statistically significant difference (*) was in the humus layer after about 35 years (Olsson and Strömgren 2016).

Ten-year-old studies in Finland

In ten-year-old practical clear-cuts with mechanical site preparation in Finland, there was no statistically significant difference in soil carbon stocks between sites with or without stump harvesting. However, carbon stock mean values were slightly lower on stump-harvested clear-cuts than on clear-cuts with site preparation only, suggesting a weak effect (Hyvönen et al. 2016). As for the new Swedish trials, the carbon stocks studied here did not include stumps and coarse roots in the comparison.

Twenty-five year-old trials in Sweden

In a study of four field trials 25 years after harvesting, carbon stocks in the upper soil layer and the total stocks in both soil and forest, biomass was lower on treatments with stump and slash harvest than in treatments with only stem harvest (and in this case without mechanical site preparation) (Strömgren et al. 2013). In addition, there was no difference in soil carbon stocks between stem-only harvest sites, and sites where slash was left on sites but stems and stumps were harvested.

Comparisons 20-30 years after stump removal in central Sweden

In the 1970s and 1980s, stumps were harvested at a commercial scale in the provinces of Uppland and Gästrikland in central Sweden with the aim of supplying wood biomass to a local pulp mill (Mackmyra near the city of Gävle). A comparison of the carbon stocks in stump-harvested sites and sites with mechanical site preparation was made 20-30 years after the stump harvesting by Persson et al. (2017). They found no difference in carbon and nitrogen stocks in the soil profile as a whole, but in the stump-harvested sites the amount of carbon in the humus layer was significantly lower than in sites with site preparation only. Conversely, there was a tendency for higher carbon contents at large soil depths in the stump-harvested sites, which showed that stump harvesting provides increased mixing of soil layers compared with mechanical site preparation.

Kardell´s 35-year-old experiments

The most long-term data on effects of stump harvesting in Sweden – after about 35 years - are based on experiments established in the late 1970s by Lars Kardell. These trials compared the effects of slash and stump harvest, separately and in combination, and included mechanical site preparation in all treatments (Jurevics et al. 2016). No significant effects of stump harvesting on total soil carbon stock (this estimate also included the carbon in tree stumps and coarse roots) were found. Additionally, Olsson and Strömgren (2016), also using the Kardell experiments, found that the carbon concentration in the humus layer was significantly lower after stump and slash harvesting than after stem-only harvest, which can be interpreted as a higher admixture of mineral soil in the humus layer caused by the soil disturbance (Figure 7.1).

Trials with deep ploughing

In the late 1980s, Örlander et al. (2002) started two trials, one in northern and one in southern Sweden, with stump harvesting combined with deep scarification with a deep-going plough for land reclamation (northern trial) and an excavator (southern trial). The entire soil profile was largely affected with the organic layer partly found at 50-60 cm depth in the mineral soil. The treatment was compared with stem-only harvest and manual site scarification (patch scarification). More than 20 years after the treatment, significantly lower carbon and N stocks were found in the soil in the northern trial, but not in the southern trial. In both experiments, tree growth was higher after stump harvesting, and the greater growth resulted in faster litter production which partly offset the negative effect of site preparation and stump harvesting on carbon and N stocks in the soil (Egnell et al. 2015). The intense site preparation applied in these trials reached deeper soil layers and affected the whole surface area, which is not the case with conventional site preparation methods. The experiment revealed effects of an extreme soil treatment combined with stump harvest with significant scientific value, but this effect does not reflect potential effects of conventional site preparation methods currently used in the Nordic countries. Moreover, the higher carbon stock in tree biomass following deep soil scarification counteracted carbon losses in the soil and the total carbon stock (soil + tree biomass) did not differ between treatments. This shows the connection between soil carbon dynamics, nutrient availability and tree growth. An important lesson here is that one cannot draw conclusions about the impact of stump harvest on the carbon balance (and its effect on climate) by studying carbon stocks separately in the soil or in the tree biomass.

Nitrogen determines soil carbon accumulation in the long term

There are several possible explanations why stump harvesting has not affected soil carbon storage in available field studies. There may be small, true effects, that are difficult to detect in field trials because they are masked by other factors and natural variability. On the other hand, by using the same methods, we have revealed long-term effects of other forestry measures on carbon stocks, such as fertilization, tree species selection and slash harvest. This suggests minor effects of stump harvest on forest carbon stocks.

In the long run, carbon accumulation in soils is largely determined by forest growth, which in turn is highly dependent on the availability of N in boreal forests. Low forest production generally gives low soil carbon accumulation. Many field trials have shown that slash harvest, particularly in thinnings but also at final fellings, may reduce forest growth. Nitrogen losses due to slash harvest are the most likely explanation for this effect (Egnell 2016). Stump harvesting does not seem to result in reduced forest growth, rather the opposite (e.g., Jurevics et al. 2016). The relatively small additional N loss due to stump harvest could be a contributing factor to this. This means that stump harvest is unlikely to affect the long-term soil carbon stock as a result of reduced forest growth and thereby reduced litterfall.

Direct measurements of carbon emissions from the soil in the new trials have not provided support for the hypothesis that soil disturbance increases the decomposition of soil organic matter. The results rather indicate the opposite (Strömgren et al. 2016). This could also contribute to the poor empirical evidence for reduced soil carbon stocks after stump harvest.

Are stumps for energy environmentally acceptable regarding carbon stocks?

Model studies have demonstrated that it is likely that stump harvesting leads to some reduction in soil carbon stocks (e.g., Melin et al. 2009, Eliasson et al. 2013). On the other hand, most empirical studies of stump harvesting on well-drained sites in Sweden and Finland have not shown any negative effects on soil carbon storage if the reference is a mechanically site prepared site. Therefore, there is no strong support from field experiments that stump harvest leads to significant soil carbon losses. The discrepancy between model results and the empirical evidence can be that it is difficult to statistically determine small changes in carbon stocks in forest soils owing to the great spatial variation of carbon.

On the other hand, models are often designed to provide answers to general questions rather than to give precise predictions. The valuation of stumps for energy from a greenhouse gas perspective must be based on knowledge of how soil carbon stocks and tree carbon stocks in forests are influenced in different scales of time and space. If one only looks at the effects of stump harvesting on soil carbon stocks, the empirical studies provides argument that stumps as a fuel has acceptable properties with respect to greenhouse gas balances.

8. STUMP HARVESTING AND THE SOIL/ATMOSPHERE EXCHANGE OF CO_2

Kristina Mjöfors (SLU, Uppsala), Monika Strömgren (SLU, Uppsala), Achim Grelle (SLU, Uppsala), David Hadden (SLU, Uppsala), Anders Lindroth (Lund University) and Patrik Vestin (Lund University)

After lifting of the stumps, the stumps (including coarse roots) are shaken and divided into 2-4 parts to remove stones and soil from the biomass and to improve the drying process. Then the stumps are stacked in piles on the clear-cut and later forwarded to the roadside. The soil disturbance as a result of mechanical site preparation and stump extraction does not seem to increase the emission of carbon dioxide. This is in contrast to what was previously believed.

Soil disturbance from stump extraction and site preparation will initially lead to a reduction in carbon dioxide emissions from the soil. This is one result achieved from a series of new experiments established throughout Sweden and is contrasting to what was previously assumed. After one year however, this initial reduction had disappeared and emissions were around the same level for both disturbed and undisturbed soil.

Forests and forest soils contains large volumes of carbon in the form of biomass and organic matter within the mineral soil and humus layers. The carbon stock in Swedish forest soils is estimated to be 1.7 billion Mg C. This is the equivalent to 100 times the annual Swedish emission of carbon dioxide. This means that even a small change in the forest soil carbon stock can have a big impact on the national carbon budget.

One concern has been that stump harvest would reduce carbon stocks in the soil, partly because of the greater extraction of biomass and partly as a result of significant levels of soil disturbance. If this would have been the case, then stump wood could be a dubious source of energy.

The carbon cycle

All plants absorb carbon dioxide through photosynthesis to build up their biomass (Figure 8.1). They also release carbon dioxide when respiring, a process known as autotrophic respiration. As long as there is a biomass growth, the uptake of carbon dioxide will be greater than that being released. The carbon input to the soil is supplied by dead organic matter, such as needles, leaves, roots and dead twigs from the plants. When the litter reaches the soil, it begins to be decomposed by fungi and bacteria. In this process carbon dioxide is released, known as heterotrophic respiration. The decomposition of woody litter is slow, and when the supply of litter-bound carbon is larger than the amount emitted by decomposition, the soil carbon will accumulate. The organic matter which has accumulated in the soil over centuries has built up large carbon stocks within the forest soil.

When trees are harvested, they will no longer photosynthesize. During the first year after forest felling, ground vegetation is often very scarce and does not contribute to any appreciable photosynthesis. However, the decomposition and respiration from soil organic matter and woody residues continue, which means that after the felling phase the forest becomes a carbon source.

A series of newly established experiments show that soil disturbance from stump extraction and site preparation will initially reduce the carbon dioxide emissions from the soil. This is contrary to what was previously assumed. After one year however, this initial reduction has disappeared and emissions are similar for both disturbed and undisturbed soil.

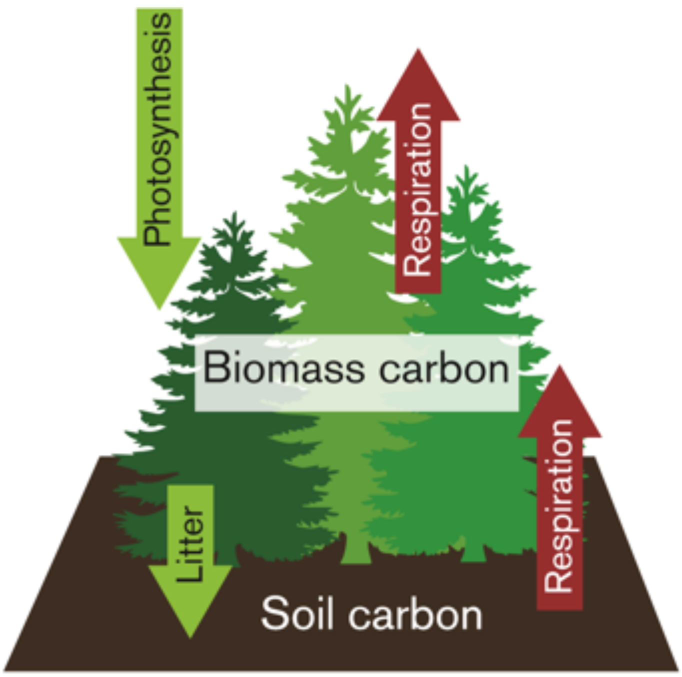

Figure 8.1. The carbon cycle in a forest. Green arrows show processes in which carbon dioxide is absorbed into the ecosystem and the red arrows show processes in which carbon dioxide is emitted.

A large proportion of the soil surface is disturbed by stump extraction

A commonly established "truth" is that the disturbance and mixing of soil will increase soil carbon mineralization due to improved conditions for decomposition. This would mean that the proportion of disturbance of the soil surface area will be of great importance. From 14 site preparation and stump extraction experiments an average of 70% of the soil surface area was disturbed by stump harvesting and scarification (See this report, chapter 6). Harrowing, which is a standard site preparation method along with patch scarification and mounding had significantly lower levels of soil-surface disturbance with 54% and 40%, respectively.

The experiments also showed that some soil disturbance was not caused by site preparation or stump removal, but already incurred during harvesting and transportation of biomass. In plots where neither stump harvest nor site preparation had taken place, 10% of the soil was disturbed, particularly by ruts.

Small effects of soil mixing on carbon dioxide emissions

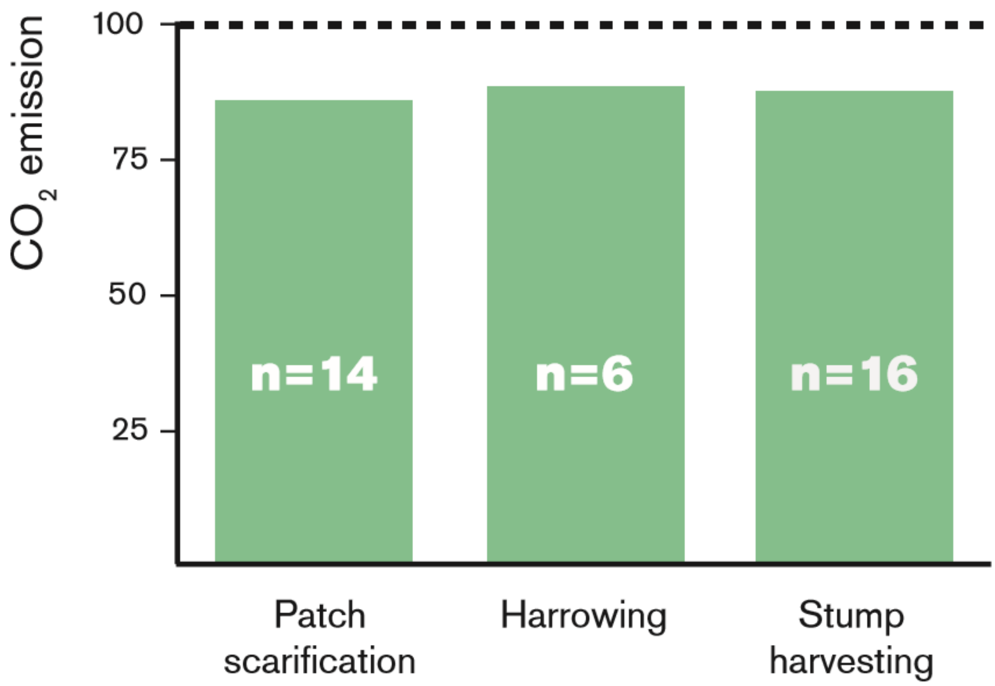

Figure 8.2. Mean carbon dioxide emission during the first year after patch scarification, harrowing and stump harvesting in relation to the undisturbed control treatment. 100% corresponds to the carbon dioxide emission from undisturbed soil. n = number of observations per disturbance type.

The result of a recent experiment shows that the emissions of carbon dioxide from the soil do not increase but rather decrease during the first year after soil mixing (Figure 8.2). A transient increase in carbon dioxide emissions has been observed after stump removal, but this disappeared after only a few weeks. Results from a stump harvesting and site preparation study comprising 14 experiments (See this report, chapter 6) showed that plots with stump removal or site preparation had 12% lower carbon dioxide emissions in the first year after treatment compared to the undisturbed soil, whilst by the second year there were no significant differences. There was some variation in carbon dioxide emissions, but during the first growing season, only two of the 14 experiments had higher emissions of carbon dioxide after stump harvest as compared to the undisturbed control. The carbon dioxide emissions from plots subjected to site preparation were lower than from the undisturbed control plots on all sites.

The results are likely a consequence of differences in the type of soil disturbance. The lowest carbon dioxide emissions were measured from a soil surface where the mineral soil was exposed. This result is expected since a large proportion of the carbon dioxide comes from the humus layer. If the treatments of stump extraction and site preparation were to give the same carbon footprint as the undisturbed soil, the low emissions from the mineral soil would have to be compensated for with high emissions from the areas where humus materials and soil have accumulated (e.g. in mounds and furrows). However, this was not the case. It is even so that the undisturbed soil generally emitted more carbon dioxide than the different disturbance types.

One reason for lower carbon dioxide emissions after stump extraction is that the stumps are removed – if they had remained, they would have started to decompose and emit carbon dioxide. In previous studies, the carbon dioxide emission from remaining stumps and roots was estimated to account for approximately 5% of the total emissions. If these emissions were to be taken into account, the results from the 14-experiment study would not be changed statistically. Stump harvesting will still emit significantly less carbon dioxide in the first year and have almost the same level of emissions as the undisturbed control treatment in the second year. Furthermore, there will be no significant difference between site preparation and stump harvesting.

Field vegetation is important for carbon fluxes in a clear-felled forest

During the first year, vegetation plays a negligible role in the carbon exchange in a clear-felled area. However, after only a couple of years the field vegetation begins to re-establish. This could be demonstrated using the Eddy-flux technology (see fact box) to measure carbon dioxide fluxes, showing that the uptake of carbon dioxide was substantial during daytime. If the vegetation had re-established before the performance of stump harvesting or site preparation, parts of the field vegetation would be destroyed leading to a reduced uptake of carbon dioxide than before the treatment. In practice, Eddy-flux measurements over large areas have shown that the emissions after stump harvesting as compared to site preparation were higher for a short time period only, and after a few months to a year later the difference was no longer visible.

The various soil disturbances created during stump extraction and site preparation can promote the establishment of field vegetation and trees. It is therefore important to continue to monitor the establishment and growth of field vegetation and trees for some years after stump extraction and site preparation. This would also give the opportunity to detect any delays in soil carbon losses after stump harvesting.

Conclusions

The general conclusion from published experiments and on-going current Swedish experiments is that stump extraction and site preparation results in less carbon dioxide emissions from the soil during the first year after treatment and that there are no significant differences in carbon dioxide emissions between areas subjected to stump harvest and site preparation and undisturbed control plots during the second year. The concern that stump harvest due to soil disturbance leads to increased emissions of carbon dioxide from the soil appears to be incorrect. From a climatic perspective, this means that stump removal and site preparation has little or no negative impact on soil carbon emissions.

The studies also show that the field vegetation is important for the carbon balance of the clear-cuts and that stump harvesting and soil preparation may initially provide a reduction in photosynthesis if they take place once field vegetation is established.

Measurement of carbon stock changes after stump extraction and site preparation

The soil contains a large carbon stock. Therefore, it is difficult to detect short-term losses or accumulations because the per cent changes are usually small. To see the effect on soil carbon stocks over the course of a few years, measurements of carbon dioxide fluxes is more efficient. It can be done by means of micro-meteorological methods (eddy-covariance technology), which measures the direct carbon dioxide exchange between ecosystems and the atmosphere over a large area (at stump extraction the radius is about 50 m provided that the eddy-flux sensors are positioned at about 3 m height). It can also be done by chamber measurements, which determine carbon dioxide fluxes from a limited area of soil. With the latter technique, one can estimate the differences from different types of soil disturbance. If the size of the area affected by disturbances, such as stump harvest, is known, the results can be scaled up to the clear-cut level to get an overall estimate of the emissions from an entire area. By weighing the results from these two measurement techniques, one can get a clear picture of how stump extraction and site preparation affects the carbon balance.

9. STUMP HARVESTING CAN AFFECT THE EMISSIONS OF METHANE AND NITROUS OXIDE

Anders Lindroth (Lund University), Patrik Vestin (Lund University) and Monika Strömgren (SLU, Uppsala)

Stump harvesting has a potential to result in an extra release of the greenhouse gases methane and nitrous oxide. These gas fluxes were measured by special chambers installed on frames that were inserted into the soil. Here you can see the frames installed at the Smällfallet location in the province of Västmanland.

The emissions of the greenhouse gases methane and nitrous oxide were consistently low in relation to carbon dioxide emissions at four experimental sites. Stump harvesting did not seem to affect the emissions of methane and nitrous oxide. Soil moisture was a major factor for methane emissions – independent of soil treatments. These studies are the first ones in the world and should be interpreted with care until further data have been obtained.

Background

To fully understand the impact of stump harvesting on greenhouse gas (GHG) emissions from the soil all relevant GHGs have to be included. The exchange of methane (CH_4) and nitrous oxide (N_2O) must be quantified in addition to carbon dioxide (CO_2). In a 20-year perspective, the effect on the radiative forcing of a molecule of methane and nitrous oxide is 84 and 264 as high as that of carbon dioxide, respectively.

Removal of stumps causes a considerable disturbance of the soil system. Soil mixing can result in an increased supply of substrates to the decomposer organisms, which in turn can lead to increased N mobilization. Increased production of nitrate-N can increase the emission of nitrous oxide. Nitrous oxide exchange is also affected by other factors, such as soil moisture and temperature, factors which are affected by clear-cutting and stump removal. Emissions of nitrous oxide are poorly studied, partly because of methodological difficulties and large variability in time and space.

It is also poorly understood how the methane exchange is affected by soil disturbances. Methane is normally taken up in forest soils, and soil moisture and N availability are factors impacting the uptake. Clear-cutting will reduce transpiration, which causes the water table to be raised and possibly reduce methane uptake.

The studies of stump harvesting on the exchange of nitrous oxide and methane reported here are the first of their kind in the world and should be interpreted with some caution.

Experiments with chambers

Measurements of nitrous oxide and methane emissions with special chambers (Figure 9.1) were performed at 3 of the 14 scarification and stump-harvesting experiments on Swedish clear-cuts (Strömgren et al. 2016). The experimental sites (Lunsen, Porrtjärn and Smällfallet) were all located in central Sweden. The soils are mesic-moist and fairly rich in nutrients, so the potential for nitrous oxide emissions was judged to be larger than in drier and nutrient-poor soils. The gas exchange measurements were made during the growing seasons of 2013 and 2014 and included three treatments, namely, stump harvesting, mechanical patch scarification and undisturbed control, where the trees were felled and removed but where the soil surface was intact.

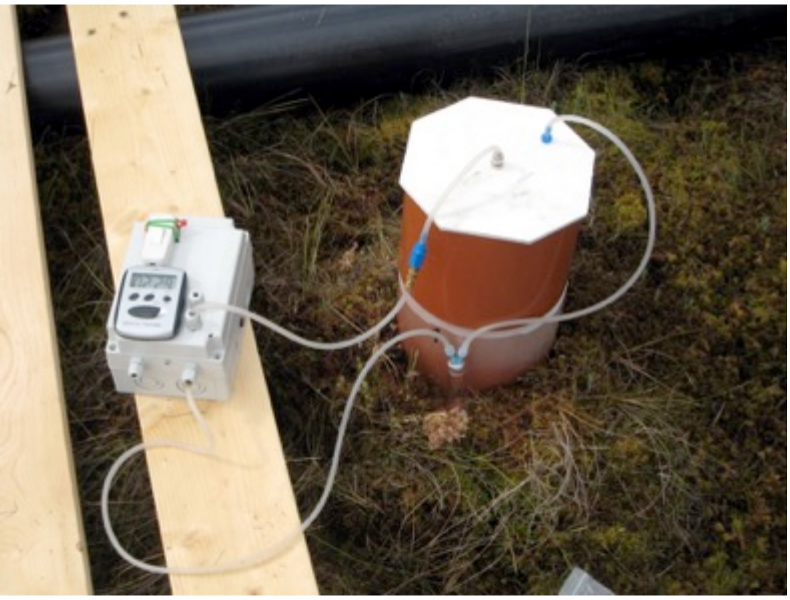

Figure 9.1. Measurements of nitrous oxide and methane emissions were made with a chamber system with 48 pre-installed frames per site. During each measurement, the chamber was added on top of the frames and the air samples collected were analyzed by a gas chromatograph.

Nitrous oxide

The measurements showed no or only small differences in N_2O emissions between undisturbed, scarified and stump-harvested treatments. The N_2O emissions were also generally low. At one of the sites, no emission could be detected, which might be due to the fact that the ground vegetation, which was rapidly established, assimilated most of the inorganic N or that the NO_3^- formed was denitrified to N_2. At Smällfallet, which had the highest fluxes of greenhouse gases,

N_2O accounted for 4-8% of the total greenhouse gas fluxes in terms of CO_2 equivalents. For Porrtjärn and Lunsen, N_2O amounted to a maximum of 1% of the total fluxes (2nd year).

Methane

Fluxes of methane were generally low, with both uptake and emissions recorded. Total methane fluxes corresponded to only 1-2 ‰ (per mille) of the total greenhouse gas fluxes (in CO_2 equivalents), and there was no difference between stump-harvested and control areas. Significant methane emissions were, however, measured in wheel ruts and on patches of mineral soil, especially when these were filled with water.

Micrometeorological measurements

Nitrous oxide and methane exchanges were also studied on a fresh clear-cut belonging to Norunda Häradsallmänning, 30 km NW of the city of Uppsala, in the province of Uppland, central Sweden. Measurements were constantly carried out from July 2011 to September 2013 for nitrous oxide and from June 2010 to May 2013 for methane. The experiment included four plots; two plots with stump harvesting and some additional soil scarification and two plots with soil scarification only. Each treatment contained one plot with moist and one with mesic soil.

Nitrous oxide

The measurements indicated that the mesic plots had higher emissions of nitrous oxide than the moist plots (Figure 9.2). During 2011-2012, the individual plots differed markedly, and the stumped plot had lower N_2O emissions than the non-stumped plot in the moist soil type, while the stumped plot had higher N_2O emissions than the non-stumped plot in the mesic soil type. The same pattern also occurred during 2012-2013. Thus there seemed to be an interaction between treatment and moisture for the N_2O emissions. These emissions were generally low compared to the CO_2 emissions with the exception of the stump harvested plot in the mesic soil. When "translated" into CO_2 equivalents, they amounted to 14% of the CO_2 emissions from this plot.

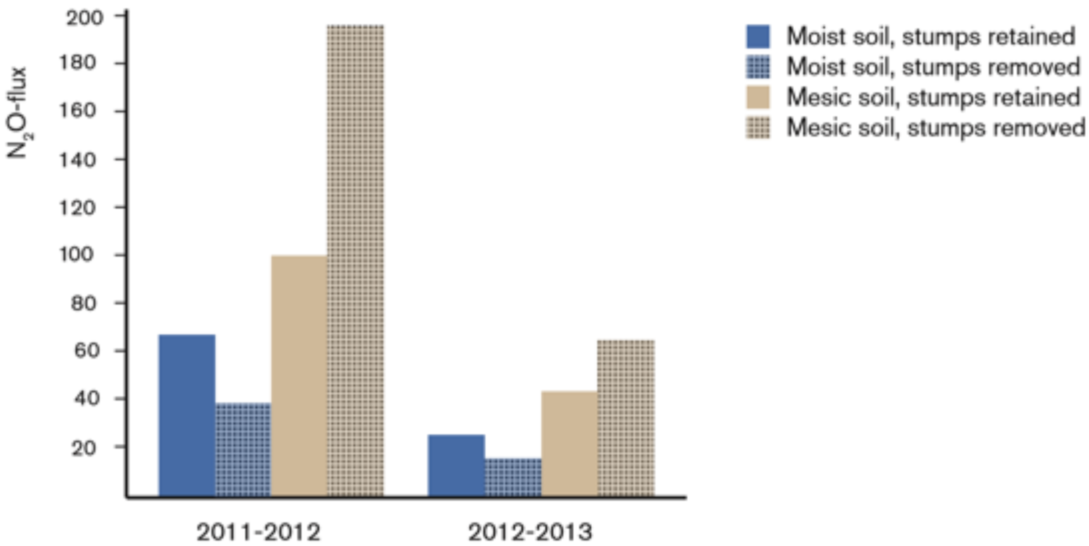

Figure 9.2. N_2O fluxes at Norunda indicated as g CO_2 equivalents per m^2. Note that the second measurement year (2012-2013) is only represented by three months of measurements.

Methane

The emissions of methane at Norunda resulted in a significant addition to the total greenhouse gas emissions. The methane fluxes showed a strong dependence of soil moisture with higher emissions in moist and wet areas (Figure 9.3). The highest methane emission was recorded during 2012-2013 on the moist control plot and corresponded to 37% of the CO_2 emissions on the same plot this year. The lowest methane emission was recorded during 2011-2012, when it amounted to only 12% of the CO_2 emissions on the same plot. The emissions were lower after stump harvesting than after site preparation, but with an exception for the third year in the mesic area, where they were slightly higher.

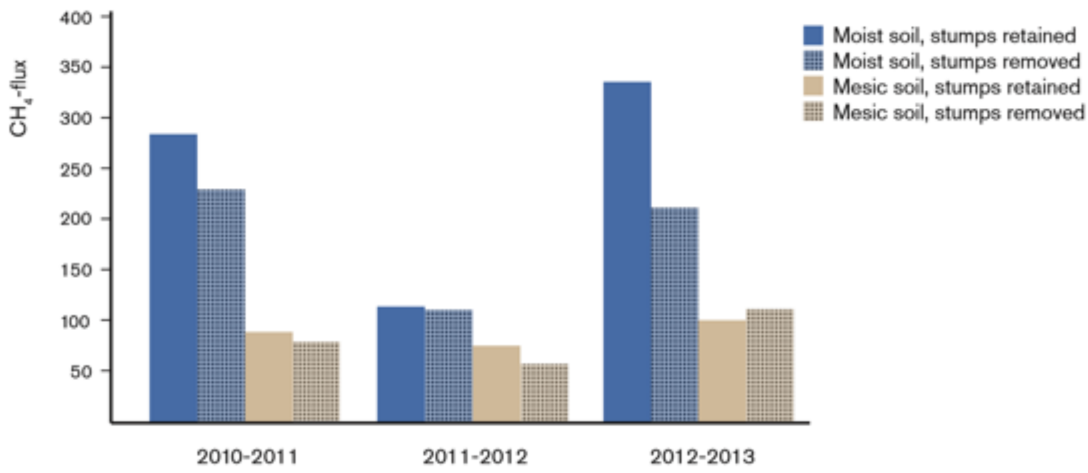

Figure 9.3. Methane emissions at Norunda. The fluxes are indicated as g CO_2 equivalents per m^2.

Total emissions of greenhouse gases

All greenhouse gases were measured at Norunda. The CO_2 emissions were consistently higher from the mesic than from the moist soils in 2010-2012, while the stump-harvested plot with mesic soil had the lowest CO_2 emission during 2012-2013.

The total greenhouse gas emissions were clearly lower after stump harvesting than after site preparation in the mesic soils. The moist stump-harvested plot had lower total greenhouse gas emissions in 2010-2011, higher in 2011-2012 and equally large in 2012-2013, as compared to the moist scarified plot.

There was a clear trend of reduced emissions from year 1 to year 3 from the mesic soil, both on the stump-harvested plot and on the plot with stumps retained. This tendency was not equally clear for the moist soils.

Conclusions

Nitrous oxide emissions were consistently low in relation to carbon dioxide emissions at all sites. There were no consistent effects of stump harvesting, but the relatively high N_2O emission from the stump-harvested plot with mesic soil in 2011-2012 at Norunda was unexpected and motivates further studies.

Methane fluxes were not significantly affected by stump harvesting or soil scarification in any of the trials, although there was a tendency of lower emissions in the stump-harvested plots than in the site preparation plots at Norunda. Soil moisture was a major factor for methane emissions, which were higher in the moist areas than in the mesic areas at Norunda – independent of treatments. High methane emissions were also recorded from moist and wet wheel ruts in the soil chamber study.

For all the greenhouse gases combined, the mesic soils at Norunda showed lower emissions from the stump-harvested than from the plots with stumps retained. The differences between treatments in the two moist plots were less evident. As a whole, the greenhouse gas emissions, being dominated by CO_2 efflux, were often lower after stump removal than after site preparation or no soil disturbance at all.

10. N MINERALIZATION AND N LEACHING AFTER STUMP HARVESTING

Tryggve Persson (SLU, Uppsala) and Bengt A Olsson (SLU, Uppsala)

Forest landscape in central Finland near the lake Haukilahti, where most of the Finnish studies on stump harvesting in this chapter were made.

Stump harvesting increases the risk of nitrate leaching, and two factors are likely to be responsible. (1) Fungi decomposing stumps and coarse-roots can import ammonium and nitrate to the stump/root system from the surrounding soil. When stumps are removed, mobile inorganic N is left in the soil and can be leached. (2) At stump harvesting, the soil is disturbed and mixed, whereby ammonium oxidizing microorganisms from deep soil layers can be incorporated into soil layers with plenty of ammonium, which they convert to nitrate. Both factors would result in increased risks of nitrate leaching, and in a field experiment in southern Sweden increased nitrate leaching below the rooting zone was also documented.

Nitrogen cycling will change after clear-cutting

At final felling soil nitrogen (N) turnover will change dramatically. The decomposer organisms, mainly bacteria and fungi, incorporate carbon and N in their cells. When the assimilation of N is greater than what is needed for cellular growth, the microorganisms excrete N as ammonium, a process often called N mineralization. When there is a shortage of N, ammonium is taken up and its availability is reduced (N immobilization). Sometimes mineralization and immobilization of N occur simultaneously in the soil, and the net result is then either net mineralization or net immobilization of N. Ammonium may then be oxidized to nitrate, which is called nitrification. The nitrification takes place in two steps, first to nitrite by ammonium oxidizing bacteria and Archaea and then to nitrate by nitrite-oxidizing bacteria. Some decades ago, the Archaea were classified as bacteria, then called archaebacteria, but modern genetic research has shown that the Archaea constitute an organism kingdom of their own. New research has also shown that archaeans are just as important as bacteria in oxidizing ammonia to nitrite (Leininger et al. 2006). The first step in the nitrification process is considered to control the nitrification rate. Ammonium N, nitrite N and nitrate N is together called "mineral N". However, in practice this means just the sum of ammonium and nitrate-N when talking about mineral N, because nitrite always has a low concentration in the soil. Normally, nitrification is favoured by high pH and good supply of ammonium, but some nitrifiers are tolerant to low pH and can form nitrite and nitrate even below pH 4.

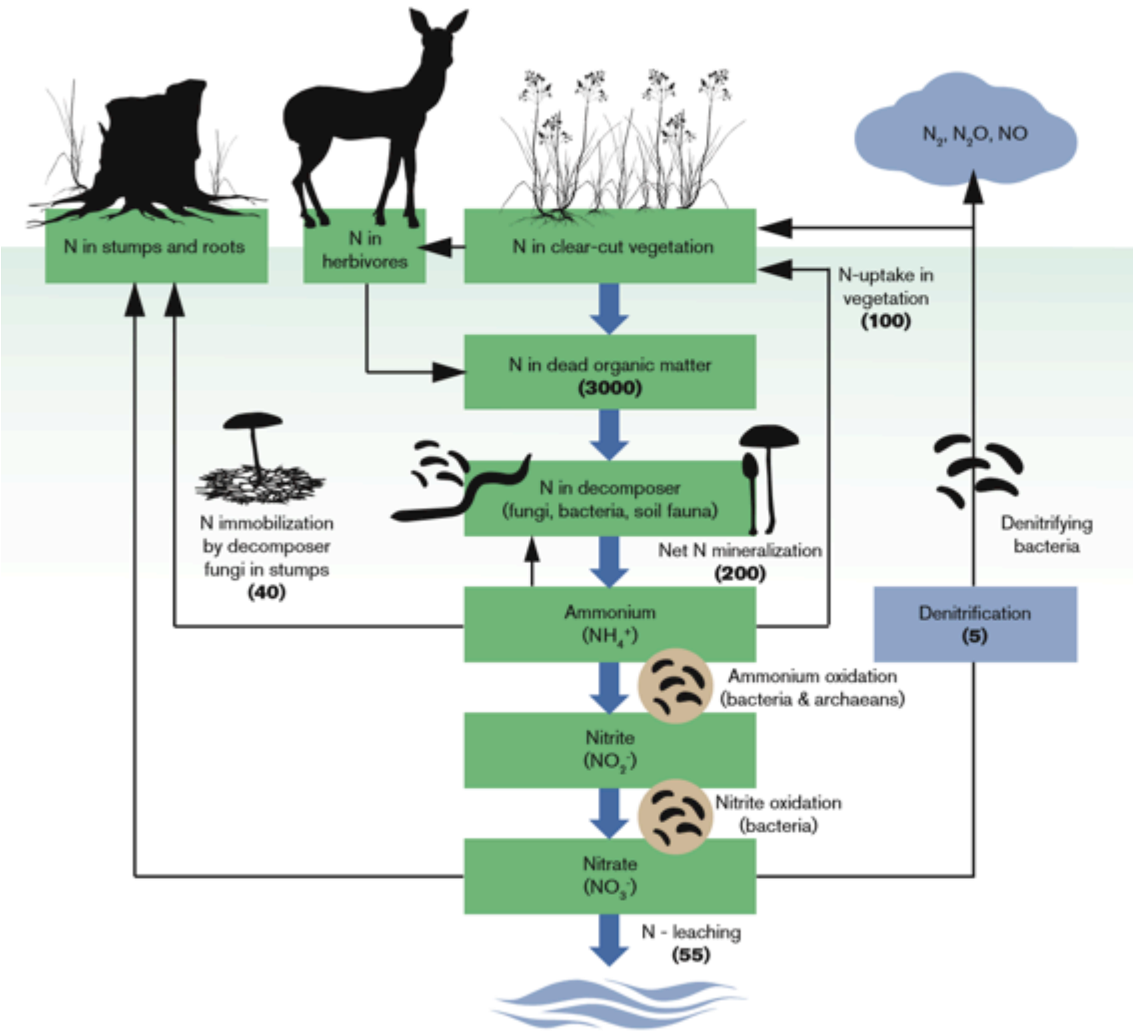

Figure 10.1. N budget for a clear-cut in Blekinge, the most southeastern province in Sweden, during the first four years after the tree-felling (simplified after Bergholm et al. 2015). The figures denote kg N per hectare. Of the 200 kg N mineralized during this 4-year-period, 100 kg was taken up by the clear-cut vegetation, 40 kg was immobilized in dead roots and stumps, 55 kg was leached (mostly as nitrate) and 5 kg was denitrified (uncertain value). Moreover, 35 kg N came as atmospheric deposition, which meant that the N budget was not fully balanced.

One difference between recently harvested and actively growing forests is that mineralized N in a clear-cut can no longer be absorbed by the trees, but will be accumulated in the soil, be taken up by clear-cut vegetation, be leached from the soil system or be emitted in the air as gaseous N. But even dead stumps and coarse roots can take up N after tree harvesting through the action of decomposer fungi importing N from the surrounding soil.

Stumps and dead roots immobilize N

Stumps and roots predominantly consist of N-poor wood. In Finnish studies, Palviainen et al. (2010) and Palviainen and Finér (2015) showed that stumps and coarse roots take up N from the environment during their degradation, probably because decomposer fungi import N from the surrounding soil to decompose the stumps. Bergholm et al. (2015) estimated that the N uptake of stumps and roots was 9-10 kg per hectare per year during the first four years after a final felling in southern Sweden. The results therefore suggest that as much as 40 kg of mineral N per hectare may be immobilized into the stumps and roots during the early clear-cut phase (Figure 10.1). When stumps are harvested, the amount of mineral N in the soil should thus increase for this reason.

Net N mineralization and nitrification at Norunda

There are very few studies of N mineralization in soils, where scarified and stump harvested experimental plots have been compared. At the experimental site Norunda in Uppland, a six hectare forest with 120-year-old pine and spruce were clear-felled in 2009. Branches and tops were left. The area was divided into four experimental plots, and in May 2010 stump harvesting was carried out in two of these plots, whereas patch scarification was conducted in the other two plots. A complementary site preparation was done in the stump harvesting plots to obtain sufficient planting points. A year and a half later, in November 2011, soil samples were collected. The samples from different soil layers were sieved, and sub-samples were incubated at the same temperature (15 °C) and soil moisture. Net N mineralization and net nitrification were estimated by determining the increase in the concentration of ammonium and nitrate over 25 days.

According to the 2011 sampling, there was no clear difference in the amount of mineral N in scarified and stump harvested plots. On the other hand, there was a clear difference between intact and disturbed soil (regardless of what brought about the disturbance). The disturbed soil contained more mineral N than the intact one (12 and 5.5 g m^{-2}, respectively). Most of this N was in the form of ammonium, and nitrate-N accounted for only 4% and 1%, respectively, of inorganic-N.

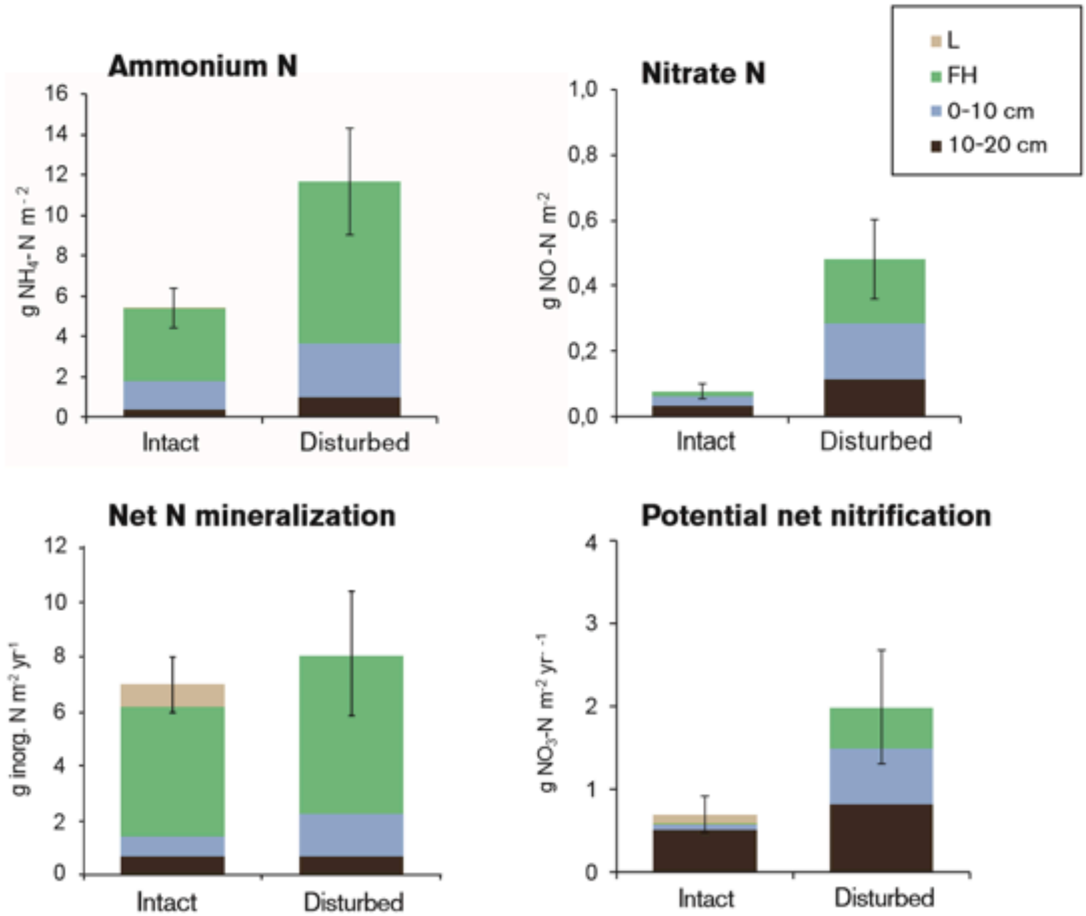

Figure 10.2. Amount of ammonium N and nitrate N at Norunda, Uppland, as measured in intact and disturbed plots during late autumn in 2011, 2½ years after clear-cutting and 1½ years after stump harvesting and soil scarification. In addition, the estimates of annual net N mineralization and net nitrification on intact and disturbed areas at Norunda are shown.

Based on these data, one might suspect that soil disturbance increases N mineralization. However, this was not the case, because the N mineralization study in the laboratory showed that there was no detectable difference in net N mineralization between intact and disturbed areas (Figure 10.2). One explanation of the difference in the field may instead be that the ground vegetation had sufficient capacity to take up a part of the newly formed mineral N on the intact soil.

There was a difference in net nitrification between intact and disturbed soil (0.7 and 2 g nitrate N per m^2) calculated per year (Figure 10.2). In the disturbed areas a litter (L) layer was lacking, which at stump harvest and site preparation instead had been incorporated into the underlying humus (FH) and mineral soil layers.

Previous studies have shown that the nitrification potential is high at 10-30 cm depth in the soil (Rudebeck and Persson 1998; Bergholm et al. 2015). At this depth, net N mineralization is often low, and the availability of ammonium then limits the formation of nitrate. The strikingly greater nitrate formation in the humus layer (FH) and the 0-10 cm mineral soil layer of the disturbed areas could be explained by mineral soil from large depths with their specific nitrifiers (probably Archaea) being intermixed into the soil layers forming high ammonium concentrations.

The difference in nitrate formation in intact and disturbed soils is also relevant in evaluating the role of stump harvesting on nitrate formation. In Norunda, the proportion of disturbed soil was about 40% in mounded areas and 70% in stump-harvested areas. Based on the percentage of intact and disturbed surfaces, mounding should lead to an approximate production of 12 kg nitrate N per hectare and year and stump harvesting to 16 kg nitrate N per hectare and year, i.e. 33% higher in the stump removal alternative.

N mineralization in central Finland

Studies of N mineralization and nitrification potential have also been made in Haukilahti, close to Tampere in central Finland by Kataja-aho et al. (2012). Soil samples were taken 1-5 years after clear-cutting from exposed mineral soil surfaces, either caused by stump harvesting or mounding. As at Norunda, soil samples were taken to the laboratory where they were incubated at a constant temperature (14 °C) and moisture. Both net N mineralization and net nitrification were clearly higher after stump harvesting than after mounding one year after treatment, but after two years the differences seemed to be completely wiped out concerning net mineralization, while the mean values of net nitrification were still higher after stump harvesting. After four and five years, there was no significant difference between treatments. The difference in nitrate formation between mounding and stump harvesting would, as at Norunda, be explained by the fact that stump harvesting results in a stronger mixing of soil layers than mounding which favors nitrification following stump harvesting.

N mineralization in northern Uppland

During the period 1977-1987, stumps were commercially harvested in a fairly limited area in the provinces of Uppland and Gästrikland, with the aim of supplying the pulp mill in Mackmyra (near the city of Gävle) with raw materials. Although many clear-cuts were stump harvested, there were also many clear-cuts that were only subjected to site preparation (patch scarification). Eight of these former clear-cuts were studied in 2009 by Persson et al. (2017), that is, 20-30 years after stump harvesting, for N pools and net N mineralization. Nearby stands with stump harvest and mounding were regarded as pairs, and a total of four pairs were studied with or without stump removal. As at Norunda and in the Finnish experiments, soil samples were taken to the laboratory for further determination of net N mineralization. The analyses showed that soil mixing was more pronounced in stump harvested than in mounded plots, but neither net N mineralization nor net nitrification differed between stump harvested and non-harvested plots. In 20-30 year-old forests, trees are generally N limited, and their roots and mycorrhizae are effective competitors for N with the free-living soil microorganisms. Low availability of ammonium for a long time may affect the nitrifier populations negatively which, in turn, may explain why the nitrate formation was almost negligible.

N leaching after stump harvesting

One of the few studies carried out on N leaching after stump harvesting was done at Tönnersjöheden in Halland (southern Sweden) by Staaf and Olsson (1994). During a 5-year period, they examined the soil water chemistry at 30 cm soil depth after clear-cutting followed by varying degrees of harvest levels: (i) stem-only harvest, (ii) harvest of stems and forest residues (slash), and (iii) harvest of stems, slash and stumps. Stump and slash harvesting increased the ammonium concentration in the soil compared to just slash harvesting during the first two years, but during the third and fourth years nitrate levels increased dramatically in the soil water. The concentrations in the plots with stump and slash harvest were, on average, five times higher than in areas with just slash harvest, which corresponded to an outflow of 50 and 10 kg nitrate-N per hectare, respectively, in these two years. The difference in nitrate leaching between stump-harvested and stem-only harvested plots cannot be explained by differences in ground vegetation, because the ground vegetation cover showed a complete recovery from year three onwards. The most likely explanation for the higher nitrate leaching after stump harvesting is therefore the absence of N immobilizing stumps/roots in combination with strong soil mixing.

Conclusions

Stumps and roots contribute to the nitrogen immobilization during the early clear-cut phase. At stump harvesting, this capability is reduced, and large amounts of especially nitrate N are at risk of being leached. Stump extraction increases the soil disturbance, which may increase net N mineralization immediately after stump lifting. Even more important is that net nitrification will increase the years following a disturbance, and especially after stump harvesting, which results in a more efficient mixing of soil layers than for example patch scarification. This mixing seems to increase the nitrification potential. In conclusion, stump harvesting should lead to an increased risk of nitrate leaching. Increased nitrate leaching (below the rooting zone) after stump harvesting has also been found in a five-year study in southern Sweden with relatively high soil N pools and N deposition, but in areas with small N pools and low N deposition, stump harvesting does not seem to affect nitrate leaching (Laurén et al. 2008; Becker et al. 2016).

11. STAND GROWTH AND NATURAL REGENERATION AS AFFECTED BY STUMP HARVEST

(Gustaf Egnell (SLU, Umeå), Riitta Hyvönen (SLU, Uppsala), Bengt A Olsson (SLU, Uppsala) and Monika Strömgren (SLU, Uppsala)

Root rot is often caused by the harmful fungus *Heterobasidion annosum sensu lato* (the white fungus in the photo), which can lead to serious economic losses in forestry. Stump harvesting can reduce the fungal infection in the next tree generation, but to provide adequate control of the *Heterobasidion* frequency, a majority of rot-infected stumps must be removed.

Long-term experiments in Sweden and Finland show that stump harvesting will probably not have a major impact on the forest production in the next rotation. Theoretically, stump harvesting should result in reduced damage of the pine weevil *Hylobius abietis* and a lower frequency of root rot in the next stand rotation, but it still remains to be shown that this is the case in practice. Removal of stumps increases the area of exposed mineral soil, which promotes natural regeneration of pine and birch.

When nutrient-rich slash (tops and branches) is harvested as an energy assortment, the biomass harvest is moderately increased, as compared to when only the merchantable stem wood is harvested, while the nutrient export with the harvest increases substantially. This has raised concern about negative effects on future forest production. Negative effects on forest production following slash harvest have also been reported from long-term field experiments although the results have not been unequivocal.

The biomass potential in stumps is roughly the same as in slash in a final felling, but the nutrient content is lower (Hellsten et al. 2013). It is therefore reasonable to assume that the direct effect on future forest production as a result of nutrient withdrawal with the harvested biomass will be less following stump harvest as compared to slash harvest. Stump-harvest may also affect future forest production by affecting:

- Pine weevil damages on the seedling
- Root rot infection rates
- Competition from vegetation
- Nutrient availability
- Seedling survival rates
- Natural regeneration

Pine weevil damages

The pine weevil, *Hylobius abietis*, is a common cause of mortality in seedlings used to restock forest sites after clear-felling. The scent of monoterpenes from fresh stumps and felling residues attracts the weevils from long distances. Typically, adult weevils feed on bark of the main stem, and when it is girdled by extensive and deep feeding wounds, the young seedling is killed (Figure 11.1). The weevils then lay their eggs in the soil close to the roots of the felled trees. After hatching, the weevil larvae crawl through the soil to a suitable root, where they feed on the inner bark. The larvae will pupate during the second summer, and after metamorphosis the new adult weevils emerge and start to feed on the seedlings. A new study shows that stump harvest can reduce seedling damage during the first attack if the stumps are forwarded to a large pile at the landing rather than being scattered in small piles all over the clear-cut (Rahman et al. 2015). Studies also show that soil disturbance measured as the proportion of exposed mineral soil often is increased following stump harvest – a feature that also may reduce the damage since the weevils avoid open spaces. Theoretically also the second attack from the second generation of weevils would be reduced when their breeding substrate is harvested. This has been difficult to document in field studies – possibly as a consequence of the weevil being a good flyer that flies in from the surrounding landscape. To have a significant positive impact it may be that stumps have to be harvested on a certain proportion of the clear-cut area in the landscape, making the effect difficult to reveal in experiments on single clear-cuts.

Figure 11.1. The smell of fresh stumps on a clear-cut attracts adult pine weevils to fly towards the clear-cut. The weevils feed on the seedlings and lay their eggs in soil pits close to the roots, where the next generation of pine weevils will develop. It is possible to reduce the weevil damage to some extent if the stumps are stacked in a large pile at the landing rather than left in several small piles on the clear-cut.

Root rot

The root-rot fungus *Heterobasidion annosum* (and related species) is a major pest in Scandinavian forests causing large quality and production losses annually. Root rot is spreading between trees through root contact – but also through spores infesting exposed wood on mechanically damaged trees or the exposed wood on stumps. Infected stumps act as a vector that transmits the disease to the next tree generation. Recent research gives clear evidence that the infection rate in the next rotation is reduced if stumps are harvested in infested stands (Cleary et al. 2013). But to be efficient, the stump harvest has to include most of the stumps and particularly the infested ones. This is not necessarily the aim in a practical stump harvest operation to procure biomass for energy purposes.

Competition from other plants

One of the reasons to prepare the site mechanically before regenerating forests is to reduce the competition from other plants than the planted ones. Another option is to use herbicides, but this is not allowed in Swedish forestry. Several studies show that the proportion of exposed mineral soil increases when the stumps are harvested (e.g. Kataja-Aho et al. 2012; Kardell 2008). This was also the experience when 14 new long-term field experiments with stump harvest were established throughout Sweden with financial support from the Swedish Energy Agency in 2012-2015. This soil disturbance has the potential to reduce the early competition for tree seedlings in the next tree generation and thereby have a positive effect on their establishment and growth.

Nutrient availability

The prevailing opinion seems to be that the soil disturbance caused by mechanical site preparation and stump harvest will result in increased decomposition rates of organic material in the soil and thereby release the nutrients bound therein – something that would stimulate seedling establishment and growth. Indirect evidence for this has been reported from stump-harvested sites as increased N concentration and decreased carbon to N ratio (Kataja-aho et al. 2012), while direct measurements of emitted CO_2 (an estimate of carbon turnover rates) indicates that it is unaffected (Uri et al. 2015) or even that it sometimes decreases as a response to stump harvest or mechanical site preparation compared with a site with the stumps remaining (Mjöfors et al. 2015). This suggests that the increased soil N concentrations observed after stump harvest rather is linked to reduced amount of competing vegetation, as described above.

Plant survival

On top of the factors described above, survival and growth of planted seedlings may be affected by changes in the microclimate at the planting spot caused by the harvest intensity and by competition from natural tree regeneration. A Finnish study indicated that seedling survival was higher for Scots pine and Norway spruce seedlings planted following stump and slash harvest as compared to seedlings planted after slash harvest without any additional site preparation (Karlsson and Tamminen 2013). In Swedish field experiments, there are no large differences in survival rates and they are normally not statistically detectable although a slightly higher survival rate following stump harvest was revealed on a poor site planted with Scots pine (Egnell 2016). These results are supported by results from a survey study, where survival rates on 37 stump-harvested sites did not differ from that on 10 control sites (Saksa 2013). It should be noted that, in contrast to the study by Karlsson and Tamminen (2013), all other studies included some sort of mechanical site preparation on the reference treatment with the stumps remaining.

Natural regeneration

For natural regeneration there is scientific evidence for a difference with natural regeneration of pioneer species like pine and birch being stimulated by stump harvest, whereas secondary species like spruce are disfavoured (Karlsson and Tamminen 2013; Saksa 2013). One explanation for the stimulated natural regeneration of pioneer tree species might be that the increased soil disturbance caused by the stump harvest provides good conditions for seed germination and early establishment. If the recruitment of naturally regenerated spruce seedlings primarily originated from advanced growth, already established at the time of harvest, increased soil disturbance could also explain the reduced number of naturally regenerated spruce seedlings if they were killed during the harvest operation. Altogether this suggests that the stem density may increase as a result of stump harvest and thereby may increase forest production. But as the increase in stem density primarily is a result of increased natural regeneration of pioneer tree species, the final effect on forest production also depends on later silvicultural practises including decisions on which trees to remove during pre-commercial and commercial thinning.

Forest production

Currently there is a shortage of old long-term field experiments with stump harvest where effects on forest production can be studied. In Figure 11.2 stem-wood production of the subsequent stand following stump harvest is compared with the production of stem-only harvested control plots. Based on these field experiments from Finland and Sweden, the general picture is that stand productivity is not negatively affected by stump harvest or the combined harvest of stumps and slash. It is rather a positive effect on stand productivity, at least in Scots pine plantations. There is also a trend suggesting that stand productivity on poorer sites (low site index) is affected more in a positive direction.

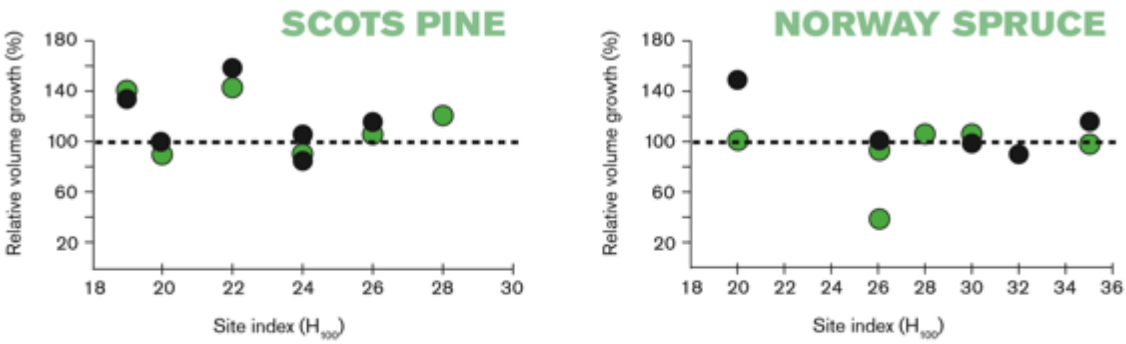

Figure 11.2. Relative volume growth after 24-36 years in pine and spruce plantations planted after stump harvest (black dots) or stump and slash harvest (green dots) in relation to growth on control plots (100%, dashed line), where only the stem-wood was harvested and the seedlings were planted after mechanical site preparation. Results from long-term field experiments in Sweden and Finland. Site index (SI) is a term used in forestry to describe the potential for forest trees to grow at a particular location, and H100 indicates the mean tree height of the dominant trees at an age of 100 years.

The experiments behind Figure 11.2 are not fully comparable due to differences in experimental design and silvicultural regime applied. In one Finnish study, studying both pine and spruce at the same site (SI = 28), also slash was harvested on control plots. Furthermore, the control plots were not site prepared. In one out of the two Swedish experimental series behind Figure 11.2, all treatments including the stump-harvested plots were also mechanically site prepared (harrowing), and natural regeneration was included in the stand production estimates. The relatively high production on stump harvested and stump and slash harvested pine plantations originates from that series (SI = 22). In the other experimental series, control plots were not mechanically site prepared and natural regeneration was removed in pre-commercial thinning and not included in the production. The relatively low production on one of the stump and slash harvested spruce sites originates from that series (SI = 26). This experimental site was characterized by moist soil conditions and stump harvest in combination with slash harvest, which resulted in a lot of natural regeneration that was not accounted for in the production estimates at the same time as it competed with the planted spruce seedlings resulting in seedling mortality and an overall slow start for the plantation.

Conclusion

Practical implications of these results, and only considering forest production, would be that stumps should be harvested rather than slash. However, slash is, for practical reasons, also harvested on sites where stumps are harvested, as the slash would constitute a physical impediment for the stump harvest operation. With current technology it is also cheaper to harvest slash than stumps. Thus slash will in most cases be the first option with stumps kicking in later as market demand and price increases. Practical experience says that spruce stumps are easier to harvest, as less force normally is required to harvest spruce stumps as compared to pine stumps due to their root architecture.

12. HIGH SPECIES RICHNESS IN SPRUCE STUMPS

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The first animals invading the fresh stumps are insects specialized in exploiting newly dead wood. These jewel beetles, *Buprestis haemorrhoidalis*, arrive later and prefer sun-exposed dead wood without bark.

Stumps of Norway spruce are very rich in species. The studies performed during the programme found 1,355 fungal species, 491 beetle species, 237 species of other small invertebrates, 93 lichen species and 35 moss species in and on spruce stumps. In total, this makes about 2,200 species. None of the studies are, however, comprehensive in terms of tree species, stump ages and regions, so there are certainly even more species in the stumps than indicated by the figures shown. The stumps with the highest species richness seemed to be the 10-20 year-old ones with a moderate degree of degradation.

Stumps as a resource

A fresh tree stump on a clear-cut contains nutrients and a lot of energy. When the trunk is cut, there is no longer any active defense against attackers. Those who are first on the scene can give their offspring a fine start in life. These, the first colonizers, will occupy the most readily available food sources and then quickly leave for other fresh wood pieces. But the stumps are still there and contain resources to live on for decades. Different species will replace each other in a succession, in which they interact in various ways. In the initial phase, there are many individuals but relatively few species. The number of species increases and will reach a peak after 10-20 years. The fungi are responsible for most of the chemical decomposition, but they interact with insects that spread fungal spores, perforate the wood and chew it to pieces. Pretty soon, an entire food web has been formed in the stump; fungi that decompose the wood, insects and other invertebrates that eat fungal mycelia and spores, and predatory animals that in turn eat the fungal feeders. On the stump surface, lichens and mosses are growing, and with time also dwarf shrubs will cover the decaying stumps.

One task of the thematic programme was to find out which species are using stumps. The knowledge base was highly variable. For some species groups, the knowledge of biology and distribution was comprehensive. For others, such as springtails, mites and enchytraeids, information was even lacking as to whether they occurred in stumps. This chapter summarizes the investigations made within the thematic programme about (1) which species occur in and on stumps, (2) when during the stump decay process different species occur, and (3) how important stumps are for the different species in relation other substrates, for example, the forest floor or other types of dead wood.

Fungi

Wood fungi were earlier studied by observing sporocarps (fruiting bodies). A limitation of this is that fruiting bodies are often visible only at certain times of the year and that many fungi do not produce fruiting bodies at all. To get a more complete picture of which fungi are available in wood we used a method called DNA barcoding, where the DNA of a species is compared with a 'library' of identified species (Kubart et al. 2016). In our case, we used sawdust wood samples from the stumps, logs and other types of wood and brought the sawdust to the laboratory for DNA analysis.

Figure 12.1. The fungal species with the largest amount of mycelium in the wood was primarily species with fruiting bodies. The most widespread fungi were generalists such as the bracket fungus *Fomitopsis pinicola*.

About 500 spruce stumps were investigated in young (3-10 years) and old (11-20 years) clear-cuts in seven localities along an 1100-km long latitudinal gradient from southern to northern Sweden. The species richness of fungi was high. In the 3-year-old stumps, there were many species known as pioneer species. Species richness increased with increasing stump age. Altogether we found 1,355 different "operational taxonomic units ", OTUs (roughly equivalent to species). Of these species, 19% could be determined down to the genus or species level using reference DNA. About 100 were bracket fungi and other large fungal species that form visible fruiting bodies, but most were fungi that live inside the wood, without visible sporocarps. The species that dominated the mycelium in the wood was primarily species with fruiting bodies. The most widespread fungi were generalists such as *Fomitopsis pinicola* (Figure 12.1), *Leptodontidium elatius*, *Resinicium bicolor* and *Coniophora puteana*. Root/heart-rot fungi such as *Heterobasidion* and *Armillaria* were mainly found in southern Sweden. Four of the wood fungi found are red listed.

For each of the localities we also took wood samples from logs (lying dead wood) in nearby reserves and key habitats. As a whole nearly 1 500 different OTUs (species) were identified in more than one stump or log. Species richness was about as high in the stumps as in the logs. More than 1,000 species were found in both stumps and logs, more than 200 in just the logs and more than 200 in just the stumps. Certainly many more species occur in both logs and stumps, but because the observations were based on relatively few and small wood samples, the importance of stumps in relation to other types of dead wood can only be evaluated for the most frequent species.

No fungal species has had an evolutionary history based on fresh stump wood, but there are species that have benefited from such substrates, such as the root-rot fungus *Heterobasidion*. An overall analysis showed that the fungal communities in logs and stumps were clearly separated. The most common species were common, but they occurred in different frequency. This pattern was consistent from southern to northern Sweden. Of all the findings of red-listed fungi, 97% were in logs. The most frequently occurring red-listed fungal species, *Phellinus nigrolimitatus* and *Amylocystis lapponica*, were found in 140 and 40 logs, respectively, but not in any of the 3-20 year-old stumps.

Beetles

The first animals invading the fresh stumps are insects specialized in exploiting newly dead wood. Early arriving beetles, particularly bark beetles and longhorn beetles, feed on the most nutritious part of the stump, the cambium. These beetles also bring various fungi, which in many cases degrade the wood in such a way that the beetle larvae are able to absorb the nutrients in the wood. The cambium-feeding species are in turn preyed upon by predatory insects. As the number of fungal species increases during the stump decomposition, more fungal-feeding beetles can be established.

Figure 12.2. To determine the beetle fauna, we collected wood samples from spruce stumps and let the beetles hatch inside wooden boxes. The insects could then be trapped when they moved towards the light in glass tubes sticking out of the boxes.

Many wood-living beetles have specific requirements of which kind of wood they can use, and they can sense the odour of suitable wood from long distances. Therefore, there are great differences in the composition of beetle species between different species of trees (Jonsell and Hansson 2011). This was studied by examining sieved stump bark and by letting beetles be hatched out from wood samples (Figure 12.2). After sieving, the beetles were extracted from the sieved material in Tullgren funnels. Aspen, birch, spruce and pine stumps had about as high species numbers (between 49 and 65) of wood-dwelling species. As a whole, 125 species were found, but only 15 were common to all tree species. The species composition in spruce and pine was more similar to each other than that in aspen and birch.

Stumps of Norway spruce have so far been the most interesting kind of tree to harvest, and therefore most studies have focused on this particular tree species. The total number of wood-living species in spruce stumps found in our combined studies, 276 species (Table 12.1), was markedly higher than the numbers of species found in the tree-species comparison. The higher figure is due to the considerably more samples collected, and with more samples, the number of beetles determined to species has also increased. In total, 52,200 beetles were found in 2041 wood samples (Table 12.2). Several different methods have also been used; sieving, hatching in the laboratory and hatching in the field; and with different methods different species will also appear. When species that are not dependent on dead wood were included, the figure was just under 500 (Tables 12.1 and 12.2). Among the latter species, less specialized fungal feeders, many predatory beetles and species only temporarily visiting the stump are included. If most of the 275 wood-dwelling beetles really live on or in spruce, this means that approximately half of all wood-living species considered to live in spruce wood in Sweden (about 450 species) have been found on or in stumps. This is more than we had imagined at the start of our project, but perhaps not so strange. Spruce is a species-rich tree species for wood-associated beetles, and stumps can accommodate a large percentage of the species found in decaying logs and high stumps.

Among the species found, 20 red-listed species living in wood were detected, and another two red-listed ones were classified as non-wood associated (Table 12.1). One might ask whether a stump-living species can really be red-listed. If it is widespread across many clear-cuts, the red-listing has probably gone wrong because of lack of knowledge about the insects found in the stumps. However, there are probably species that are only found in certain clear-cuts, perhaps because the forest history or the surrounding landscape is special. These species should still be relevant for red listing, but to safely define which species belong to this category, we would need to know more about where they are and about their requirements.

Something that has previously been neglected as regards beetles is that a large portion of the stump wood and coarse roots is actually found below ground. This wood has never before been investigated in terms of species diversity, perhaps with the exception of substrate for pine weevils. An important reason for this may be that it is very laborious to dig up the wood below ground. When comparing the above- and below-ground parts of the stumps, 50 beetle species were found above ground and 27 species below ground (Victorsson and Jonsell 2016). Ten out of the total 60 species were found only in the coarse roots. The wood below ground was certainly significantly more species-poor than above ground, but there are some species that thrive in the wood below ground, such as certain weevils and bark beetles and thus likely to be neglected by sampling just above ground.

Of the 52,200 beetles found, the bark beetle *Crypturgus pusillus* was the overwhelmingly most abundant beetle and accounted for 41% of all beetles found, followed by another bark beetle, *Dryocoetes autographus* (12%). These species prefer young stumps, and their high number depends on the ability to utilize the tree when the nutritious cambium is still there. Species that will arrive later in the succession never achieve such densities.

Small invertebrates

In a large study in southern and central Sweden, most groups of invertebrates were studied (Persson et al. 2011, 2013). The invertebrates encountered were animals with a lesser size than earthworms, e.g. enchytraeids, springtails (Collembola), mites (Acari), insects, spiders and myriapods. Nematodes and land snails were not included in the study. The overall objective was to identify species and other taxa that have such a strong preference for stumps compared to the surrounding soil that they might be sensitive to stump harvesting.

To find out, we took cylinder core samples in stumps, bark, stump periphery and surrounding soil (Figure 12.3).

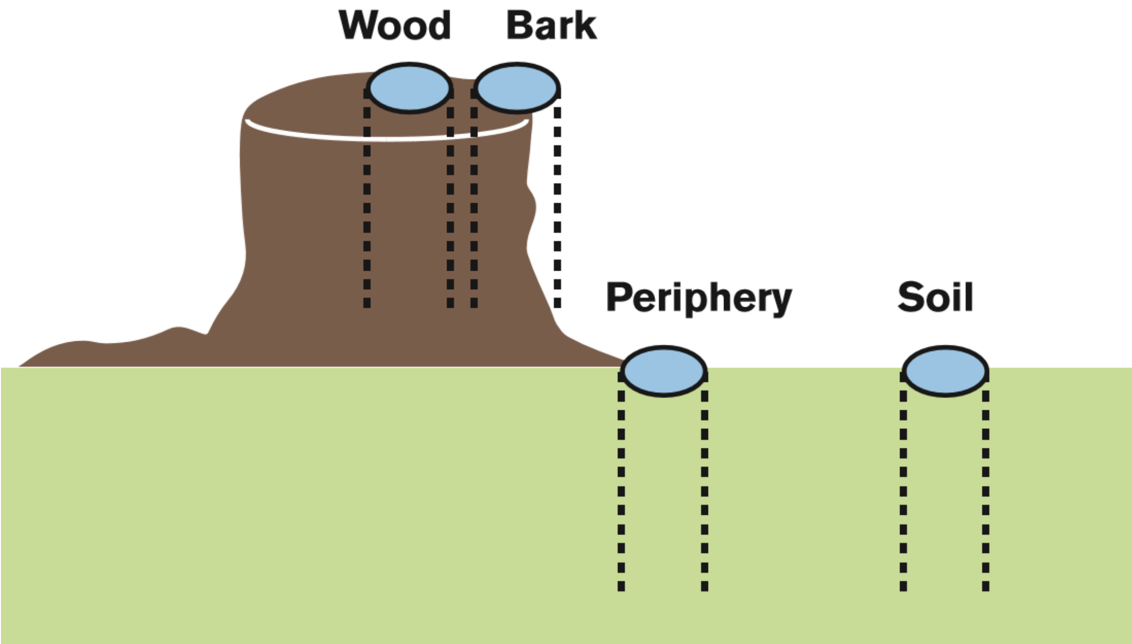


Figure 12.3. Illustration of how the samples were taken at each tree stump. The comparison of the number of invertebrates is based on the sampling areas viewed from above, 16 cm^2.

The stumps sampled were also of different age (5, 10 and 20 year-old) and tree species (Norway spruce and Scots pine), but here the results of only spruce stumps are accounted for. The animals were extracted out of their samples using Tullgren funnels (for air-dwelling animals) and Baermann funnels (for water-living animals). The number of invertebrates is in the following text given as individuals per m^2, where the cylinder-core surface (16 cm^2) is the basis for the estimates. For some animal groups such as springtails and mites, the numbers in the periphery were not counted.

Enchytraeids

Enchytraeids (pot-worms) are related to earthworms and are common in coniferous forests, where they (almost always) have higher biomass than all other animal groups combined. They are also common in the bark of 5-10 year-old stumps, where e.g. *Cognettia sphagnetorum* was one of the most numerous species (Figure 12.4). As a whole, we found eleven enchytraeid species, nine of which were in the stumps. As a taxonomic group they were still significantly more abundant in the soil than in the stumps, and none of the species seemed to be dependent on stumps for survival.

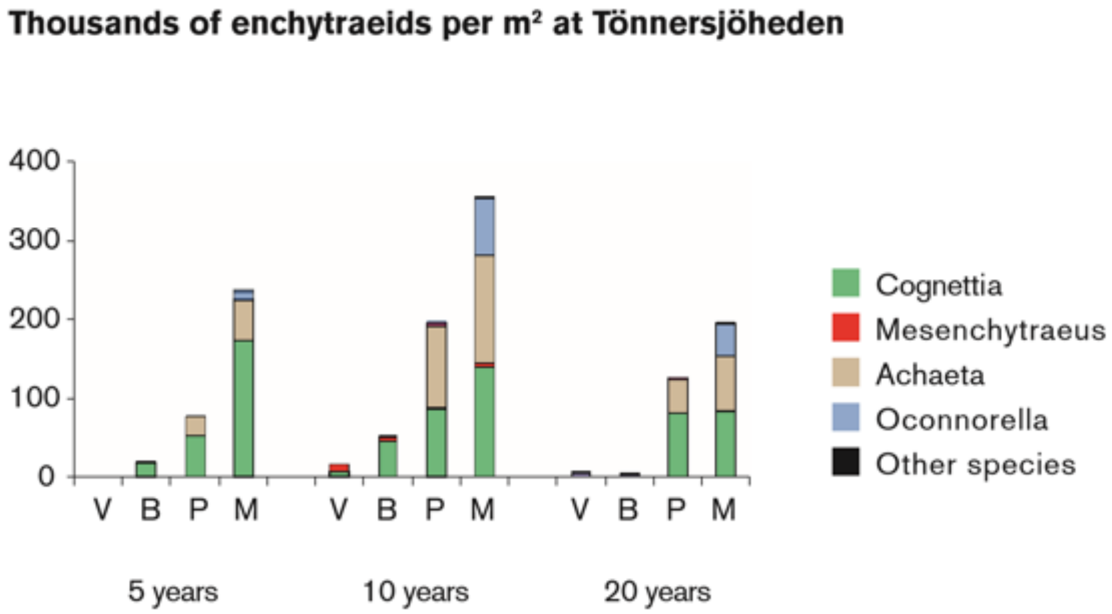


Figure 12.4. Abundance of enchytraeids (thousands) within and close to spruce stumps on 5, 10 and 20 year-old clear-cuts at Tönnersjöheden (the province of Halland). Different colours show the contribution from different species. W=wood, B=bark, P=periphery and S=soil.

Springtails

Springtails (collembolans) had their highest densities in the bark of 10-year-old stumps (Figure 12.5). No wood samples were taken when the stumps were 5 years, but in the 10 and 20 year-old stump wood, springtails were more abundant than in the soil. In all, 50 springtail species were found, of which 45 were found in stumps. Fourteen species were found exclusively in the stumps, but if some exceptional findings were disregarded, eight species seemed to be clearly favoured by stumps (more than 50 times higher density per m^2 in stumps than in soil).

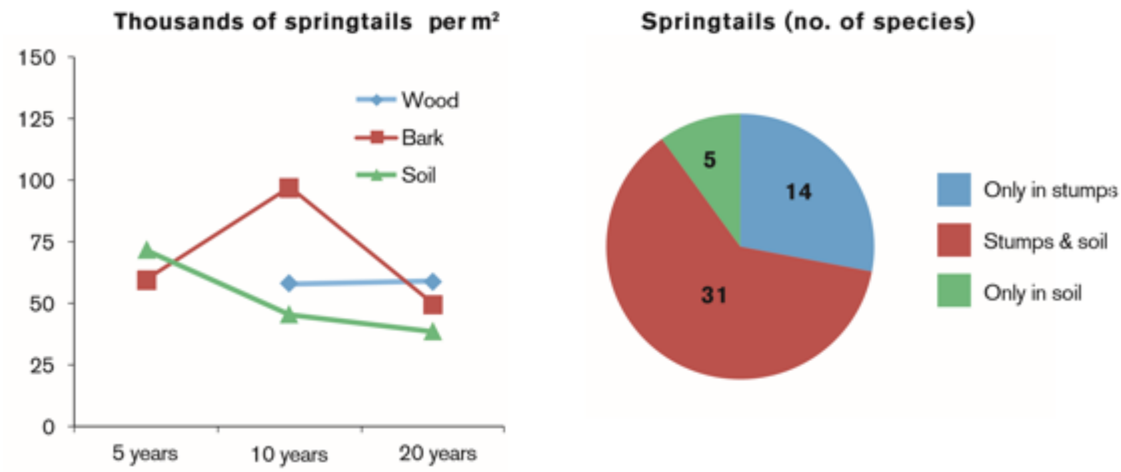
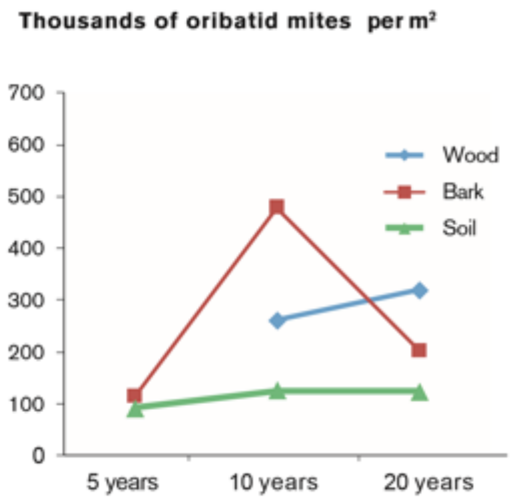


Figure 12.5. Thousands of springtails per m^2 of wood and bark (= stump) and surrounding soil 5, 10 and 20 years after clear-cutting and where the species were found viewed over all ages. The results are based on means of spruce stumps from Tönnersjöheden, Asa and Jädraås.

Oribatid mites

Most oribatid mites are considered to be typical soil animals. It was therefore unexpected that old stumps had more oribatid mites per m^2 than the soil (Figure 12.6). The highest densities were found in 10-year-old bark. When stumps became 20 year-old, more oribatid mites were found in the stump wood than anywhere else. As a whole, 101 species were found (some animals were only determined to family). Of these, a total of 90 species were found in the stumps of which 39 was unique for the stumps. When the individual findings were analyzed, at least 27 species were considered to be favoured by the stump habitat (more than 50 times higher density per m^2 in stumps than in soil). Certain fungal and lichen feeders were especially favoured by the stumps. As a curiosity, the cup lichen *Cladonia norvegica* only gets its species-typical red spots on the thallus after bite marks by the stump-favoured oribatid mite *Carabodes marginatus* and other *Carabodes* species.



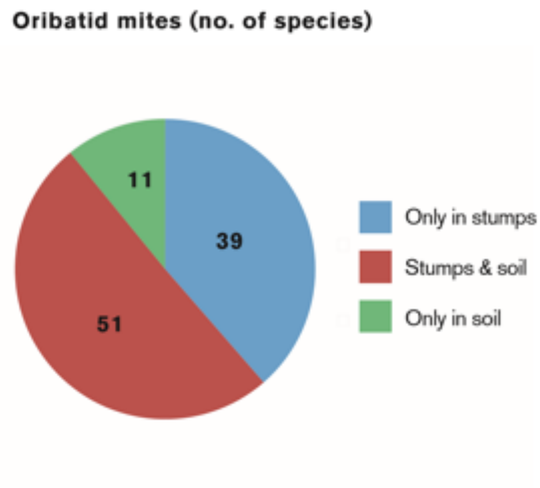


Figure 12.6. Total number of oribatid mites per m^2 of wood and bark (= stump) and surrounding soil 5, 10 and 20 years after clear-cutting and where the species were found viewed over all ages. The results are based on means of spruce stumps from Tönnersjöheden and Jädraås.

Predatory mites

Gamasid, uropodid and sejid mites belong to Mesostigmata, a group of mainly predatory mites. The abundance of predatory mites per m^2 was highest in the bark of 5-year-old stumps, but many also in the bark and wood of 10-year-old stumps (Figure 12.7). In all, 46 species were determined to species of which 34 occurred in stumps and 11 solely in stumps. The high abundance in the young stumps was mainly due to nematode feeders.

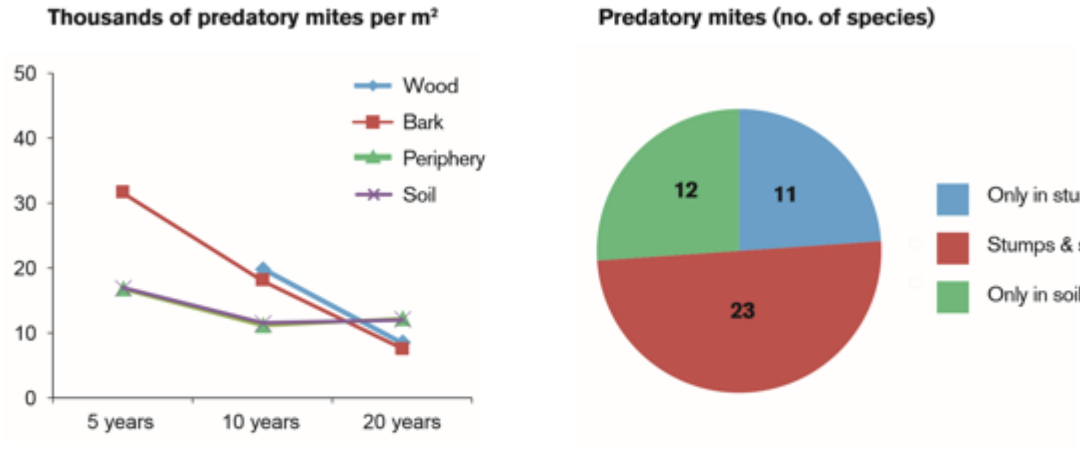


Figure 12.7. Total number of predatory mites per m^2 of wood and bark (= stump) and surrounding soil 5, 10 and 20 years after clear-cutting and where the species were found viewed over all ages. The results are based on means of spruce stumps from Tönnersjöheden, Asa and Jädraås.

Macroarthropods (large arthropods)

The macroarthropods studied were, with the exception of beetles (see above), woodlice, myriapods, insects, spiders, opilionids and pseudoscorpions. A total of 60 species and other taxa were determined, including 45 species/groups found in stumps (Figure 12.8). The species richness was certainly considerably higher, but the determination of midge and fly larvae could only be made to the family level. The most numerous macroarthropod species was by far the millipede *Proteroiulus fuscus*. This single species contributed 38, 37 and 22% to the total number of all macroarthropods in the bark of 5, 10 and 20 year-old stumps, respectively. Another common species was the stump-living ant *Lasius platythorax*, which had colonies in 30, 75 and 27% of all surveyed 5, 10 and 20 year-old spruce stumps, respectively (Figure 12.9).

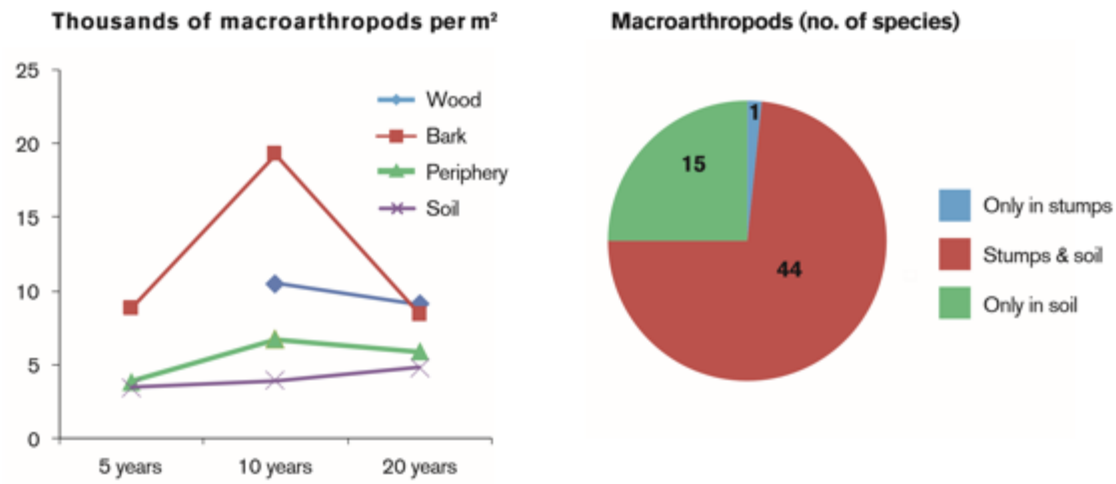


Figure 12.8. Total number of macroarthropods per m^2 of wood and bark (= stump) and surrounding soil 5, 10 and 20 years after clear-cutting and where the species were found viewed over all ages. The results are based on means of spruce stumps from Tönnersjöheden, Asa and Jädraås.

Figure 12.9. Bear-demolished 10-year-old spruce stump, in which the ant *Lasius platynothrus* had a colony.

Lichens

Many lichen species grow on top of the cut stump and on bark surfaces (Figure 12.10). Many of these species can also grow on other types of substrates, such as branches, bark of living trees or on rocks, and for such generalists the stumps probably have little importance. In a study of two forest provinces in central Sweden (Östergötland and Dalecarlia), various types of dead wood including stumps were surveyed for the presence of lichens (Svensson, 2013; Svensson et al. 2013, 2016). Stumps and logs seemed to be equivalent substrates for wood-living lichens. Wood-dependent lichens were more common in managed forests younger than 60 years than in older forests. This is likely due to the fact that younger forests contain more coarse dead wood than older ones, mainly because of the presence of cut trees and stumps after thinning. The survey included a total of 576 spruce stumps which harboured 77 lichen species. Significantly more lichen species were found on 16-19 year-old stumps than on 4-7 year-old ones. Fourteen species were more or less specialized on woody surfaces in sun-exposed positions. Wood-dependent lichens were relatively rare on the stumps, partly because they were easily out-competed by more rapidly growing lichens, and partly because they were often overgrown by mosses. In a study of lichens on 450 spruce stumps in Uppland, Caruso et al. (2008) found 52 lichen species. Most species occurred on 12-13 year-old stumps, and 16 of the species were new in relation to the study by Svensson et al. (2013).

Figure 12.10. Ten-year-old spruce stump with lichens on both wood and bark surfaces. Mosses have started to grow onto the stump from the outside and will eventually cover the lichens.

Mosses

Numerous moss species can be found on the stumps. Unlike lichens, mosses preferably grow in shaded positions. In a study of 449 spruce stumps in Uppland in an age series of 4-5, 8-9, 12-13 and 16-18 years, Caruso and Rudolphi (2009) found that the species richness increased with increasing stump age, increasing decay status and increasing shadow. As a whole, 35 moss species were found. A comparison with lichens showed that lichens were faster colonizers of stump surfaces than mosses, but mosses increased in frequency as time went on. As with lichens, there were only a few rare species, and most species growing on stumps can also grow on rocks and on the soil surface around the stumps. Stumps connected to key habitats or other diverse forests can, however, host mosses more worthy of protection, species that actually belong to the closed forest (Caruso et al. 2011).

How many species can be found in spruce stumps?

In the studies presented above, more than 1,355 species of fungi (of which 260 were identified and named), 491 species of beetles (253 alone in the study by Work et al. in Nordmaling), 223 species of other macroarthropods, 93 species of lichens and 35 species of mosses (Table 12.2). Overall, this adds up in 2,197 species. But a large number of species within the groups of nematodes, wasps, gnats, flies, flat worms, water bears (tardigrades) and mites, e.g. within the diverse group of Prostigmata, can be added. All together, these groups should perhaps add another 300 species resulting in at least 2,500 species. This figure can certainly also increase by extending the number of tree species, regions, stump numbers and stump ages. The question of how many species can be found in and on stumps can, therefore, only be answered by that there are at least 2,500 species, surely many more if we continue to take a better look.

The question of how old stumps should be to contain the highest number of species and individuals depends on the organism group. For fungi, it was found to be 11-20 years, i.e. before they became too degraded (Kubart et al. 2016), for most small animals 10 years (Persson et al.

2011, 2013), for lichens 12-13 years (according to Caruso and Rudolphi 2009) or 16-19 years (according to Svensson 2013) and mosses 16-18 years (Caruso and Rudolphi 2009). Beetles have in most cases been studied in young stumps (1-7 years), but the stump-age study in southern and central Sweden showed that the highest number of beetle species was found in 10-year-old stumps.

Table 12.1. Compilation of the beetle species observed on or in spruce stumps in the studies performed. The table also shows if they are wood-living and how the species are classified according to the Swedish red list for 2015.

	WOOD-LIVING SPECIES	OTHER SPECIES	TOTAL
LEAST CONCERN (LC)	256	213	469
NEAR THREATENED (NT)	17	1	18
VULNERABLE (VU)	3	1	4
TOTAL	**276**	**215**	**491**

Table 12.2. Number of species (genera, families) found in or on spruce stumps in different studies. The provinces are indicated by their Swedish abbreviations.

	NO. OF PROVINCES	NO. OF STANDS	STUMP AGE (YEARS)	NO. OF STUMPS	NO. OF SPECIES	REFERENCES
FUNGI	7 (Sm-No)	40	3-10, 11-20	485	1355	Kubart et al. (2016)
BEETLES	1 (Ån)	20	2-3½	1049	253	Work et al. (2016)
"	1 (Ån, Vb)	10	5-7	30	68	Hjältén et al. (2010)
"	1 (Hs)	10	3-7, 8-14	79	74	Jonsell and Schroeder (2014)
"	1 (Up)	7	1, 4-5	28	70	Jonsell and Hansson (2011)
"	1 (Up)	4	5-7	50	25	Ols et al. (2013)
"	1 (Up)	14	1-5	112	70	Jonsell (unpubl.)
"	3 (Hs, Vg, Ög)	16	2	160	46	Victorsson and Jonsell (2013a, b)
"	3 (Up, Vs,	12	1-2½	96	60*	Victorsson and

	Sm)					Jonsell (2016)
"	3 (Vs, Nä, Ög)	25	1-3½	392	235	Victorsson (2016)
"	3 (Ha, Sm, Gä)	9	5, 10, 20	45	29	Persson et al. (unpubl.)
BEETLES TOTAL			1-20	2041	491	
ENCHYTRAEIDS	3 (Ha, Sm, Gä)	9	5, 10, 20	90	9	Persson et al. (2011)
SPRINGTAILS	3 (Ha, Sm, Gä)	9	5, 10, 20	90	45	"
ORIBATID MITES	3 (Ha, Gä)	6	5, 10, 20	60	90	"
PREDATORY MITES	3 (Ha, Sm, Gä)	9	5, 10, 20	90	34	"
MACROARTHROPODS	3 (Ha, Sm, Gä)	9	5, 10, 20	90	45	Persson et al. (2013)
LICHENS	2 (Dr, Ös)	48	4-7, 16-19	576	77	Svensson et al. (2013)
"	1 (Up)	30	4, 8, 12, 16	450	52 (16**)	Caruso et al. (2008)
MOSSES	1 (Up)	30	4, 8, 12, 16	450	35	Caruso and Rudolphi (2009)
TOTAL					**2197**	

* Including stump and root samples. Stumps above ground contained 50 species in this study.

** Lichen species in addition to the 77 species found in Svensson et al. (2013).

13. STUMP EXTRACTION AND BIODIVERSITY

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Lichens grow on the stump surfaces and are comparatively easy to study by checking the stump exterior with a pocket lens with strong magnification, preferably in moist weather, when the lichen thalli are well developed.

Stump extraction affects forest biodiversity. A clear-cut where 75% of the stumps have been removed will lose 25% of the wood-living species. At higher extraction levels, the species loss will be even more pronounced. However, the intensity at which stump extraction is implemented at the landscape level is more important. Modelling studies indicate that the risk for regional extinction of species is small if stump extraction is performed on only 10% of the clear-cut area in a landscape. When stump extraction intensity increases, primarily "rare specialists on sun-exposed wood" are negatively affected. The added soil disturbance due to stump extraction seems to have only minor effects on ground-living invertebrates. Stump storage piles created at stump extraction can be an ecological trap for insects attracted to these piles. The trap effect was however confined to only a few species.

Effects on biodiversity

Stump extraction can affect biodiversity in at least four ways:

- Organisms dependent on dead wood will be short of habitats.
- Ground living species can be affected by the added soil disturbance.
- Species using stumps as a structure providing shelter and shade can be negatively affected.

- Stump storage piles can attract egg laying insects, whose offspring are killed when the stumps are incinerated at the heating plant.

Species-rich dead wood

Mainly organisms dependent on dead wood have been studied within the research programme. Stumps harbour a high diversity of saproxylics (wood-living species), and it has been estimated that 2,500 species can be found in Norway spruce stumps (see preceding chapter). Spruce stumps seem to harbour the same number of species as spruce logs. Fungi, lichens, and mosses living on stumps are primarily common species (Kubart et al. 2016; Svensson 2013; Caruso and Rudolphi 2009), whereas among saproxylic beetles there are some red-listed species, especially in hardwood stumps.

Figure 13.1. The species that prefer dead wood on clear-cuts are probably adapted to exploit large-scale disturbances. Clear-cuts offer more sun-exposed dead wood than any other stand type in managed forests. The amounts are however far lower than those created after, for example, a wind storm. The photo shows the result of the storm “Ivar” that leveled almost all trees at the edge of this nature reserve adjacent to a relatively young clear-cut.

There are no saproxylics specialized on stumps. Their vulnerability to stump extraction therefore depends to a large degree on what other types of dead wood they can utilize and the availability of those alternative substrates. Since dead wood is an ephemeral resource, dispersal is an important factor in the life cycle of all saproxylics. Dispersal takes place on a larger scale than that of an individual forest stand, especially for species adapted to sun-exposed dead wood. In natural forests, sun-exposed dead wood is mainly created at large-scale forest disturbances such as forest fires and wind storms (Figure 13.1). Therefore, the effects of forestry measures should be evaluated at the landscape level since dead wood is available in all types of stands even if the amount and quality of dead wood vary widely between different forest age classes and between different types of management. Most saproxylic insects and many fungi have rather strict habitat demands regarding host tree species, substrate diameter, sun exposure and type of wood rot. The amount of suitable dead wood varies widely between forest types but is crucial in determining the population level effects for a given species.

The goal in the second part of the stump research programme regarding stump biodiversity was to determine the effects of stump extraction on the survival of saproxylic populations. Several landscape level studies were therefore performed but also studies at the stand level comparing stump extracted clear-cuts with ordinary clear-cuts.

Effects at the clear-cut level

Stump extraction normally reduces the stump-wood volume at the clear-cut level by 75%. The abundance of stump-living species is assumed to decline proportionally in relation to this reduction, whereas the species richness decreases non-linear with increasing stump extraction intensity (see the species accumulation curve in Figure 13.2). Since there are many individuals of a given species, the effect of removing the first stumps will be less than the effect of the removal of the last stumps. Data from clear-cuts in the provinces of Ångermanland and Västerbotten in the northern part of Sweden showed that with a normal 25% stump retention, the reduction in the number of saproxylic beetle species was 24% (Figure 13.2, Work et al. 2016). Since the slope of the species accumulation curve increases with increasing stump extraction levels, a reduction to 15% stump retention will, for example, decrease the species richness with 38%. On the other hand, if the stump retention is as high as 50%, only 10% of the species will be lost.

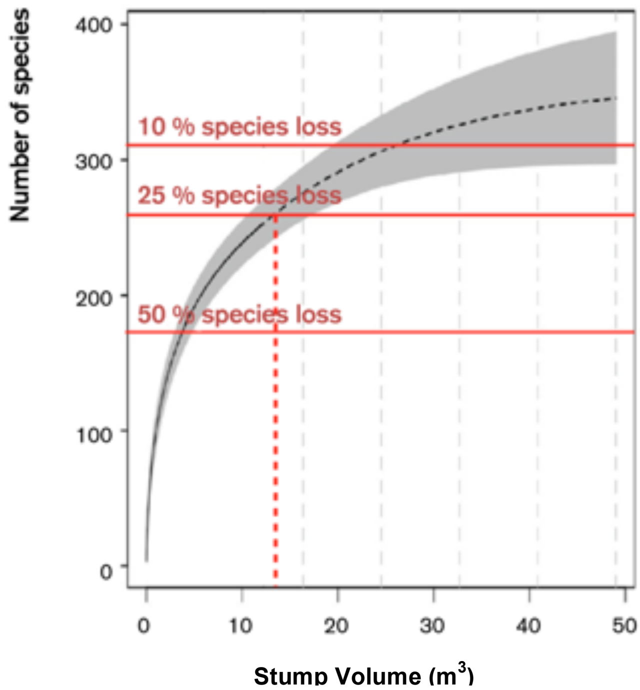

Figure 13.2. Species accumulation curve showing changes in species richness at an average-sized clear-cut (6 ha) at different levels of stump extraction intensity. The indicated level of 25% species loss is what can be expected when 75% of the stumps are extracted. The downward slope of the curve increases rapidly with increasing stump extraction intensity above that level, leading to a rapid species loss. The grey zone indicates the uncertainty (95% confidence interval) in the calculation.

Besides the predictable effect that stump extraction reduces the number of species at the clear-cut level, there are also two studies that indicate that there are fewer species or individuals per stump in the remaining stumps. In saproxylic beetles in clear-cuts in central Sweden the species number was reduced from 18 to 15 when summed over ten stumps (Victorsson and Jonsell 2013). Similarly, the abundance per stump of two dead-wood associated millipedes was halved in stump-extraction clear-cuts compared with ordinary clear-cuts (Taylor and Victorsson 2016). In the previously mentioned study from northern Sweden, there was no such effect (Work et al. 2016). The reason for these different results is not known, but there are several possible explanations. Firstly, many ground living beetle species (not dependent on dead wood) were included in the northern study. Secondly, the northern study sampled a wider age range of clear-cuts. Thirdly, different forest companies could use different protocols for stump extraction. For example, retaining stumps primarily in wet parts of the clear-cut is beneficial regarding loss of soil nutrients and erosion, but stumps on wet ground are less utilized by saproxylic beetles. Several species prefer stumps on dry soil, whereas no species seem to prefer stumps on wet soil. This results in lower insect diversity in stumps on wet soil (Ols et al. 2013).

The species accumulation curve (Figure 13.2) could be used as an argument for limiting stump extraction to 50% of the stump volume in any given clear-cut, if you accept 10% as a tolerable species reduction at the clear-cut level. Every stump that is removed beyond that leads to a greater species loss since the slope of the curve increases. Alternatively the curve could be used to argue that it would be beneficial for the saproxylic diversity to extract at a maximum level in the clear-cuts that are scheduled for stump extraction in order to decrease the number of clear-cuts that are stumped at a landscape level. In other words, it is presently not possible to give recommendations on stump extraction levels based on these studies at the clear-cut level since the surrounding landscape is so important.

Stump extraction and ground living insects

The effect of stump extraction on ground-living insects has been studied in comparisons between stump extracted clear-cuts, ordinary clear-cuts, and mature forest. There was only a small effect of stump extraction on species composition, even if generalist and open-habitat species benefited somewhat from stump extraction (Kataja-aho et al. 2016). On the other hand there was a large effect of the clear-cutting itself, with a strong effect on species composition, so the effect of the increased disturbance due to stump extraction was comparatively small.

Effects at the landscape level

Lichens

Saproxylic lichens have been studied in two landscapes with a long history of forest management, one landscape in the province of Östergötland and one in the province of Dalecarlia (Svensson et al. 2016). Out of the 20 species studied, 11 had more than half of their populations on stumps and four species were confined only to stumps. The results indicate that clear-cut stumps harbour a large part of the populations of these species. The stumps were much more important than the other types of bioenergy wood, slash and fine-diameter dead wood, which were only utilized by five species. Furthermore, for all those five species other types of wood were more important than the small-diameter wood.

Results from a landscape study in the province of Hälsingland indicate a partly different pattern (Hiron et al. 2017). In that study, clear-cut stumps were not important for any species, while slash was very important for two out of 15 species. This landscape differs from the two others by having a much shorter history of forestry.

Fungi

In the landscape level study in Hälsingland, saproxylic fungi were also studied. Also among these species 15% of the species had half of their population or more in bioenergy wood. Slash and stumps were of equal importance for saproxylic fungi (Hiron et al. 2017).

Beetles

Among 39 beetle species in the same forest landscape in Hälsingland, it was estimated that 26% had more than half of their population in clear-cut stumps (Figure 13.3, Jonsell and Schroeder 2014). Two species were estimated to have their entire population in stumps. This is most likely an overestimate, since no species so far can have evolved to be a stump specialist, but it shows the importance of stumps for these species. Unfortunately there were no data from fine woody debris in this study.

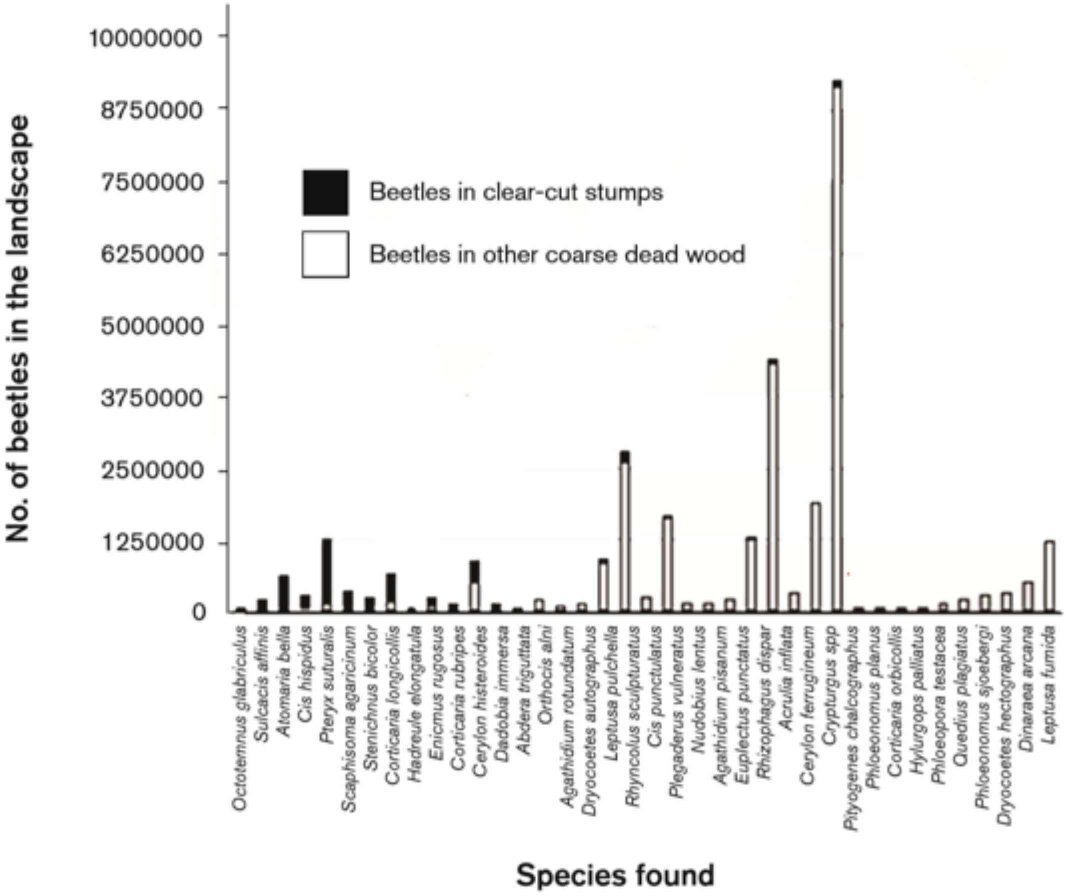

Figure 13.3. Number of beetles in clear-cut stumps and other types of dead wood in a landscape in northern Hälsingland. The species are ordered after the proportion of their population that occurred in stumps created at final felling. The common species usually had a fairly low proportion of their populations in stumps.

In the study mentioned above by Hiron et al. (2017), the results showed that most of the beetle species in the 39-species study that had a high proportion of their population in clear-cut stumps also had a fairly large part of their population in slash. If the shares of the population in slash and stumps are added, then nine of these species had between 46 and 95% of their populations in bioenergy wood. An exception is the minute tree-fungus beetle *Hadreule elongatula* that had most of its population in high stumps in clear-cuts. Species that to a large degree utilize slash and stump wood are adapted to sun-exposed dead wood created by large scale disturbances such as forest fires and storm fellings. In the today´s managed forest landscapes, clear-cuts are the main provider of that habitat type, and retained slash and stumps are therefore important for these species.

Modelling study

In a modelling study covering 200 years, eight fictitious species were allowed to colonize and go extinct in dead wood with varying levels of stump and slash extraction (Johansson et al. 2016). The species were assigned different ecological traits regarding dispersal ability, habitat specialization and rarity. The extinction probability varied between species due to these traits. Rare species decreased more than common species, especially species that also had poor dispersal ability and a specialized habitat choice regarding dead wood quality. The most sensitive combination was "rare specialists on sun-exposed dead wood", and these species had some extinction risk already at a level of stump extraction of only 10%. The negative effects could be mitigated by concentrating the extraction of bioenergy wood to only a part of the landscape (Figure 13.4). In many cases it took 100 simulated years before the population level of a given species had declined and reached a new equilibrium after the introduction of stump extraction. We can therefore expect that the effects of stump extraction on biodiversity will take a long time to materialize even with a large-scale implementation of stump extraction.

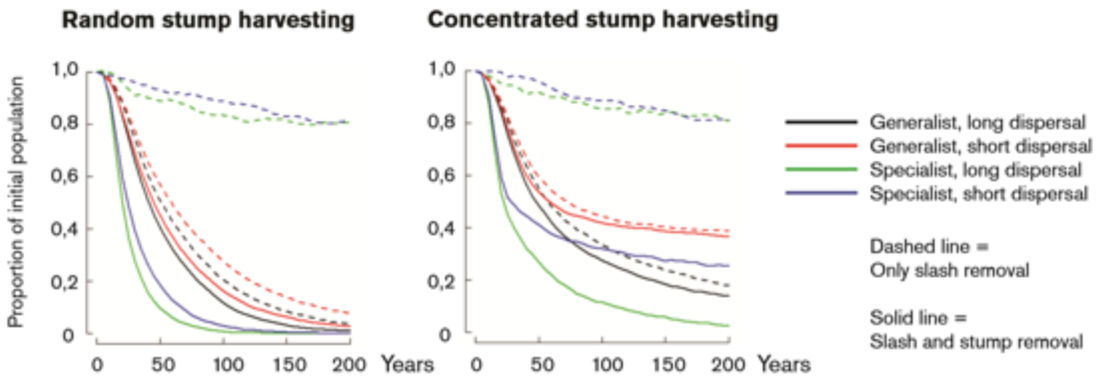

Figure 13.4. Examples of population change over time in four fictitious, rare species occurring in only 20% of the clear-cuts in a landscape. Stump extraction is performed in up to half the available clear-cuts in this model landscape. Specialists on sun-exposed wood and large-diameter wood were affected more rapidly. The population decline was less pronounced if the bioenergy wood extraction was concentrated to only a part of the landscape (compare the two figures).

Stump storage piles as an ecological trap

After extraction, the stumps and coarse roots are stored close to the clear-cut for one to several years (Figure 13.5). There is a risk that these storage piles become ecological traps for egg-laying saproxylic insects. If they use the piles for oviposition, all offspring are killed at energy extraction. Attraction to the piles can potentially be large since saproxylic insects find substrates by using olfactory cues, and the piles have a potential to emit attractive chemical signals.

Figure 13.5. Stump storage piles can be ecological traps for saproxylic insects since the piles emit odors attractive to many species looking for suitable breeding substrates. The piles are however only severe ecological traps for a small number of species – most species are more common in the stumps left in the extraction clear-cut.

To quantify the trap effect, we compared the beetle abundance in stump storage piles to the abundance in the remaining stumps in the extraction clear-cut adjacent to the piles. We found that 66% of the suitable habitat, i.e. the available bark area, was found in the piles and 34% in the remaining stumps. Despite this only 14% of the saproxylic beetle abundance was found in storage piles (Victorsson and Jonsell 2013). Out of the 15 species that could be tested, 11 species were more abundant in the clear-cut than in the piles and for these species the trap effect was small. The four species that had a higher abundance in the piles experienced a trap effect. Three species were about seven times more abundant in the piles, which indicates a severe trap effect for these species.

Consequently, the trap effect is small if you consider all saproxylic beetles, possibly because stump storage piles dry fast and might be a poor substrate for many species. Furthermore, spruce-living species are not under pressure in Scandinavian landscapes, since the amount of Norway spruce is increasing. At moderate levels of stump extraction, the risk for regional extinction of species due to trap effects should therefore be low. For other types of bioenergy wood, where there is less rapid substrate drying, or where the type of dead wood is rare, the trap effect could be much larger.

Conclusions

Some forest living saproxylic species have a large part (more than 50%) of their populations in clear-cut stumps. It is difficult to predict which level of stump extraction these species can tolerate without negative effects. However, we can say that primarily "rare species specializing on sun-exposed dead wood" are most at risk.

Modelling studies indicate that the risk for species extinction increases already when only 30% of the clear-cut area in a landscape is stump extracted.

The additional soil disturbance due to stump extractions seems to have surprisingly small effects on invertebrates living on the soil surface.

Stump storage piles attract some saproxylic beetles, but only a small number of species seem to prefer the piles over the remaining stump on the extraction clear-cut.

14. HOW ARE TREES RETAINED ON CLEAR-CUTS AFFECTED BY SLASH AND STUMP HARVEST?

Jörgen Rudolphi (SLU, Umeå) and Lena Gustafsson (SLU, Uppsala)

Trees, snags and logs retained after stem harvest are positive for keeping the biodiversity. But what happens to the retained logs saved for conservation reasons when slash and stumps are harvested? This activity involves many heavy machines, which increases the risk of damages on retained trees and logs. Here a log has been flattened by one or more of these vehicles.

An inventory of retained trees at 122 clear-cuts showed small differences between stump-harvested, slash-harvested and conventionally harvested stands. The logs in the stump-harvested stands had however slightly more ground contact, and there were also somewhat fewer standing dead trees.

Retention forestry and voluntary set-asides along with strictly protected areas, such as national parks and nature reserves, constitute corner stones in nature conservation both nationally and internationally.

Figure 14.1. There are few studies of how nature conservation is linked to biofuel extraction, but where trees are retained, lichens seem to be favoured.

A large number of studies on the effects of retention forestry on biological diversity have been carried out. Studies have also been performed synthesizing current knowledge on the effects of retaining trees at clear-felling in both Europe and North America. These studies clearly indicate positive effects when compared with clear-felling lacking retained trees, especially for ectomycorrhizal fungi, epiphytic lichens and insects that benefit from disturbance (Figure 14.1). Studies on other processes such as N retention, tree regeneration and pest outbreak are fewer. Also studies on esthetic aspects are few in number, although they do exist. No studies have yet been found that cover retention forestry from cultural or recreational aspects.

Studies on how retained trees are affected by forest fuel harvest are very few. One of few scientific studies on this was done in Sweden, and it shows that rather much coarse dead wood is lost – wood that otherwise would have been retained to benefit flora and fauna.

Significantly lower volumes of for example high stumps and logs were found in slash harvested clear-fellings in comparison to conventional clear-fellings according to a study in the eastern parts of central Sweden. An analysis of data gathered by the Swedish Forest Agency during the 2000s shows significantly lower grades for the factor "damage to ground and water" in slash-harvested clear-fellings.

Large Study

The above mentioned studies, field observations and discussions with forestry actors have led to a fear that the level and quality of the retention effort may be jeopardized not only by slash but also stump harvest. This is mostly due to the increased number of machines operating in the clear-felled areas. As a result of slash and stump harvest, no less than six different machines are involved: harvester, forwarder, slash forwarder, stump excavator, stump forwarder and soil scarifier. This not only risks causing increased soil damage but also risks harming the living and dead trees retained to benefit biological diversity.

To investigate this, we investigated 122 clear-fellings with respect to level and quality of the retained trees during 2012 and 2013 (Figure 14.2). The clear-felled stands were selected according to three different categories:

1) Slash harvested,

2) Slash and stump harvested,

3) Conventionally harvested stands (control stands) without any extraction of biofuel.

The aim was to see how the trees retained at clear-cuts were affected by extraction of slash and stumps and also if there is a regional variation.

The size of the clear-fellings varied between 2 and 51 hectares. Stump-harvested stands were, on average, more than 6 ha larger than stands where only slash or no biofuel were harvested.

Figure 14.2. Nature conservation items on 122 clear-cuts were investigated. The clear-cuts were either conventionally harvested without removal of logging residues (control sites) or subjected to slash harvesting or slash + stump harvesting.

Main Results

The main results are summarized in Table 14.1.

- We could not find any significant differences between clear-cut categories with respect to the volume of lying dead wood or number of living retention trees.
- The proportion of logs that were broken due to machines driving over them did not differ between clear-cut categories.
- Logs on stump-harvested clear-cuts had a higher degree of ground contact when compared with the other two categories of clear-cuts.
- There were significantly fewer standing dead trees on stump-harvested clear-cuts than on the control stands.

The higher degree of ground contact of the dead wood after stump harvest is likely to lead to a faster decay of the wood. This means that the time during which dead wood will be available for organisms that demand this substrate will be shorter. The higher degree of ground contact may be a result of a higher number of machines driving on the clear-cut area. On the other hand the number of wood objects run over by machines did not differ between biofuel harvested and control stands. Thus it seems as if lots of woody material is run over during final harvest, and that slash and stump harvesting does not lead to an increase in this respect. Since we did not register to what extent every single piece of wood was destroyed, we cannot draw any conclusions concerning how biofuel harvest affects individual logs.

The lower number of snags in stump-harvested stands can potentially affect wood-living beetles, and also lichens and fungi. Snags on clear-cuts have been shown to be of significant importance for many species, and it is important that the trees retained at final harvest are preserved.

That fewer snags were found after biofuel harvest matches the result from the earlier mentioned study that also showed that the number of natural high stumps was lower on slash-harvested stands when compared with stands where branches and tops were retained.

Although this study was primarily designed to provide answers to the relative differences between logging categories, it can be concluded that the levels of tree retention were generally low. It underlines the importance of retained trees and the recommendation that they are not damaged by biofuel harvest.

Table 14.1. Mean values for the variables measured in the study. Figures in bold indicate a significant difference in relation to the control stands. Standing dead wood (high stumps and snags), living retention trees and clear-cut stumps are presented as numbers per hectare.

	SLASH HARVEST (N=41)	SLASH AND STUMP HARVEST (N=45)	CONTROL (N=36)
LYING DEAD WOOD (M^3 HA^{-1})	7.5	5.0	6.5
GROUND CONTACT (%)	15.8	**20.6**	11.5
WHEEL DAMAGE (%)	52.0	41	40.0
STANDING DEAD WOOD (NO. OF OBJECTS HA^{-1})	4.3	3.7	5.2
NO. OF HIGH STUMPS	2.6	2.5	3.1
NO. OF SNAGS	1.7	**1.2**	2.1
LIVING RETENTION TREES (NO. HA^{-1})	3.6	3.1	3.2
DBH 15-50 CM	3.5	3.0	3.1
DBH > 50 CM	0.1	0.1	0.1
STUMPS (NO. HA^{-1})	575	**216**	517

15. CAN INCREASED EXTRACTION OF FOREST BIOFUELS BE COMBINED WITH ACCEPTABLE ENVIRONMENTAL CONCERNS? – RESULTS OF INTERVIEWS WITH FOREST ACTORS

Karin Gerhardt (SLU, Uppsala), Marie Appelstrand (Lund University) and Johnny de Jong (SLU, Uppsala)

Different kinds of forest machines, entrepreneurs and people are involved when forests are being harvested for timber, as well as branches, tops and stumps. In this study we performed a series of interviews with different stakeholders within the "logging and biofuel sector". The results show that there are discrepancies/inadequacies in planning, logistics and communication between the different actors, particularly when there were different entrepreneurs involved (one for timber harvesting, another for harvesting slash, and another harvesting stumps). The answers showed that there is a need for increased "practice training" within existing forest education. Additionally the field knowledge that exists among experienced entrepreneurs and forest machine operators should be better taken care of in the organizations where they work

To obtain a good understanding of different actors know-how, attitudes and motivation to combine biofuel harvesting with environmentally sound practices, 28 in-depth interviews were undertaken with land owners, entrepreneurs, forest machine operators, employees in the forest authority and environmental NGOs.

The key questions were:

- Can extensive harvest of forest biofuels be combined with a high standard in environmental concerns?
- How can the actors be motivated to combine the two above objectives?
- What are the incentives (both pros and cons) to include biofuel harvesting operations according to the different stakeholders?

The interviews were in some cases combined with field visits. The results demonstrated that there are severe inadequacies in planning, logistics and communication between the different actors, particularly when there were several entrepreneur companies involved. Lack of planning between the different harvesting steps increased damages in harvested forests (biodiversity, damages on remaining dead wood and compaction damage to the soil) and increased the process time for the different operators, leading to higher costs than necessary for the operation.

It also became clear that the entrepreneurs had a tough working situation with broken contracts, short time frames and a large personnel turnover. Some replies indicated that the status of the machine operators need to be increased, as they have valuable practical experience which are seldom listened to within their organizations or forest companies.

Another improvement of the situation would be to increase the technical development of the harvesters and excavators to do more of the operations, which would lead to fewer machines and consequently fewer negative effects on the environment.

There was also a consensus among several of the stakeholders to have an increased "field training" within existing forest education programmes/courses.

Figure 15.1. Sometimes there is a lack of environmental concern when harvesting stumps. Here the excavator has been passing a wet area in the harvesting site leading to ugly soil damages.

Figure 15.2. Key themes for the 28 in-depth interviews that were done with land owners, entrepreneurs, forest machine operators, authority officials, environmental NGOs to get their views on biofuel extraction with a focus on stumps.

Some Key Answers

Economy

- Imports of household waste to burn for heating has decreased the demand for forests biofuels in Sweden
- When the price of biofuel is too low, there is no incentive for the forest companies to harvest biofuels
- The entrepreneurs harvesting the biofuels can use these as a payment for the costs of scarification in the harvested site
- "Stumps are easier to store than branches and tops, which could lead to a profitable

assortment in the future" (forest company officer)

Environment

- "Personnel from the construction sector are sometimes hired to harvest stumps, and their lack of knowledge in stump harvesting can lead to destroyed forest stands and destroyed conservation objectives" (entrepreneur)
- "Why do you even consider harvesting stumps when dead wood is a limiting resource in the forest?" (officer from an environmental NGO)
- "There is no difference in environmental concern between stem-only harvest and stem + biofuel harvesting" (officer in a forestry company).
- "Aesthetic and game concerns are more important than environmental concerns" (private land owner)
- "There is more valuable biodiversity in logs, snags and high stumps than in low stumps, which can be removed for biofuel" (officer in a forestry company)

Technology and logistics

- "Lack of planning leads to unnecessary driving with the heavy machines" (entrepreneur, official at a forestry organization)
- "The forest machines are used in stands even when the soil is considered too wet, which leads to more soil and dead-wood damages than necessary" (private land owner)
- "Too much machine transportation time between different harvesting sites" (entrepreneur, officer in a forestry company)
- "The research to develop new and better machines is on-going" (biofuel specialist in a forestry company)

Knowledge and education

- "There is still a lack of knowledge, so we cannot increase the intensity in stump harvesting" (official authority, officer in a forestry company, entrepreneur)
- "There is a general deficit of practical field training within forest education/training" (entrepreneur, forest machine operators)
- "The boards of the forest companies need to be educated" (officer from an environmental NGO)

Attitudes and motivation

- "The need of forest biofuel is society-driven rather than from the forest sector. This is a political issue!" (officer in a forestry company).
- "Private land owners often let the environmental concern be performed by the entrepreneurs without an instruction from the land owner. The final responsibility for the forest operation is up to the land owner, not the entrepreneurs" (private land owner)
- "People who only own forest as an investment are often less interested in nature concerns than a land owner that lives close to the forest" (private land owner and forestry consultant).

16. IT IS POSSIBLE TO COMPENSATE FOR BIOMASS EXTRACTION BY CREATING MORE HIGH STUMPS

Thomas Ranius (SLU, Uppsala) and Jörgen Rudolphi (SLU, Umeå)

Slash and stump harvesting can be detrimental for many species associated with dead wood. However, most of these species may also utilize high stumps, and our analysis reveals that it is cost-effective to combine slash harvesting with the creation of high stumps. Many snags are required to achieve full compensation. In contrast, according to the analysis it is not cost-effective to combine stump harvesting with creation of high stumps. The difference is primarily due to that the net revenue is lower for stumps.

Background

One of the main arguments against biomass extraction is that it is detrimental to forest organisms, especially to those dependent on dead wood. This can make it difficult to gain acceptance for more extensive stump extraction in Sweden.

An alternative to restrict the extraction of stumps is to compensate with measures that increase the amount of dead wood. Globally, compensation measures are applied to an increasing extent. They represent a compromise between activities with negative impact on biodiversity and the conservation of biodiversity (McKenny and Kieseckar 2010). They are used, for instance, to preserve wetlands in the U.S. and are a part of the EU's rules for Natura 2000 areas. Compensatory measures in forestry, such as creating more high stumps as a compensation for stump extraction, have been discussed by Hjältén et al. (2010) but have previously not been studied systematically.

In this project, we analyzed the efficiency of a compensation measure - creation of high stumps - to increase the amount of habitats for organisms negatively affected by biomass extraction. The analysis was done at a landscape level.

The effects on biodiversity were analyzed for all species of beetles, lichens, mosses and fungi living on dead spruce wood in Sweden.

Method

The analyses were made for a normal forest of spruce, i.e. a managed forest landscape with an even stand-age distribution. Three Swedish counties in southern, central and northern Sweden were included in the analysis: Kronoberg, Gävleborg and Västerbotten.

We started by predicting forest development and calculating the optimal timing of thinnings and final felling using the so-called 'Beståndsmetoden' (the Stand Method). Based on this, we predicted the amount of dead wood in the forest by simulations.

The effects on biodiversity were analyzed by including all species of beetles, lichens, fungi and mosses that live on dead spruce wood in Sweden. We used a database of expert assessments of the types of dead wood that each individual species can utilize and prefer. By summarizing the amount of different types of dead wood we estimated the amount of available habitat for each species.

Slash and stump extraction reduces the amount of habitat for dead-wood dependent species

At a landscape-level, according to our analysis, the volume of dead wood decreases by 22-25% if slash is extracted at all final fellings and by 42-46% if both slash and stumps are extracted. The interval indicates the difference between studied regions, which was thus quite small. The figures include all dead wood, also roots under the soil surface. Currently, it is not realistic that biomass would be extracted at every felling, so in practice the reduction is smaller.

Slash and stump extractions reduce the amount of habitat by more than 50% for 8% of the analyzed species. Most of these species are fungi and beetles, as they are the most species-rich dead-wood dependent organism groups.

Slash and stump extraction may be compensated for by high stump creation

If all revenues from slash and stump extraction are used to create high stumps, most species negatively affected by biomass extraction will obtain more habitat (Figure 16.1). This implies that high stump creation is a compensatory measure that may be effective. For many species, this combination of biomass extraction and high stump creation generates much more habitat compared to doing nothing.

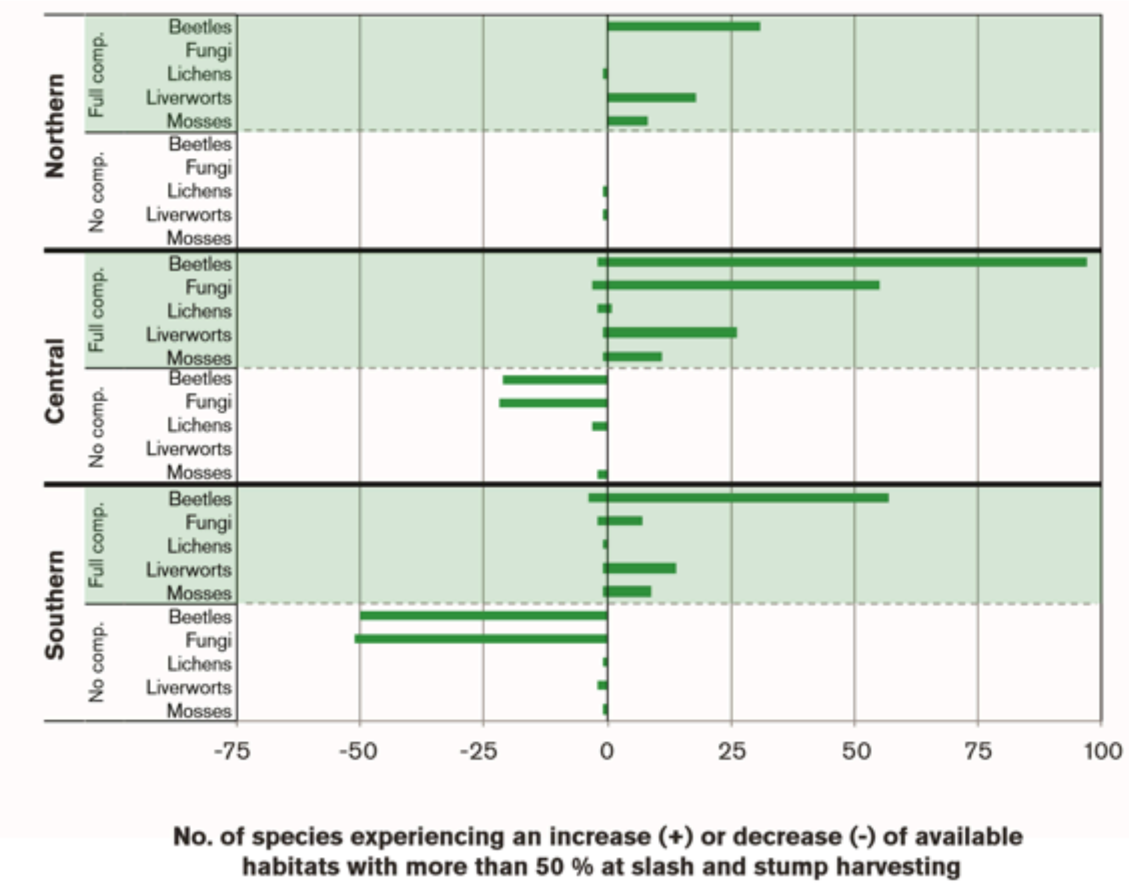

Figure 16.1. Number of species whose substrate availability was strongly affected (> 50%) by biomass extraction and creation of snags. "No comp." means that both stumps and slash are extracted at all clear-cuts and no high stumps created, while "Full comp." means that the net profits gained from slash and stump extraction are used to create snags. Results for the three studied regions in Sweden.

It is cost-effective to compensate for slash extraction with high stump creation - more questionable for stump extraction

We found that large amounts of high stumps are needed to compensate for biomass extraction. Approximately 40% of the revenue from slash and stump extraction has to be used to obtain the same biodiversity index as when slash and stumps are not extracted. With slash extraction alone, high stumps have to be created from 9% of the felled trees, if also stumps are extracted high stumps from 14% of the felled trees are needed. High stumps are today created routinely at final harvesting, but they are few in comparison to the amounts needed to achieve full biodiversity compensation and have therefore little impact on the outcome of our analysis.

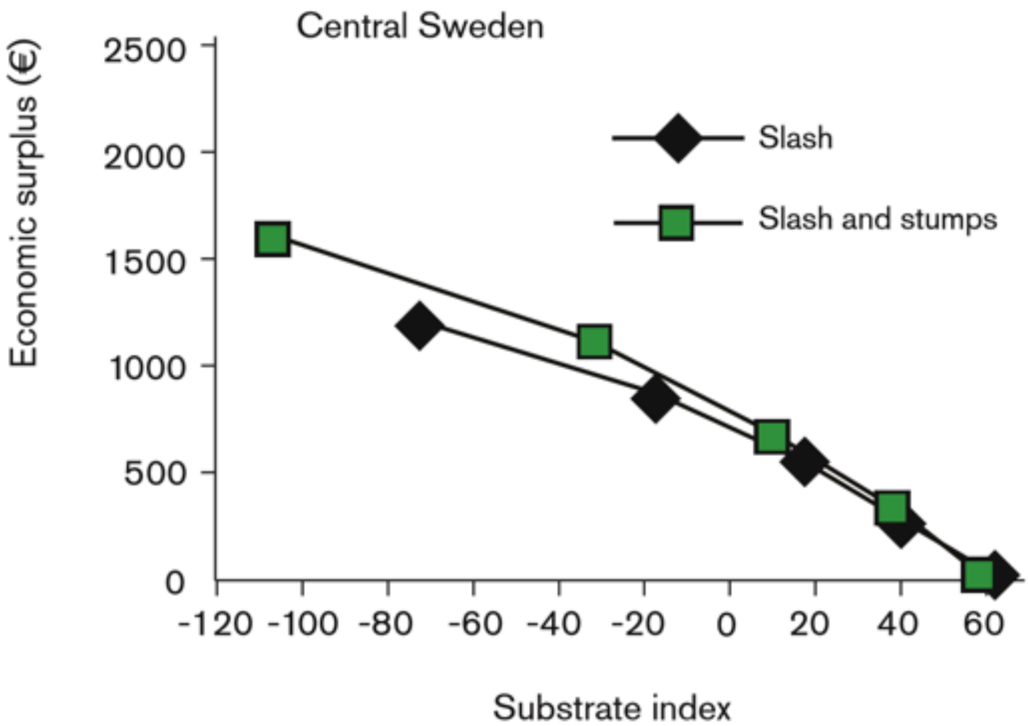

Figure 16.2. The square to the left shows the outcome of stump and slash extraction (open squares) or only slash extraction (solid squares) without any high-stump creation. This point represents the best financial outcome and the worst biodiversity index. When going to the right, the next square reflects the outcomes when using 25% of the revenue from biomass to create high stumps, and then 50%, 75% and 100%. The curves are partially within an area where both the economic outcome and the biodiversity index is better than if neither extracting slash or stumps and no compensatory measure was performed. This means that high stump creation is a cost-effective compensation. The fact that that the two lines (with and without stump extraction) are close together means that no more value is obtained by combining stump extraction with high stump creation. The figure shows the outcome central Sweden. The outcome of northern and southern Sweden looked similarly but were at slightly different levels.

It is possible to combine slash extraction with high stump creation to obtain a more favourable outcome both economically and for biodiversity (Figure 16.2). Admittedly high stumps are more expensive per cubic meter than slash, but the high stumps serve as habitat during a longer time before they are decayed, and more species can utilize coarse woody debris in comparison to slash. This means that to limit the negative effects of biomass extraction, it is better to create more high stumps than to limit the biomass extraction.

For stump extraction the outcome is not clearly positive. This means that from an economic standpoint it is equally favourable to limit stump extraction. The differences in outcome between slash and stump extractions are mainly caused by the fact that stump extraction is more expensive.

17. CONCLUSIONS ABOUT THE ENVIRONMENTAL EFFECTS OF STUMP HARVESTING

Tryggve Persson (SLU, Uppsala)

Cowberry (*Vaccinium vitis-idaea*) and bilberry (*Vaccinium myrtillus*) prefer to grow close to stumps. Several studies show that these species are unfavourably affected by stump harvesting during the initial clear-cut period.

From a climate perspective, bioenergy from stumps is better than energy from fossil fuels, and stump harvesting resulted in markedly lower emissions of carbon dioxide into the atmosphere than natural gas and coal viewed over a whole forest rotation.

Stump harvesting increases the proportion of vegetation-free soil surfaces and also increases soil mixing. In contrast to earlier hypotheses, our results suggest that the soil disturbance will reduce the emissions of the green-house gases carbon dioxide, nitrous oxide and methane into the atmosphere.

Stump removal sometimes leads to increased nitrogen leaching and can sometimes increase the amount of pits in which toxic methyl mercury (MeHg) is formed. Despite this, the MeHg concentrations in stream water have not been shown to increase.

Stump harvesting increases the natural regeneration of birch and pine trees, does not appear to affect timber production in the next forest rotation, and appears to

reduce the infection rate of root rot.

Stump extraction decreases the amount of berry-forming dwarf shrubs in young clear-cuts, and increases the occurrence of certain ferns and herbs. In a longer perspective (decades), the ground vegetation seems to recover.

Biodiversity, especially species dependent on dead wood, is adversely affected by intense stump harvest. Model studies suggest that the risk of species extinction is small if the stump harvesting is limited to 10% of the total clear-cut area in the forest landscape. Today this percentage means about 20 000 ha across Sweden. If however 30% of all new clear-cuts will be stump harvested, the risk of extinction rises for "rare species with specific habitat requirements".

The report provides a better basis than before to assess the pros and cons of stump harvest. One of the advantages of stump harvest, perhaps the greatest, is that the climate will benefit in comparison with burning fossil fuels. A disadvantage is that the species dependent on dead wood are adversely affected, but the degree of the influence is heavily dependent on the extraction level.

Questions and answers on stump harvesting

In the beginning of the second phase of the research programme in 2012 a number of knowledge gaps about stump harvesting still remained to be filled. Some important questions to answer were (1) if burning of stump biomass is better for the climate (reduced global heating) than burning of fossil fuels; (2) if the soil disturbance that is inherent in stump lifting results in additional release of carbon dioxide and, thereby, counteracts the expected climate benefits; (3) if stump harvesting increases nitrogen leaching; (4) if stump harvesting increases the runoff of methyl mercury; (5) if the timber production and natural regeneration will increase or decrease after stump harvesting; (6) to which extent the biodiversity is affected by stump harvesting; and (7) in which way the environmental concerns are impacted by stump harvesting and other biofuel extraction.

Because previous research mainly concerned stump harvesting on individual clear-cuts, there was a desire to achieve a better knowledge of landscape effects and of the impact on whole forest generations, not only during the early felling phase. The researchers have given answers to these questions in the previous chapters, which give a brief version of the recent achievements. My conclusions are based both on what is written in these chapters and what has recently been published in two special issues on stump harvesting in the journals of Forest Ecology and Management (volume 371 in 2016) and Scandinavian Journal of Forest Research (volume 32 in 2017).

Stump harvesting and climate benefits

When biomass from stumps and coarse roots is burnt in a power plant, a similar amount of carbon dioxide is emitted as when fossil fuels are burnt. The notion that bioenergy from stump harvests gives more benefit to the climate than fossil fuels is primarily based on the idea that stumps and roots remaining in the forest also produce carbon dioxide when they decompose. In the fossil-fuel option ("business-as-usual"), carbon dioxide is thus emitted from both the fossil fuel and the stumps in the forest; while in the stump-burning option the stumps in the power plant are the sole source of carbon dioxide (with exception of the stumps still remaining in the forest). The argument that you get climate benefits of using bioenergy from stumps has been questioned, mainly because stumps/coarse roots are decomposing relatively slowly (Ågren et al. 2007; Palviainen and Finér 2015; Repo et al. 2015), and therefore it may be a delay of the positive climate effect.

By using the technique of life cycle analysis in combination with ecosystem modeling, Ortiz et al. (2016) compared the climatic effect of biofuel from spruce stumps with two kinds of fossil fuels, fossil coal and natural gas, at the same energy production. In comparison with fossil carbon (C), which also emits methane at mining, stump bioenergy resulted in greater climate benefits (less increase in atmospheric temperature) from day one. Stump bioenergy had significantly better climate effects than natural gas in the long run, but because the stumps decompose relatively slowly, the climate benefits were not significant until after 20-30 years.

Soil disturbances reduce emissions of green-house gases

Stump extraction and mechanical soil preparation often result in a large part of the clear-cut area being affected and a large volume of soil will be intermixed. Previous studies, such as the review by Walmsley and Godbold (2010), warned that stump harvesting could cause large C emissions. In contrast to these concerns, several new trials in Sweden, Finland and Estonia have shown that stump harvesting and soil preparation at least initially lead to reduced emissions of carbon dioxide from the soil. After the first year, the emissions seem to be at the same level for disturbed soil areas as for undisturbed areas. So far, results from another few (3-5) years are lacking, but further studies will also fill this knowledge gap.

Nitrous oxide and methane are powerful greenhouse gases, but in a study of three 1-2 year-old clear-cuts in central Sweden, Strömgren et al. (2016) and Lindroth et al. (this report, chapter 9) showed that the contribution to global warming from these greenhouse gases were much lower than from carbon dioxide. The emissions were at about the same level on stump-harvested areas as from the areas where the stumps were retained. Scarification did not result in any clear effects. The contribution to global warming varied with soil type and disturbance type. Soils with high nitrogen availability had higher emissions of nitrous oxide than nitrogen-poor soils, and more methane was emitted from ruts with compacted wet soil with oxygen limitation. Because this is the first study in the world of how stump harvesting affects methane and nitrous oxide emissions, more studies need to be done in this research field.

Stump harvesting reduces soil and ecosystem C stocks, but for how long?

In a normal clear-cut in central Sweden at a site with high productivity, about 75 Mg (tonnes) of C can be found per hectare in the soil organic matter. In addition, there are about 30 Mg of C per hectare of stumps and coarse roots. In a new clear-cut, there is thus 75 + 30 = 105 Mg of C in the soil and stump/root system. At stump harvesting, normally 75% of all stumps and coarse roots are removed, and there will then be 75 + (0.25 x 30) = 82.5 Mg C left. The difference in stump/root C between conventional and stump harvested clear-cuts (in the example from central Sweden of 22.5 Mg per hectare) will decrease over time depending on the fact that stumps and roots are decaying.

In a soil study in central Finland, Hyvönen et al. (2016) found no difference in soil C stocks (here stumps and coarse roots were not considered as “soil C”) between clear-cuts where stumps were removed or retained 8-13 years after clear-cutting. In another study in eight field trials in different regions in Sweden, Jurevics et al. (2016) found no statistically significant difference in the amount of C in the soil between stands with or without stump harvesting 32-39 years after harvesting (in the latter study the C in stumps and coarse roots were also included). According to the decomposition model for stumps and coarse roots developed by Melin et al. (2009), 63% of the initial amount of C in stumps and coarse roots would remain after 10 years, but only 20% after 35 years, i.e., 6 Mg in clear-cuts where the stumps were retained in comparison with 1.5 Mg where stumps were removed according to the example from central Sweden. This example indicates a difference in overall soil C stocks of 5.6% after 35 years between stump-harvest and non-stump harvest, and such a small difference is difficult to verify statistically, so the lack of a significant difference in the Jurevics et al. (2016) long-term study is not at all strange.

Stump harvesting increases soil nitrate formation and nitrate leaching

Soil disturbance can increase net N mineralization during the first year after various kinds of soil treatments, for example, mechanical soil scarification and stump harvesting, at least at certain sites. Stump harvesting causes a more efficient mixing of soil layers than mounding makes. This soil mixing also appears to result in a greater nitrification potential. Stump harvesting can thus lead to an increased risk of nitrate leaching, both by the fact that a smaller amount of N can be immobilized in the remaining stumps and coarse roots (as only about 25% remain) and by increased nitrate formation. Increased nitrate leaching below the rooting zone after stump harvesting has also been documented in a five-year study in southern Sweden, but more studies are needed to better assess the risk of N leaching in different types of landscapes.

Stump harvesting does not increase methyl mercury in forest streams

Different kinds of disturbances of forest land in connection with logging have been shown to contribute to an increased runoff of mercury, including the toxic form methyl mercury. It has therefore been assumed that stump harvesting can increase the risk of creating suitable habitats for the microorganisms that convert less-toxic mercury to toxic methyl mercury. These habitats can be water-filled ruts, pits remaining after stump removal but also pits after mounding. In a new study, it was revealed that much methyl mercury was formed in such environments (K. Eklöf et al. pers. comm.). Despite the fact that there were more hollows after stump harvesting than after ordinary site preparation, where methyl mercury could be formed, the concentration of methyl mercury in forest-stream waters from these areas did not increase.

Tree growth, natural regeneration and root rot

A compilation of Swedish and Finnish long-term experiments shows that stump harvesting is unlikely to have any major effect on stem-wood production in the next forest rotation. Stump harvesting appears to be positive for the establishment of naturally regenerated pioneer trees such as Scots pine and silver birch, while the number of naturally regenerated trees of Norway spruce may be adversely affected (Egnell 2016). High rates of natural regeneration allow the vegetation to rapidly assimilate carbon dioxide. Stump harvesting has also the potential to reduce the frequency of root-rot infected trees in the next generation. Swedish and Danish experiments have shown that attacks of the root-rot fungus *Heterobasidion*, which is the main reason for root rot in Scandinavia, decreased by 20-72% after stump harvesting (Cleary et al. 2013). To obtain the maximum effect in reducing the frequency of root-rot infection and reduce the spreading of spores, stump harvesting should include as many decaying stumps as possible (Vasaitis et al. 2008).

The stump biodiversity varies over time

Stumps after final felling have replaced logs as the commonest form of dead wood in managed forests. Rare and endangered species have mostly been found in stumps of broad-leaf trees. The Swedish and Finnish stump-harvest operations have, therefore, been confined to conifer stumps and for techno-economic reasons particularly spruce stumps. In the fresh stumps the wood is often decomposed by different kinds of wood fungi. In an extensive study of 41 clear-cuts of various ages all over Sweden, Kubart et al. (2016) used DNA analysis to determine the fungal species in spruce stumps. They found 1,355 species of fungi, of which 260 could be determined to genus or species (Figure 17.1). The most common species were generalists, and only four species were red-listed.

Figure 17.1. In a large study of spruce stumps in various parts of Sweden, 1,355 species of fungi were found using DNA extraction. Most of these wood fungi do not form any visible sporocarps. Other fungi do so, such as the sheathed woodtuft mushroom (*Kuehneromyces mutabilis*), which here grows on a 2½-year-old spruce stump.

The first animals arriving at the fresh stumps are normally beetles. They mainly feed on the most nutritious part of the stump, the cambium. They can recognize a suitable food source by responding to fragrances emitted by the wood and then directly fly towards the odor source. Therefore, there are large differences in the species composition of beetles between different tree species (Figure 17.2). But not only beetles are attracted by the stumps. The space between the outer bark and wood soon becomes an attractive environment for enchytraeids, springtails, mites, centipedes, fly and midge larvae and ants. When the stumps have reached an age of about ten years, the stumps contain a higher number of individuals and species than younger (5-year-old) and older (20-year-old) stumps (Persson et al. 2011, 2013).

Figure 17.2. Many longhorn beetles (Cerambycidae) have larvae that live inside the stump wood. Here the oval exit holes unveil that hatched *Arhopalus* beetles have left their pine stump.

The biomass removed at stump harvest of spruce consists of about 30% of stump wood and 70% of coarse-root wood. It is therefore remarkable that almost no studies have been devoted to organisms in coarse roots. The study of Victorsson and Jonsell (2016) is an exception. They compared the diversity of beetles in 2-year-old stumps and roots in 12 clear-cuts in central Sweden, and found that coarse roots contained half as many species as the stumps, when they compared the same bark surface above and below ground. Only 28% of species were common to both stumps and coarse roots. One conclusion of the study is that many species will be overlooked if you are just satisfied with the species found in the stumps above ground.

Stump harvesting mainly affects dead-wood living species

Beetles are a group of organisms with many species inhabiting tree stumps. Work et al. (2016) sampled a total of 1,049 stumps in 10 clear-cuts with stump harvesting (25% remaining) and 10 clear-cuts with conventional stem harvest in northern Sweden using eclector traps to collect the beetles. A total of 9,800 hatched beetles belonging to 253 wood-living species were found. Of these, 19 species were red-listed. The authors found that there were as many species per stump whether the clear-cuts were stump-harvested or not, but the number of individuals, was – as expected - lower on the stump-harvested clear-cuts than where the stumps were retained. The data obtained was used to calculate the number of species on a whole clear-cut with and without stump harvest and the loss of 75% of stump volume in the former resulted in a species loss of about 25% of the total number of beetle species.

The effect of stump harvesting on myriapods has only been studied in a few cases. Taylor and Victorsson (2016) found that the abundance of millipedes per stump, in contrast to the beetles that have good flying ability, decreased to about 50% in the stump-harvested than in the non-harvested clear-cuts. Stump harvesting reduces the number of stumps but also increases the distance between the stumps compared with the conventional clear-cuts. The latter factor may be important for organisms that, like the millipedes, have limited mobility.

Impact on soil fauna

Stump extraction does not only affect species dependent on dead wood but also invertebrates living in the soil and litter layers. In a Finnish study of Kataja-aho et al. (2016), the soil fauna in intact forests was compared with soil fauna in conventional and stump-harvested clear-cuts. Stump harvesting resulted in surprisingly small effects on several animal groups, but springtails (Collembola) and harvestmen (Opiliones) seemed to be negatively affected by the disturbed litter layer, whereas ground beetles (Carabidae) seemed to be favoured by bare mineral soil after stump harvesting.

Ground vegetation is affected on young clear-cuts

Stump harvesting initially affects ground vegetation, both by the reduction of plant cover through disturbance and by the removal of stumps near which certain plants prefer to grow, for example, cowberry and bilberry. Andersson et al. (2017) found, for example, that cowberry and bilberry responded with sharp declines in coverage after stump harvesting than when the clear-cuts were only subjected to mechanical site preparation. Kardell (2010) followed the rate of recovery of these dwarf-shrubs and found that bilberry and cowberry had a cover of around 50% and 30%, respectively, during the first 10-year-period after logging in stump-harvested compared to stem-harvested areas. The harvest of berries was accordingly affected. Other plant species, such as the fern *Gymnocarpium dryopteris* and the herbs *Maianthemum bifolium* and *Oxalis acetosella*, were on the other hand favoured by stump harvesting (Andersson et al. 2017).

In a survey study made 8-13 years after stump harvesting in Finland, Hyvönen et al. (2016) found no statistically significant differences in the plant community between stump-harvested clear-cuts and those with site preparation only, but there was a tendency of reduced cover of mosses and cowberries after stump harvesting. In a study performed in central Sweden, 24-36 years after clear-cutting, Rudolphi and Strengbom (2016) found no differences in species diversity or composition of mosses and vascular plants when comparing stump harvested and non-harvested stands and concluded that stump harvesting does not seem to give any long-term effects on ground vegetation.

Persistence/extinction of sensitive species depends on the harvest intensity

In the absence of direct field studies, Johansson et al. (2016) made a modeling study in which they tested how contrasting harvest intensities of dead wood (e.g. stumps) affected a number of "theoretical species" with differences in dispersal ability, habitat specialization and commonness. The authors simulated the dynamics of colonization and extinction of the species based on the availability of dead wood. The simulation was run for a 200-year period in an 11 x 11 km^2 managed forest landscape in Sweden, where an annual harvest of stumps was assumed in 10, 30, 50, 70 and 90% of the clear-cuts available. Extinction risks varied with different species traits. For the sensitive combination of "rare specialists on sun-exposed wood", there was a certain risk of extinction already at 10% harvest intensity, and at the 30% harvest level, the risk of extinction after 200 years of annual stump harvesting varied between 23 and 94% for the most sensitive species. Extinction risks were also dependent on how the stump extraction was made in the landscape, and a concentrated harvest at a certain part of the landscape was found to be better for survival than a random distribution of the clear-cuts used for stump removal, particularly concerning the species with limited dispersal ability.

Environmental concerns at biofuel extraction

There is a risk that the environmental concerns in the form of living and dead trees retained for the sake of biodiversity could be negatively affected by extraction of felling residues (slash) and stumps. To quantify these risks, Rudolphi and Gustafsson (2016) made an inventory of retention trees in 122 clear-cuts in different parts of Sweden. They found no significant differences between stump-harvested, slash-harvested and conventionally managed clear-cuts. However, in stump-harvested clear-cuts the logs had a higher degree of ground contact when compared with the other two categories of clear-cuts, which might increase the rate of wood decomposition. There were also significantly fewer standing dead trees on stump-harvested clear-cuts in comparison with the control stands.

Many machines and people are engaged in the bioenergy extraction activities. In a series of interviews with various stakeholders and actors, Gerhardt et al. (2017, this report, chapter 15) showed that there are major gaps in planning, logistics and communication between the different parts of the work chain, especially when several different contractors are involved. The responses to the interviews showed that there is a need for better education to avoid unnecessary mistakes, and it is important to take advantage of the great knowledge among machine operators and contractors.

Many species living in dead wood are disfavoured by slash and stump extraction. An alternative to restrict the extraction of stumps is to compensate for these extractions by increases in the amount of dead wood, for example, to let more high stumps compensate for the harvest of slash and (low) stumps. An analysis of Ranius and Rudolphi (2017, this report, chapter 16) showed that fairly many snags are needed to achieve full compensation. It was found to be cost efficient to combine slash removal with the creation of more high stumps. However, it was not cost efficient to compensate stump removal with high stumps. The difference in these results is mainly dependent on the fact that stump harvesting is more expensive than slash harvesting.

To harvest or not harvest stumps?

Stump harvesting is a relatively expensive operation. In situations where the stump harvest is economically justifiable, our results show that stump harvesting is beneficial to the climate, it does not seem to increase the emission of greenhouse gases, it has great potential to limit the spread of root rot, and it appears to be relatively neutral in relation to the outflow of methyl mercury and the tree production in the next forest generation. A disadvantage of stump harvesting is that the species dependent on dead wood are adversely affected, but the degree of the influence is heavily dependent on the extraction level. The latter is also true for berry-producing cowberry and bilberry, which thrive growing next to stumps.

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