Technology and Systems for Stump Harvesting with Low Ground Disturbance

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Abstract

Tree stumps could make a significant contribution to the transition from a fossil- to a bio-based economy, but current stump harvesting operations have adverse ecological effects. The ground disturbance caused by the up-rooting leads to increased carbon emissions from the soil and increases risks of leaching of heavy metals and nutrients, while removal of stump wood increases nutrient removal and reduces amounts of dead wood in the forest. However, the ground disturbance could be reduced by introducing new techniques. The overall objective of the studies this thesis is based upon was to investigate possible future systems for stump harvesting capable of reducing ground disturbance, and estimate their economic sustainability. Studies were based on experimental field studies and simulations. The ground disturbance depends on the type of harvesting head, as harvesting the whole stump creates more disturbance than harvesting the central part of the stump; the ground disturbance is also larger on peat soil than on mineral soil, but does not depend on time since clear cutting; and the root breakage diameter is surprisingly small (5-30 mm) after whole stump harvests and is not affected by the time since clear-cutting. Twisting stumps loose requires large torques and cannot be considered a viable way of extraction. The ground disturbance and cost to industry was estimated for four systems: a conventional whole stump harvesting system (WSH), a stump centre harvesting (SCH) system and two possible future systems for integrated harvest and forwarding of stem and stump centres with separation of the stump centres at either the landing (IHL) or industrial sites (IHI). The IHI and SCH systems are estimated to be up to 100 % and 60 % more costly, respectively, than WSH. However, costs of IHL were estimated to be similar with WSH for large trees. WSH (up-rooting) caused five times more ground disturbance per hectare compared to the other systems. In conclusion, the conventional up-rooting system was estimated to be best from an economic perspective, but caused more ground disturbance then harvesting of stump centres only. If ground disturbance restrictions are introduced, and new technologies are developed accordingly, costs of utilizing stump wood will be higher than at present. In development of integrated stump centre harvesting systems, as described here, it is crucial to design techniques and methods that minimize possible risks of damaging the stem wood in order to secure timber quality. Finally, regardless of future regulations, whole stump up-rooting technologies will still be warranted for treating stands infected by root rot.

Keywords: integrated harvest, system cost, root breakage diameter, nutrient removal, fuel consumption

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Contents

List of Publications

This thesis is based on the studies described in the following appended papers, which are referred to by the corresponding Roman numerals in the text:

I Berg S & Nordfjell. Effect of stump size and timing of stump harvesting on ground disturbance and root breakage diameter. (manuscript).

II Berg S, Bergström D, Athanassiadis D & Nordfjell T (2012): Torque required to twist and cut loose Scots pine stumps. *Scandinavian Journal of Forest Research* 27(8), 724-733.

III Berg S, Bergström D & Nordfjell T (2014): Simulating conventional and integrated stump- and round-wood harvesting systems: a comparison of productivity and costs. *International Journal of Forest Engineering* DOI: 10.1080/14942119.2014.941640

IV Berg S, Prinz R & Nurmi J. Comparison of ground disturbance during stump harvest caused by using a stump drill and a stump rake on frozen peatland. (manuscript).

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The author's contributions to the appended papers were as follows:

- I Responsible for planning, execution of experiments, analysis and writing.
- II Responsible for planning in collaboration with supervisors. Responsible for execution of experiments, analysis and writing.
- III Responsible for planning, execution of experiments, analysis and writing.
- IV Responsible for planning, execution of experiments, analysis and writing.

Abbreviations

ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
BAW	Basal area weighted
DBH	Diameter at breast height (1.3 m above ground)
DSH	Diameter at stump height, either at cut height or at 1 % of tree height for standing trees.
h	hour
ha	Hectare
o.b	Over bark
OD	Oven dry
PM_0	Productive machine time, excluding delay time
t	Metric ton

Paper-specific Abbreviations

T1	Treatment in which stumps are twisted (Paper II)
T2	Treatment in which roots around the stump are cut with one or two knives (Paper II)
H	Roundwood Harvester (Paper III)
F	Roundwood Forwarder (Paper III)
SH	Stump harvester (Paper III)
SF	Stump forwarder (Paper III)
FP	Feller-puller, extracting tree and stump centres (Paper III)
P	In-stand processor for extracted tress (Paper III)
FFP	Forwarder used for the extracted trees (Paper III)
Basic model	The FP harvests 8.5 % more wood based on the tree volume and the SH cleans and splits stumps over the uprooting point
CH & MS	Model in which the SH cleans while moving stump pieces
Svol 32%	Model in which the FP harvests 32 % of the stump volume

1 Introduction

1.1 History of stump harvesting

Historically, stumps have been harvested on large scale for various purposes. This section briefly reviews historic trends in their use, particularly in the Nordic countries, but also considering relevant practices elsewhere. Stump harvesting on a larger scale has historically been conducted several times for multiple purposes. As early as 1734 Swedish law prescribed that dead dry trees, branches and stumps should be used as fuel wood before healthy trees were cut (Holmberg, 2005). Stumps have also been commonly used in Latvia as fuel since at least the early 1800s (Lazdinš *et al.*, 2012). In addition, tar was produced for a long time from pitchy Scots pine (*Pinus sylvestris*) wood in Sweden and Finland (André, 1993; Hakkila, 1972). Sources of this wood were partly debarked Scots pine trees that were left to fill with resin before harvest, old Scots pine stumps and storm-felled Scots pines (André, 1993). However, in 1759 the Västerbotten county governor issued a proclamation forbidding the debarking of healthy trees for tar production, recommending that stumps and damaged trees should be used instead. In the mid-19th century Scots pine stumps were the main sources of pitchy wood for tar production in Sweden, while stem wood started to have higher value as a source of saw logs (Karlsson, 2007). The part of the stump that was valued for tar production was the heartwood. Thus, at that time stumps were left for about 10-12 years in the ground to allow the unwanted sapwood to decay before harvest and facilitate extraction (Lundberg, 1915). Tar production continued to be important in the early 20th century (in 1915 there were 15 operational tar plants in Sweden), but declined thereafter due to competition from fossil sources.

About half of the Swedish energy demand was met by imported coal before the first world war (Lundberg, 1918). After the war there was great concern about energy independency in Sweden and elsewhere, notably Latvia (Lazdinš *et al.*, 2012). The vast forests were obvious sources of energy. However, the roundwood had to be used for other, export income-generating purposes (Lundberg, 1918), and the bark was mostly removed before floating the timber to industrial sites (Törnlund, 2002). Thus, stump wood and logging residues (branches and tops) were seen as the only possible sustainable energy sources (Lundberg, 1918). There was also increasing concern about the damage caused by stump harvesting on the regeneration when stumps were harvested 10-12 years after cutting (Lundberg, 1915). This also increased interest in mechanised stump harvesting. In 1918 it was considered possible to harvest stumps after logging, as new man- or horse-powered machines had been developed to facilitate their harvest. Blasting was also trialled and found to have similar costs, with lower man-power requirements (Lundberg, 1918). The earlier practice of waiting until the roots partly decomposed reduced the energy content in the stump wood so the mechanisation also led to a better fuel. Stump use slowly declined and almost ceased by the 1950s in Sweden, Finland and Latvia (Lazdinš *et al.*, 2012; Karlsson, 2007; Hakkila, 1972), apart from a large temporary increase during the second world war in their use for both fuel wood and tar production (Carlsson, 2003; Jonsson, 1985). Tar was refined during this war to produce fuel for vehicles, but this practice ceased when it became possible to import large quantities of cheap oil (Jonsson, 1985). As stump wood was still harvested manually after the second world war the price of the stump wood also increased due to increases in labour costs (Hakkila, 1972).

There was still a demand for stump wood in other countries after the second world war, mainly for pine (*Pinus* spp.) stumps used as feedstock for manufacturing chemicals (Hakkila, 1972). About 500 000 m^3 solid was used for this purpose in the Soviet Union annually, about 100 000 in Poland, and 300 000 in the USA. In the mid-1960s stumps also began to be used for fibre board and pulp production (Czereyski *et al.*, 1965), and they are still used for particle board production (Spinelli *et al.*, 2005). Most of the stumps in Poland and the Soviet Union were still harvested by blasting in the late 1960s, despite efforts to mechanise their harvest since the mid-1960s (Hakkila, 1972), while in the USA they were mostly harvested by crawler tractors.

There was renewed interest in stump harvesting in Finland and Sweden in the early 1970s (Jonsson, 1985; Hakkila, 1972). In Finland the wood processing industry had strongly expanded during the 1960s and could not continue to expand without new raw material sources (Hakkila, 1972). The shortage was especially critical for the sulphate pulp industry. It had been found that Scots pine and Norway spruce (*Picea Abies*) stumps could be used to manufacture sulphate pulp, which had led to a large interest in stump harvesting in Finland. The pulp industry in Sweden also started to look for alternative raw material sources in the early 1970s (Jonsson, 1985) due to concerns about future shortages (Karlsson, 2007). There were similar concerns in the Southern USA in the late 1960s and 1970s (Grillot, 1976). The global oil crisis of 1973 initiated the widespread interest in alternative energy sources (Jonsson, 1985). To address these problems a national “full tree utilisation” program was launched in Sweden. Initially it mostly focused on ways to use stumps for pulp production, as the wood has suitable properties for this purpose. However, later in the project the possibilities for using stumps for energy generation were investigated (Karlsson, 2007). In the beginning of the 1980s 200 000 m^3 solid stump wood was used annually in Sweden, about 4% of which could be sustainably harvested. Of that 200 000 m^3, 150 000 m^3 was used for pulp chips, but this was more costly than traditional pulpwood, mainly due to contamination by soil and stones (Karlsson, 2007). The stump wood that was used for energy generation had the same problem, it was too expensive compared to other sources, such as oil. Therefore the stump harvesting ceased in the 1980s.

1.1.1 Recent interest in stump harvesting

Increasing concern about global warming, driven by anthropogenic emissions of carbon dioxide and other “greenhouse gases”, has fostered increased interest in renewable energy sources (Björheden, 2006), including biomass from the forest. This is considered a carbon-neutral source as the carbon emitted during its combustion will be recaptured during regrowth of the forest (Repo *et al.*, 2012). In 1991 Sweden introduced taxation on fossil fuels that made wood fuels cheaper than oil and coal (Björheden, 2006). Later, in 1997, Sweden signed the Kyoto Protocol, which was ratified by the parliament in 2002. This further increased the cost of fossil fuel and increased demand for forest bioenergy. Initially, the main interest was in harvesting logging residues, but as the sources close to customers started to be fully utilised interest in stump harvesting re-awakened (Egnell *et al.*, 2007). Subsequent European Union (EU)-level targets to mitigate climate change further increased interest in renewable energy sources: including targets to reduce greenhouse gas emissions from the EU by 20 %, relative to the 1990 baseline, and meet 20 % of the EU’s primary energy demands from renewable sources, by 2020 (European Commission, 2010). Sweden and Finland were given more ambitious national targets, to meet 49 % and 38 % of their total demands from renewable sources by 2020 (European Commission, 2011a). A longer-term goal for the EU is to reduce greenhouse gas emissions by 80-95 %, relative to the 1990 baseline, by 2050 (European Commission, 2011b). Thus, demand for renewable energy will probably continue to rise in the future.

These developments renewed interest in stump harvesting, which re-started in 2001 in Finland (Hakkila & Aarniala, 2004; Paananen & Kalliola, 2003). The forest companies in Sweden started harvesting stumps a little later, in 2005 (Swedish Forest Agency, 2009). However, stump harvesting is currently very limited in Sweden as FSC certification only allows accredited organisations to harvest 2500 ha annually (FSC, 2012a). The Swedish Forest Agency (2009) believes that stump harvesting could initially be allowed from an ecological perspective on 5-10 % of the annually clear cut area, corresponding to 10 500 - 21 000 ha per year (Christiansen, 2013). The area notified to the Swedish forest agency in 2012 for stump harvesting was 3360 ha, and usually some areas that are notified for harvesting are not harvested (Christiansen, 2013). The situation is different in Finland where the corresponding FSC standard does not limit the area in which stumps can be harvested, but it restricts the numbers of stumps that can be harvested on a site and the types of sites that can be harvested (FSC, 2012b). In 2010, stumps were harvested in areas covering 20 000 ha in Finland (Helmisaari, 2011), and 1 003 000 m^3 of stump wood chips was delivered. This increased to 1 089 000 m^3 in 2012 (Ylitalo, 2013). Thus, the currently harvested area is probably slightly over 20 000 ha per year in Finland. Stumps are also harvested in other countries, among others they are extracted from poplar plantations for various purposes in southern Europe (Spinelli *et al.*, 2005), stumps of several species are extracted for bioenergy production in the UK (Price, 2011), and they are harvested in British Colombia, Canada, for controlling rot root, but there is also interest in using them for bioenergy production (Berch *et al.*, 2012).

1.2 Technology and systems for stump harvesting

Jonsson (1977) defined four basic working operations (which may involve various methods) in the stump harvest supply chain: uprooting, splitting, stump cleaning and transportation. Comminution or comminution and sieving can also be added to current operations (Asikainen, 2010). A stump harvester usually performs the first three of these basic elements (see, for instance, Athanassiadis *et al.*, 2011a; Laitila *et al.*, 2008; Karlsson, 2007). Von Hofsten (2010) has defined three types of harvesting heads: forks, splitters and root cutters (heads that cut off the roots and only harvest the central part of the stump and root system). Machines that harvest stumps as an integral part of harvesting trees could also be added to the list. In some cases normal excavator buckets or buckets equipped with a thumb are also used for stump harvesting (Berch *et al.*, 2012; Tolosana *et al.*, 2011).

1.2.1 Conventional harvesting techniques in the Nordic countries

Stumps are currently harvested on clear cuttings, mainly situated on mineral soil, after logging residues have been removed from the site, during the part of the year that is free from ground frost and snow (Anerud, 2010; Laitila *et al.*, 2008). They are usually harvested within a year of clear-cutting (Laitila *et al.*, 2008). The harvest is usually conducted with 20-25 t excavators as base machine (Kärhä, 2012). Excavators have stronger cranes than large roundwood harvesters, although the latter are strong enough to lift stumps (Lindroos *et al.*, 2010). Excavators are also less expensive than roundwood harvesters as they have much larger production series and hence lower investment costs (Laitila *et al.*, 2013; Laitila *et al.*, 2008). However, they are more clumsy in the terrain (Laitila *et al.*, 2008). The stump and roots are uprooted and split with a special stump harvesting head and shaken to clean of soil before being piled into heaps on-site (Laitila *et al.*, 2008). Currently only splitting and (less frequently) fork type heads are used in the Nordic countries (Kärhä, 2012).

The productivity of stump harvesters partly depends on the harvesting head used (Table 1). The productivity is highest when lifting birch (*Betula spp.*) stumps followed by Norway spruce and then Scots pine (Athanassiadis *et al.*, 2011a; Lazdinš & von Hofsten, 2009; Nylinder, 1977). The productivity increases with increasing stump size to a certain threshold, then decreases with further increases, and increases with increases in the number of stumps (of a given size) harvested per hectare (Kärhä, 2012; Lazdinš *et al.*, 2012; Athanassiadis *et al.*, 2011a; Laitila *et al.*, 2008; Nylinder, 1977). There may be a 20 % difference in productivity between removing 200 and 800 stumps per hectare (Nylinder, 1977). Infection by root rot also affects the time required for harvesting; infected stumps requires less time to harvest but probably have a lower OD mass (Lazdinš *et al.*, 2012). The productivity also decreases with increases in ground roughness and slope, mainly because of associated reductions in the speed of the stump harvester’s movements (Athanassiadis *et al.*, 2011a; Nylinder, 1977). The soil type also affects stump harvesting productivity, as it is lower on sedimentary soils than on glacial tills (Nylinder, 1977), and lower on clay soils than on sandy soils (Kärhä, 2012; Kärhä & Mutikainen, 2009). Soil moisture may affect the productivity too, but findings in this respect have been inconclusive (Hedman, 2008; Karlsson, 2007). The productivity is lower on sites (generally drier sites) where the trees have been able to develop deep root systems (Lazdinš & von Hofsten, 2009).

When the practise of stump harvesting was restarted in the Nordic countries in the early 2000s it was applied simultaneously with soil scarification, but the operations are now usually applied separately (Kärhä, 2012; Paananen & Kalliola, 2003), mainly because the combined operation results in poorer quality planting spots (Rantala *et al.*, 2010). If soil scarification is done simultaneously with stump harvesting on average 3.2-3.3 hour per ha is spent on the scarification work, according to recent reports (Kärhä, 2012; Laitila *et al.*, 2008), which reduces productivity by 13-48 % (Laitila *et al.*, 2008). The time required for soil scarification increases with increasing number of scarification points (Karlsson, 2007) and decreases with increased number of harvested stumps per hectare (Laitila *et al.*, 2008).

Figure 1. Top left: a current stump forwarder (photo by Kareliatech Oy). Top right: a fork-like stump grapple (From Jonsson, 1985, page 21, figure 20). Bottom row: two pictures of specially designed stump forwarders in the 1970-80s (photo by Mats Nylinder).

Table 1. *The productivity(ODt/PMh_0): when stump harvesting (H) for stumps with DSH exceeding 200 mm of Scots pine (P), Norway spruce (S), deciduous trees (D) and birch (B); when soil preparation (SP) is conducted while harvesting stumps: and when stump forwarding (F); grinding (C), coarse grinding (CG) and sieving (SI) at the landing (L) or terminal (T)*

Work	Species	Machine	Head and notes	Productivity
H[1]	S	24 t, Hitachi EX 225 USR	Väkevä	1.9-10.4*
H+SP[1]	S	24 t, Hitachi EX 225 USR	Väkevä	1.6-7.1*
H[1]	S	24 t, Hitachi EX 225 USR	Järvinen	2.6-8.0*
H[2]	S	23 t, Hyundai 210 LC & Volvo EC 210 in	Pallari KH-160	1.2-5.7
H[2]	P	23 t, Hyundai 210 LC & Volvo EC 210 in	Pallari KH-160	0.9-4.9
H[3]	S	17 ton, JCB JS 160 L	Kantokunkku	2.6-6.2 *
H+SP[3]	S	17 ton, JCB JS 160 L	Kantokunkku	1.2-4.3*
H[4]	P; S; D	Hyundai LB21LC	CBI	4.5-6.5
H+SP[5]	P; B; S	New Holland 215B	MCR-500	2.7-5.2
H[6]	S	Orenstein-Koppel, type RH 6; Lokomo excavator; Kokum feller buncher	Pallari or Cranab head	2.0-4.4*
H[6]	P	Orenstein-Koppel, type RH 6; Lokomo excavator; Kokum feller buncher	Pallari or Cranab head	1.1-2.8*
H[6]	S	ÖSA Feller-buncher	ÖSA splitter uprooter	2.1-5.7*
H[6]	P	ÖSA Feller-buncher	ÖSA splitter uprooter	1.7-4.1*
F[7]	-	John Deere 1710D	-	16.2
F[4]	-	John Deere 1110D	-	5.6-7.7
F[3]		6-wheel Ponsse Bison S15 B1	60 m^3/ha	3.1-4.3*
F[8]	-	-	-	2.6
F[6]	-	-	-	2.6*
CG+SI+L[9]	-	-	-	37.5#
C+L[10]	-	Vermeer Hg 6000	-	40.7-44.8
C+L[11]	-	CBI 5800	-	16.8
C+SI[7]	-	Doppstadt Büffel DW-3060	-	16.2
C+L[12]	-	Doppstadt DW-3060 Büffel	-	5.9-21.2#
CG+L[13]	-	Doppstadt 3060 W	-	18.5-20.0
C+L[4]	-	-	-	10.0
C+T[14]	-	Doppstadt DW 3060	-	18.7
C+T[14]	-	Doppstadt SM 620	-	20.4

- indicates that the information was not given in the study * The productivity was converted from m^3 to ODt with the following factors (Jonsson, 1985): Pine stump 450, spruce stump 410, and birch stump 510 kg/m^3; corresponding values for roots were 450, 500 and 410 kg/m^3, respectively. # Adjusted to PM_0 using factors presented by Eriksson *et al.* (2014b). [1] (Kärhä, 2012). [2] (Athanassiadis *et al.*, 2011a). [3] (Laitila *et al.*, 2008). [4] (Lazdinš *et al.*, 2009). [5] (Lazdinš *et al.*, 2012). [6] (Nylinder, 1977). [7] (von Hofsten *et al.*, 2012b). [8] (Lazdinš & Zimelis, 2012). [9] (von Hofsten & Granlund, 2010). [10] (Lindberg, 2008). [11] (Eliasson *et al.*, 2012). [12] (von Hofsten & Brantholm, 2013). [13] (Bertilsson, 2011). [14] (Fogdestam *et al.*, 2012).

After harvesting, stumps are initially stored in heaps on-site so they can be further cleaned by rain and dried by the sun, then forwarded for further storage in windrows (Laitila *et al.*, 2008). They are currently forwarded by essentially conventional forwarders with modified load spaces (enlarged load space, with more bunks, covered sides etc.) intended to increase the payload (Figure 1) when transporting the bulky stumps (Laitila *et al.*, 2008; Karlsson, 2007). However, the payloads may still be 50 % lower than the maximum load the forwarders can transport (Lazdinš & von Hofsten, 2009). To improve loading and unloading time the forwarders are also equipped with a fork-like grapple (Figure 1) (Laitila *et al.*, 2008; Jonsson, 1985). Their productivity increases with increases in load and grapple size, and decreases with increasing forwarding distance (Laitila *et al.*, 2008). Increases in amounts of stump wood per hectare increase productivity as more stumps can be loaded per stop (Laitila *et al.*, 2008). Increases in size of the stump pieces also increase productivity since higher stump volumes can be handled in each loading cycle (von Hofsten *et al.*, 2012a). There were also experiments with more purpose-built stump forwarders in the 1970s and 80s (Jonsson, 1985), including forwarders with whole sides and load spaces that could be tilted, and forwarders that could clean the stump wood while forwarding (Figure 1).

The stumps are stored in windrows by the landing to accommodate time differences between harvesting and demand (Anerud & Jirjis, 2011). Generally the ash content is reduced by storage, but all handling should be done on unfrozen material to maximise the removal of contaminants. However, only marginal differences in effects of storage in heaps or direct storage in windrows have been observed on moisture and ash contents (Anerud & Jirjis, 2011). Storage also sharply reduces the stump wood's moisture content from around 50 % initially after harvest to 20-35 % during the spring and early summer. Some re-wetting may occur in the autumn, but relatively little, so ideally stumps should be stored for at least half a summer before use (Anerud & Jirjis, 2011; Laurila & Lauhanen, 2010; Nylinder & Thörnqvist, 1981). The reduction in moisture content is lower if there is a high degree of contamination in the stump wood (Jonsson, 1985).

After storage in windrows for several months the stumps are either further transported to a crushing site, or crushed at the roadside before transportation (Asikainen, 2010). The transportation of stumps is associated with several problems, mainly because stumps are bulky but partly because contaminants (soil and stones) are also transported (Jonsson, 1985; Hansen, 1976). All stumps have some contamination, including soil stuck to the surface of the wood and embedded stones (Anerud, 2010). In severe cases the ash content may be up to 25% (Lindberg, 2008). After reaching the landing there are three main stump hauling/crushing systems (Kärha, 2011; Larsson, 2011). In two of the systems the stumps are transported whole from the landing either to the end user or to a terminal and comminuted there. If stumps are comminuted at a terminal the hog fuel are later transported to the end user. When stumps are transported whole a stump truck with a loading space enclosed by thick steel plates and equipped with a sliding loading system is used (Larsson, 2011). In the third system the stumps are comminuted at the landing then transported to the end user in chip trucks, which increases the trucks' payloads (Kärha, 2011; Larsson, 2011). The stumps are not clean enough to be chipped, instead they are shredded or ground. Comminuted material is transported by a chip truck or in some cases a self-loading chip truck, when the landing is too small for direct loading. Sometimes stumps are only coarsely ground at the landing to remove contaminants and increase payloads, but then they have to be finely ground at the end user's facilities (Bertilsson, 2011). It is also possible to combine grinding and sieving at the landing, which can reduce contamination (von Hofsten & Brantholm, 2013; Fogdestam *et al.*, 2012). The drawback of sieving is that some of the wood is rejected. Cost analyses of the transportation systems indicate that direct transportation is best for short-distances and commination at the landing best for longer distances (Table 2).

Table 2. *Summary of main findings of system analyses by indicated authors for stump wood transport*

Study	Findings
(Eriksson *et al.*, 2014a)	Cheapest systems: at ≤10 km direct transportation; at 30-70 km the site volume is the key determinant; at >90 km, or for fuel with high ash content, comminution at landing.
(Eriksson *et al.*, 2014b)	Self-loading chip trucks cheaper than direct loading and direct transportation
(von Hofsten & Granlund, 2010)	Coarse grinding at landing cheaper than direct transport
(Lindberg, 2008)	Cheapest systems: at <70km direct transport; at >70 km comminution at landing; at >250 km comminution at terminal and train transport.
(Larsson, 2011)	Coarse grinding, chip truck, then fine grinding at the end user is cheapest.

1.2.2 Conventional harvesting techniques in other countries

In the Mediterranean countries stumps are removed from tree plantations when clones are changed or the land is converted back to agricultural use (Picchio *et al.*, 2012; Tolosana *et al.*, 2011; Spinelli *et al.*, 2005; Czereyski *et al.*, 1965). Stumps can be harvested with either a drill, usually mounted behind a farm tractor, which cuts off the side roots and extracts the central part of the root system while grinding the side roots (Spinelli *et al.*, 2005; Czereyski *et al.*, 1965), or by an excavator equipped with a standard excavator bucket (Tolosana *et al.*, 2011). The stumps may also be ground into small chips which is left in the soil on the site (Picchio *et al.*, 2012). The method used depends on the price of the wood chips produced, as the harvest is more expensive than pure grinding (Picchio *et al.*, 2012; Spinelli *et al.*, 2005). When stumps are recovered after stump drill harvest they are cleaned by a separate wheel-based excavator with a chain-flail cleaner (Spinelli *et al.*, 2005), and usually transported directly to the end user by 10 t 3-axle lorries or a farm tractor with a 10 t 3-axle trailer, loaded by the cleaning unit. Similar techniques (without the grinding of side roots) have been tested in the Nordic countries (Table 3), but using excavator-based stump harvesters and conventional stump forwarders with crushing at the landing (von Hofsten *et al.*, 2012b; von Hofsten & Nordén, 2007). However every part of the system (harvest, forwarding and comminution at landing) was found to be more expensive than the conventional Nordic system, and the total cost of hog fuel was about 50 % higher (von Hofsten *et al.*, 2012b). The system also seems to be more sensitive to the storage conditions, as the unsplit stump centres dry better if they are initially stored in heaps (Anerud & Jirjis, 2011). This problem has been partly resolved by the latest version of the Nordic stump drill, which can split stumps and to some extent clean them (von Hofsten *et al.*, 2012b).

In Canada the aim of stump harvesting is to reduce the frequency of root rot in the next forest generation (Berch *et al.*, 2012). Stumps are usually harvested using an excavator with a standard bucket equipped with a gripping thumb and the stump is left inverted in the stump hole. This practise eliminates the need for any other machines. Bulldozers equipped with brush-clearing blades are also sometimes used to uproot stumps (Omdal *et al.*, 2001). Pushover logging is a rarely used method (Berch *et al.*, 2012), in which the tree is pushed over with the stump and skidded to the landing with stump and branches (Davis & Machmer, 1998).

There have also been experiments with other types of harvesting heads, and a system for stump harvesting after thinning. The latter involved use of a cone-shaped drill that split stumps in the ground, then a forwarder both uproots the split stumps and cleans them, but the productivity was about 70 % lower than conventional stump harvesting (Läspä & Nurmi, 2010). Harvesting heads using vibrations to harvest the stump have been trialled in the USA (Colquitt, 1980). This removes more of the root system than other techniques and also produces cleaner material.

Table 3. *Productivity (ODt/ PMh$_0$) for the harvester (H), forwarder (F) comminution (C), Cleaning (CL), Loading (L) and transport (T) in the stump drill system in indicated countries*

Work	Country	Notes	Machine	Head	Productivity
H[1]	Sweden	-	Volvo LC210B	Stump drill	2.25-2.76
F[1]	Sweden	Stump drill	John Deere 1710D	-	7.57
C[1]	Sweden	Grinding + sieving	Doppstadt Büffel DW-3060	-	14.9
H[1]	Italy	Stump drill	Farm tractor/prime mover	Ellètttari mod. 200	2.3-7.9
CL[1]	Italy	Chain-flail	Farm tractor/prime mover	Masèra-Ellèttari	2.3-8.8
L[1]	Italy	-	Farm tractor/prime mover	-	5.5-20.6
T[1]	Italy	20 km, 18 min unloading	Farm tractor 3-axle trailer/ 3-axle lorry	-	1.7-4.2
H[3]	Sweden	Stump drill	Komatsu PC 210 LC	-	1.0-2.5*

* The productivity was converted from m^3 to ODt using the following factors (Jonsson, 1985) for pine, spruce and birch stumps:450, 410 and 510 kg/m^3, respectively. Corresponding values for roots were 450, 500 and 410 kg/m^3, respectively. – indicates no value. [1] (von Hofsten *et al.*, 2012b). [2] (Spinelli *et al.*, 2005). [3] (von Hofsten & Nordén, 2007).

1.2.3 Integrated stem and stump harvesting

Integrated stem and stump harvesting was first conducted in the early 20th century (Lundberg, 1915). The stem was used as a lever and pushed over, which uprooted the stump, then the stump was cut off. In Sweden it was considered to be more expensive than separate cutting and stump harvesting, and there were problems with damage to the stem on some soil types where the stumps were firmly rooted. However the method was used more widely in Denmark and Germany.

Integrated harvest was again tested in the 1970s in both Sweden and the USA (Table 4). In both cases the aim was to extend the butt-log with the stump centre to get a longer saw log or more pulp wood (Grillot, 1976; Fryk, 1975). The extension was assumed to give 7-10 % additional volume or 1-2 dm longer saw logs in Sweden (Jonsson, 1985; Fryk, 1975), while the increase was estimated to be 18 % for Slash pine (*Pinus elliottii*) in the USA (Grillot, 1976). In Sweden the trees were pulled up with the roots then the roots were cut off, while in the USA a sharp cylinder was pushed down around the tree, cutting the roots in the soil. It was possible to pull trees up with the roots both in summer and winter conditions, although there was somewhat more damage in winter conditions and snow caused problems for the lifting (Fryk, 1975). Most damage was associated with lifting the tree as knifes were punched into the stem to lift it (Grillot, 1976; Fryk, 1975). Further problems were caused by soil on the surface of the stump extension, and stones embedded in the stump extensions on stony sites. Economic analysis showed that the Swedish integrated system was 3.0-8.1 % more expensive than the conventional separate system (Jonsson, 1985), and an earlier study showed that it was only profitable to use the stump extensions as saw timber for large trees (Jonsson, 1978). The reliability of the machines used for cleaning stump wood was also questioned. Analysis of the costs in the USA showed that integrated harvest could be competitive in clear-cutting but not in thinning, however the use was limited as the pulp mills had problems handling the material due to contamination (Grillot, 1976). Hardwood trees also seemed to be more difficult to harvest with the tap root than softwood trees with the tap root (Sirois, 1977). Recently, integrated harvest has been tried in Finland on peat sites that were to be converted to peat harvest (Table 4) (Laitila *et al.*, 2013). An ordinary roundwood harvester grabbed the trees and pulled them from the soil with the roots attached, and then cut off the stumps before processing the trees as normal. The results suggest that integrated harvest may be less costly for handling trees up to 200 mm DBH, but not larger trees, in these conditions.

Table 4. *Productivity (ODt/PMh_0) of integrated harvesting of stump and stem wood*

Country	Head	Machine	Notes	Productivity
Sweden	Trädplockaren[1]	-	Stem+stump centre	5.2-6.0*¤
Finland	Ponsse H53 harvester head[2]	Ponsse Cobra HS 10	Stump+stump peatland	1.1-15.1*
USA	TX-1600 Tree Extractor[3]	John Deere 544-B	Stem+stump centre	21.8-35.8[G]

* The productivity was converted from m^3 to ODt using the following factors for pine, spruce and birch stumps:450, 410 and 510 kg/m^3, respectively. Corresponding values for roots were 450, 500 and 410 kg/m^3, respectively (Jonsson, 1985). ¤ including stump wood. [G]0.510 kg/m^3 (Skolmen, 1963). – indicates no value. [1] (Fryk, 1975). [2] (Laitila *et al.*, 2013). [3] (Grillot, 1976).

1.2.4 Forces for uprooting stumps

Knowledge of the forces required to uproot stumps or cut roots facilitates improvement and development of stump harvesting heads. Thus, several studies have examined the forces required to vertically lift (Czupy & Horvath-Szovati, 2013; Lindroos *et al.*, 2010; Czereyski *et al.*, 1965) or horizontally pull (e.g. Peltola *et al.*, 2000; Liley, 1985; Golob *et al.*, 1976) stumps out of the ground. However, results of some of these studies have limited utility for the development of new harvesting heads as only regression functions are presented, without no indications of variation (Czupy & Horvath-Szovati, 2013; Liley, 1985; Czereyski *et al.*, 1965). The standard deviation is needed to establish confidence intervals for estimates of the force needed to harvest 97.5 %, 99.5 or 99.95 % of the stumps. In addition, Anderson *et al.* (1989) studied the shear strength (a type of material failure) of the root plate/soil interface of Sitka spruces in various soils by twisting stumps, but they did not report the torque needed to cause the failure. The force needed to cut roots depends on the type of cut that is used and the cutting angle (Tanaka, 1997). The forces needed to cut off the roots of pines in the southern USA from above and lift the trees once the roots have been cut have been studied (Koch & Coughran, 1975).

1.3 Ecological aspects of stump harvesting

1.3.1 Carbon perspective

The main reason that stump harvesting is of interest today is that the wood can be used as a carbon-neutral fuel source (Repo *et al.*, 2012) to substitute fossil fuel (Egnell *et al.*, 2007). The total potential is huge, but only a fraction can be harvested due to ecological and economic restrictions (Table 5). Despite differences in estimates of the size of this fraction, a substantial amount of renewable energy can be acquired to substitute fossil fuel. With current technology there are emissions from combustion of fossil fuels when the stumps are harvested, transported, and comminuted. Fortunately, the system has a high energy efficiency ratio, of 23-40:1 (Lindholm *et al.*, 2010; Eriksson-Näslund & Gustavsson, 2008). This is lower than corresponding values for other forest fuels (24-71:1), but similar or better than the value for coal (28:1, including the energy consumed in mining and transportation operations) (Mann & Spath, 2002).

Table 5. *Estimated total and harvestable potential of stump wood in indicated areas*

Study	Region/Country	Total potential (million ODt/year)	Harvestable potential (% of total potential)
(Asikainen *et al.*, 2008)*	EU27	75.8	4.4
(Asikainen *et al.*, 2008)	Sweden	10.6	11
(Gerasimov & Karjalainen, 2011)*	North-west Russia	3.6	40-50
(Athanassiadis *et al.*, 2011b)*	Sweden	11.7	36
(Swedish Forest Agency, 2008)	Sweden	11.7	-

* The productivity was converted from m^3 to ODt using the following factors for pine, spruce and birch stumps:450, 410 and 510 kg/m^3, respectively. Corresponding values for roots were 450, 500 and 410 kg/m^3, respectively (Jonsson, 1985). – indicates no value

Initial carbon emissions resulting from the combustion of stump wood are higher than those from natural gas and oil, while their magnitude relative to emissions from coal are uncertain (Repo *et al.*, 2012; Repo *et al.*, 2011; Sathre & Gustavsson, 2011; Melin *et al.*, 2010). This is because the fossil fuels have a higher carbon to energy ratio than stump wood. However, as stumps that are left in the ground gradually decompose, and also release carbon dioxide, the emissions resulting from their use decline and gradually become lower than those resulting from use of fossil fuels. Important aspects in calculations of the timeframe in which stump wood becomes superior to fossil fuels in this respect are the biomass and decomposition models applied. Stump harvest also reduces inputs to the soil carbon pool, thereby possibly reducing the pool over time if intense stump harvesting is conducted (Lindholm *et al.*, 2011; Melin *et al.*, 2010). On the other hand, stump wood replaces fossil fuel that emits carbon from geologically stable pools (Sathre & Gustavsson, 2011).

1.3.2 Soil disturbance

Soil disturbance may refer to the mixing of soil and humus material, the mixing of different soil layers, changes in soil surface height or compaction (Napper *et al.*, 2009). In this thesis it refers to mixing of soil layers and changes in surface height, while compaction is considered a separate variable. Stump harvesting causes soil disturbance and may also cause soil compaction (Table 6). In forestry another silvicultural measure that contributes to soil disturbance, with or without stump harvests, is site preparation. Disc trenching disturbs 40-60 % of the area and mounding 14-21 % (Roturier *et al.*, 2011; Roturier & Bergsten, 2006). The disturbance is increased by every operation on the site (Hope, 2007) and can be quite high after stump harvesting (Table 7). However, the disturbed area is reclaimed by vegetation much more rapidly after stump harvesting than after soil scarification. Notably, for instance, Kardell (1992) found that six years after scarification and stump harvesting 9.1 % and 16.1 % of the area of treated sites still lacked vegetation cover, respectively, but a much larger proportion of the total area had been disturbed by the stump harvesting (67.5 % versus 20.6 %). Several studies have shown that about half of the ground disturbance is caused by the uprooting and half by the harvesting machine´s tracks (Wass & Smith, 1997; Smith & Wass, 1994). To my knowledge the ground disturbance has mostly been studied at site level, and stump-level damage has only been investigated in one study in which a novel system was tested in a thinning stand. This involved use of a cone-shaped drill to split the stumps, then a forwarder to pull them from the ground, resulting on average in 3.3 m^2 of disturbed ground per stump (Läspä & Nurmi, 2010).

There are conflicting findings concerning compaction after stump harvesting. It may reportedly increase the bulk density (Thies *et al.*, 1994), but it may decrease over time (Hope, 2007; Page-Dumroese *et al.*, 1998). There are also indications that it may be increased in machine tracks but not in other parts of the site (Smith & Wass, 1994), and the impact may only be in deeper soil layers (Page-Dumroese *et al.*, 1998). However, other studies have not found any significant effects of stump harvesting on the bulk density of the soil (Zabowski *et al.*, 2008; Wass & Smith, 1997).

Table 6. *Changes (%) in bulk density and penetration resistance of indicated mineral soil layers after stump harvesting (SH) and soil scarification (SC) in machinery tracks, soil deposits after stump harvesting and depressions after stump harvesting. NA indicates no significant change*

Study	Year	Bulk density	Resistance *	Layer (cm)	Operation and Ground type
(Smith & Wass, 1994)	2	+26	-	0-10	SH-Track
	2	+20	-	10-20	SH-Track
	2	NA	-	0-10	SH-Deposit
	2	NA	-	10-20	SH-Deposit
(Page-Dumroese *et al.*, 1998)	1	NA	-	0-10	SH
	1	NA	-	10-20	SH
	1	+14	-	20-30	SH
	3	NA	-	0-10	SH
	3	NA	-	10-20	SH
	3	+9	-	20-30	SH
(Hope, 2007)	1	+10	-	0-20	SH
	1	NA	-	0-20	SH+SC
	10	NA	-	0-20	SH
	10	NA	-	0-20	SH+SC
(Wass & Smith, 1997)	2-3	NA	- 31-39	0-10	SH-Depression
	2-3	NA	- 24-28	10-20	SH-Depression
	2-3	NA	- 66-72	0-10	SH-Deposit
	2-3	NA	- 50-59	10-20	SH-Deposit
(Zabowski *et al.*, 2008)	20	NA	-	0-20	SH
(Thies *et al.*, 1994)	10	+7	-	0-20	SH

- indicates no value. * The resistance was measured in MPa with a soil cone penetrometer

The disturbance of the soil also has negative ecological effects. Soil scarification seems to increase decomposition rates, and thus carbon emissions from the forest soil, which increase with increased disturbance (Jandl *et al.*, 2007). Similar short-term results have been found for stump harvesting. Higher carbon emissions have been detected after stump harvesting than after mounding (+159 % emissions) and patch scarification (+10 % emissions), but not after harrowing (Kataja-aho *et al.*, 2012; Strömgren & Mjöfors, 2012). Mounding and patch scarification are both applied to 13 % of the annual clear-cut area in Sweden, while harrowing is applied to 47 % (Swedish Forest Agency, 2007). The cited studies indicate that CO_2 emissions from mineral soils may be increased by stump harvesting, or any other operations that significantly disturb the ground. The responses may be different on peatlands, on which soil scarification has been found to slightly increase NOx emissions, but slightly reduce CO_2 emissions, while the CH_4 emissions are solely correlated, negatively, with the water table depth (Pearson *et al.*, 2012). However, there is a need to limit soil disturbance on both mineral soil and peatlands.

Table 7. *Proportions (%) of the total site area with disturbed ground after stump harvesting (SH) and soil scarification (SC)*

		Year after operation						
Study	Operation	1	2	3	4	5	6	unknown
(Smith & Wass, 1994)	SH	-	72	-	-	-	-	-
(Hope, 2007)	SH	43-60	-	-	-	-	-	-
(Hope, 2007)	SH+SC	74-99	-	-	-	-	-	-
(Wass & Smith, 1997)	SH	-	85	-	-	-	-	-
(Kardell, 1992)	SH	67.5	56.8	45.4	35.5	26.2	16.1	-
(Kataja-aho *et al.*, 2012)	SH	-	-	-	-	-	-	68
(Kataja-aho *et al.*, 2012)	SC	-	-	-	-	-	-	48
(Rabinowitsch-Jokinen & Vanha-Majamaa, 2010)	SH+SC	-	76	-	-	-	-	-

- indicates no value

Ground disturbance can also cause leaching of various elements from the site. Several studies have found that scarification increases leaching (e.g. Eklöf *et al.*, 2014; Piirainen *et al.*, 2009; Piirainen *et al.*, 2007; Porvari *et al.*, 2003), but the effects on water quality may be minor (Mannerkoski *et al.*, 2005). Some studies have also found no significant differences in leaching between undisturbed and scarified sites (Örlander *et al.*, 1997; Ring, 1996). An important compound that increases in the soil water after soil disturbance is methylated mercury, which is toxic and may reach aquatic systems (Munthe & Hultberg, 2004; Porvari *et al.*, 2003). There have been few studies of leaching after stump harvesting. Most indicate that it increases leaching (Kiikkilä *et al.*, 2014; Eklöf *et al.*, 2012), although one indicates that it has no significant effect or even causes a slight reduction (Eklöf *et al.*, 2013). Thus, effects of ground disturbance on leaching may be site-specific and may not always affect water quality. Nevertheless, there are clear indications that increasing disturbance generally increases leaching, so disturbance should ideally be low when harvesting stumps.

1.3.3 Nutrients

In boreal forests N is generally the limiting nutrient for tree growth (Hyvönen *et al.*, 2007), so it is advisable to avoid unnecessary losses. Roots' nutrient contents increase with decreases in their diameter (e.g. Gordon & Jackson, 2000; Nihlgård, 1972). Coarse roots have lower nutrient contents than foliage but higher than in the stem wood (Hellsten *et al.*, 2013; Sicard *et al.*, 2006). Nutrient contents — especially N but also P, K, Ca Mg and Na — are negatively correlated with root diameter, thus harvesting small roots (with < 60-80 mm diameters), should be avoided to prevent undesirably high nutrient removal from sites (Hellsten *et al.*, 2013). High nutrient contents also increase ash contents, and thus reduce wood's fuel quality as fuel. However, nutrient contents are at least twice as high in logging residues (Egnell *et al.*, 2007; Finér *et al.*, 2003), which is an accepted fuel. In standard practices logging residues are extracted prior to stump removal, which should be considered when comparing harvesting systems.

1.3.4 Pests

Root rot is caused by fungal infection and causes large financial losses in forestry globally (Vasaitis *et al.*, 2008). The main species causing root rot are *Armillaria* spp., *Heterobasidion* spp., and *Phellinus* spp. The fungi infect stumps via airborne spores, and after establishment in the stumps their mycelia frequently extend to infect other trees. The fungi can survive for decades in stumps after clear-cutting and can then infect the next forest generation. Once rot root has established in a stand stump harvesting is the only effective way to reduce the disease in the coming forest generation (Gibbs *et al.*, 2002), but the effectiveness of the treatment depends on the efficiency of the machinery in removing the roots. Generally, bulldozers remove more of the stump mass than excavators (Omdal *et al.*, 2001). Excavators lift the stumps out of the soil while bulldozers push them out of the soil, removing more of the forest floor and some of the mineral soil in the process (Omdal *et al.*, 2001; Wass & Smith, 1997). The stump removal removes infected wood from the soil, but it also splits remaining roots, facilitating their colonization by root rot pathogens (Vasaitis *et al.*, 2008). Roots that are left are also often moved from deeper soil horizons to the top of the soil where the root rot pathogens can colonize them more rapidly. Nevertheless, most studies indicate that stump removal from root-rot infected sites reduces losses and increases seedlings' growth rates (c.f. Cleary *et al.*, 2013; Gibbs *et al.*, 2002)

1.3.5 Dead wood and biodiversity

Logging residues and stumps account for up to 80% of the coarse woody debris (>100 mm diameter) in a managed forest landscape (Caruso *et al.*, 2008). Stump harvesting usually removes 58-81 % of the stumps in an area (Eräjää *et al.*, 2010; Rabinowitsch-Jokinen & Vanha-Majamaa, 2010) and decreases the volume of coarse woody debris by 20 % (Rabinowitsch-Jokinen & Vanha-Majamaa, 2010). Thus, it can have negative short-term impacts on species that depend on dead wood (Victorsson & Jonsell, 2013), but only minor long-term effects (Andersson *et al.*, 2012). Stump harvesting also changes the surface structure of the soil at the site, as it leaves a smaller undisturbed area than other operations (Table 7). This difference affects the community of decomposers at the site, at least in the short term (Kataja-aho *et al.*, 2011). Changes in vegetation have been observed after stump harvests (relative to conventional site preparation), a few more forest species per site disappear and a few more species that are positively affected by disturbance appear (Kardell, 1992). Disturbance may cause disappearance of some species at site-level, but not, apparently, at landscape-level.

To limit the impacts of stump harvesting the Swedish Forest Agency (2009) has published guidelines for stump harvesting. The recommendations are to: only harvest soft wood stumps and leave 15-25 % of them; leave buffer zones by other areas that are not harvested and by water; prioritise stands with root rot; avoid harvesting in moist and wet areas; avoid harvesting in areas with high social, cultural or natural values; avoid harvesting on slopes due to risks of erosion; and only harvest stumps in 5-10 % of the clear-cut area on a landscape level. There are also recommendations for harvesting in Finland (Äijälä *et al.*, 2010) and the UK (The Research Agency of the Forestry Commission, 2009), which are somewhat different from the Swedish recommendations.

1.3.6 Forest Growth

Soil scarification increases both short- and long-term forest growth (e.g. Jandl *et al.*, 2007; Örlander *et al.*, 1996). In addition, stump harvesting before soil scarification reportedly improves the quality of planting spots (Österlöf, 1979). However, plants have been found to grow more rapidly close to decomposing stumps (Van Lear *et al.*, 2000), and stump harvesting reduces frequencies of root tips infected by mycorrhizae, which could reduce long-term forest growth (Page-Dumroese *et al.*, 1998).

Growth rates are increased when stump harvesting is conducted to reduce root rot (e.g. Cleary *et al.*, 2013). However for other cases the responses are more complex. Results of analyses of the relationship between stump harvesting and subsequent seedling growth rates are inconclusive (Table 8), and seem to depend partly on where the seedlings are planted. Seedlings planted in machine tracks after stump harvesting reportedly have lower growth but higher survival rates than controls (Smith & Wass, 1994), while those planted on soil deposits after the operation have similar or higher growth rates, and those planted in depressions have similar or lower growth rates (Table 8). The decreased growth rates in machine tracks are probably due to increases in bulk density caused by compaction (Table 6). Soil compaction generally reduces growth, but in some situations it may increase growth (Kozlowski, 1999).

Table 8. *Relative effects of stump harvesting (SH) and soil scarification (SC) on tree height, diameter (Diam) and volume compared to no treatment in gouges (G), deposits (D) and machine tracks (T), for indicated tree species; Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), hybrid spruce (*Picea glauca×Picea engelmanii*), Western white pine (*Pinus monticola*), Norway Spruce, Scots Pine and birch. NA indicates no significant change. Time = number of years since treatment*

Study	Tree species	Time (year)	Height (%)	Diam (%)	Volume (%)	Operation and Ground type
(Wass & Smith, 1997)	Douglas fir	10	+7	+8	-	SH+G
	Douglas fir	10	+ 13	+18	-	SH+D
(Smith & Wass, 1994)	Douglas fir	8	-13	-13	NA	SH+T
	Douglas fir	8	NA	NA	NA	SH+D
	Lodgepole pine	8	-12	NA	NA	SH+T
	Lodgepole pine	8	NA	NA	NA	SH+D
(Page-Dumroese *et al.*, 1998)	Douglas fir	3	-17	-23	-	SH
	Western white pine	3	NA	-10	-	SH
(Saksa, 2013)*	Norway Spruce		NA	-	-	SH
(Karlsson & Tamminen, 2013)	Norway Spruce	33	NA	-10	NA	SH
	Scots Pine	33	NA	NA	+25	SH
(Hope, 2007)	Lodgepole pine	10	NA	NA	-	SH
	Lodgepole pine	10	+25	NA	-	SH+SC
	Hybrid spruce	10	NA	NA	-	SH
	Hybrid spruce	10	NA	NA	-	SH+SC
(Kardell, 1992)	Norway Spruce	6	+54	-	-	SH
	Norway Spruce	6	+ 13	-	-	SH

* compared to soil scarification. – indicates no value

In addition to planted seedlings' growth rates, their survival rates and competition from natural regeneration are also important considerations. Several studies have shown that stump harvesting either increases their survival rates (Kardell, 1992) or has no significant effect on them (Wass & Smith, 1997). Increases in the abundance of naturally regenerating trees (mainly deciduous) have been observed after stump harvesting (Karlsson & Tamminen, 2013; Saksa, 2013). However, Kardell (1992) found larger relative increases in frequencies of naturally regenerated Norway spruce and Scots pine seedlings (200 %) than birch seedlings (87 %).

1.4 Possible solutions

Several aspects of stump harvesting warrant further study. One of the main ecological problem associated with stump harvesting is ground disturbance (Walmsley & Godbold, 2010). However, the disturbance it causes has mostly been studied at site level to date, and only once at stump-level (Table 7; Läspä & Nurmi, 2010). This makes it difficult to compare the ground disturbance caused by different harvesting methods. Thus, it is important to acquire information on the stump-level disturbance caused by using different heads. There several options to reduce the ground disturbance, but the main one is to only harvest the central part of the stump and root system. Stump drills could be used for this purpose, but they have not been as profitable as splitters and forks in Nordic conditions (von Hofsten *et al.*, 2012b). A possible alternative is to harvest the stump centre together with the stem. Previously this has been slightly more expensive than conventional, separate harvesting systems (Jonsson, 1985), but it could be viable now due to technological improvements. Further investigations are therefore warranted to see if integrated harvests could be economically feasible. Developing new harvesting heads that could reduce the ground disturbance may also be attractive, but there is a lack of knowledge concerning the torque needed to twist stumps.

There are also concerns about the increased nutrient removal when stumps are harvested (Walmsley & Godbold, 2010). To counter this problem knowledge is required of the root breakage diameter when conventional stump harvests are used, since this variable affects both quantities of removed nutrients and the fuel quality.

Stump harvesting is currently only conducted during the ground-frost and snow free part of the year (Laitila *et al.*, 2008). This makes stump harvesting less attractive for contractors. Harvesting stumps in winter conditions is difficult on mineral soils as the soil is frozen and difficult to remove from the stumps, resulting in fuel of low quality with high ash content (Anerud & Jirjis, 2011). However, stumps could be harvested from peatlands during winter as the peat that sticks to the stumps has a high fuel value (Leckner, 2007), but the ground disturbance needs to be investigated to see if it is feasible.

1.5 Aim

The overall objective of the studies this thesis is based upon was to investigate possible future systems for stump harvesting capable of reducing ground disturbance, and estimate their economic sustainability. More specific objectives of the studies were as follows. Firstly, to investigate the ground disturbance and root breakage diameter when removing stumps from mineral soil using a conventional stump harvesting head (Study I). Secondly, to determine the torque needed to twist Scots pine stumps and cut the roots around them (Study II). Thirdly, to simulate an integrated system for stem and stump harvests with low ground disturbance and compare the costs with those of a conventional system (Study III). Fourthly, to investigate the ground disturbance after stump harvesting on peatland using both a conventional stump harvesting head and a head with low ground disturbance (Study IV).

2 Material and Methods

In Study I the area of disturbed ground and root breakage diameter after stump harvesting was investigated on both a site cut six months previously and one cut 18 months previously. In Study II the torque required to twist and cut off roots around Scots pine stumps were investigated using a specially constructed test rig. In Study III a conventional separate stump and stem harvesting system was compared to an integrated system for simultaneously harvesting stems and stumps in computer simulations. In Study IV the ground disturbance on a frozen peatland after stump harvesting with two fundamentally different stump harvesting heads was investigated.

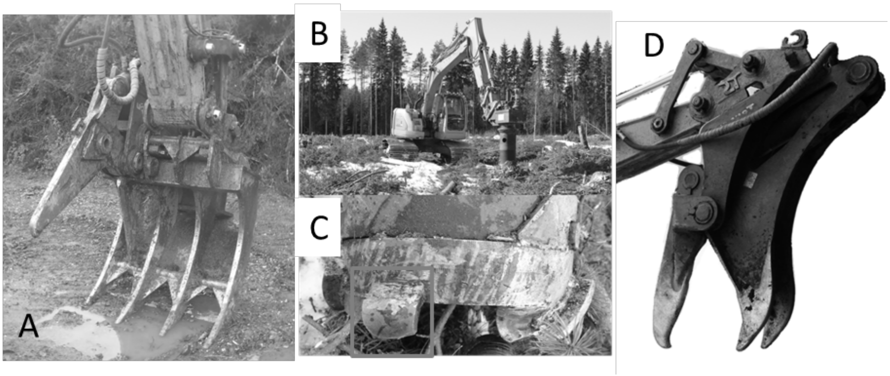

Figure 2. (A) Ecorex30 stump harvesting head (Study I), photo by Simon Berg, SLU. (B) New Holland Kobelco E200SR excavator equipped with an Ellettari stump drill, and (C) the teeth of the stump drill (Study IV), photo by Raul Fernandez Lacruz, SLU. (D) The conventional Terosa KK-900 stump splitter harvesting head (Study IV), photo by Jaakko Miettinen, METLA.

Table 9. *Characteristics of stands used in the studies. Abbreviations: pine (P), spruce (S) and deciduous (D); DSH and DBH, arithmetic (A) and weighted basal area (BA), respectively; (N) new site, (O) old site; (D) harvested with the stump drill and (C) harvested with the conventional head. Volume per stem and ha are whole stem over bark above stump values, excluding branches*

Study	Stand (plot)	Percent of species (P\S\D)	Stand density (trees/ha)	DBH (mm)		DSH (mm)		Height (m)		Volume		
										(m^3/stem)		(m^3/ha)
				A	BA	A	BA	A	BA	A	BA	
I	N1	0\100\0	344	-	-	331	395	-	-	-	-	-
I	N2	0\100\0	394	-	-	324	453	-	-	-	-	-
I	N3	0\100\0	1140	-	-	387	357	-	-	-	-	-
I	N4	0\100\0	810	-	-	289	365	-	-	-	-	-
I	O1	0\100\0	720	-	-	281	333	-	-	-	-	-
I	O2	0\100\0	800	-	-	258	305	-	-	-	-	-
I	O3	0\100\0	780	-	-	318	391	-	-	-	-	-
I	O4	0\100\0	980	-	-	258	309	-	-	-	-	-
II		100\0\0	934	179	-	-	-	14.3		-	-	-
III	151	0\88\11	880	160	185	217	253	12.5	13.8	0.143	0.200	126
III	152	0\99\1	695	162	199	225	272	11.1	12.9	0.138	0.221	96
III	153	0\75\25	625	156	201	209	264	8.6	10.4	0.104	0.188	64
III	154	0\91\9	700	200	274	263	368	13.1	16.4	0.266	0.506	186
III	251	0\91\9	1015	144	191	191	250	10.5	12.7	0.113	0.236	114
III	252	1\93\6	860	155	198	201	254	10.9	12.8	0.129	0.223	111
III	553	1\98\1	635	300	331	426	467	30.1	31.3	1.199	1.448	761
III	554	2\98\0	230	419	434	621	642	32.0	32.5	2.068	2.224	476
IV	D	99\0\1	820	-	-	246	261	-	-	-	-	-
IV	C1	85\0\15	100	-	-	229	251	-	-	-	-	-
IV	C2	87\5\8	980	-	-	224	242	-	-	-	-	-
IV	C3	74\14\12	990	-	-	255	292	-	-	-	-	-
IV	C4	84\13\3	680	-	-	255	279	-	-	-	-	-

- indicates no value

2.1 Paper I

Study I was conducted in the Swedish municipality of Östersund. A “new” site (cut 6 months previously) and an “old” site (cut 18 months previously), both on sandy glacial till, were used. There were four plots on each site (Table 9).The logging residues had been harvested on the site before the stump harvest. Cartesian coordinates were recorded for all stumps on the plots before harvest. The sites were harvested with an Ecorex30 stump harvesting head, a fork-type harvesting head equipped with a knife for splitting stumps (Figure 2, left). The stump harvest was conducted as a normal commercial harvest operation (see e.g. Kärhä, 2012). The only deviation from the normal work procedure was that small stumps with a DSH <200 mm were harvested in addition to large stumps. The coordinates of the stumps enabled some stump holes to be matched with specific stumps after the stump harvest. Overlapping holes created by lifting of more than one stump were not measured. Soil on the surface and vegetation on top of vegetation caused by the lifting of the stumps was also included in the ground disturbance area measurements. The ground disturbance was measured by placing a net (with a 0.024 m^2 mesh) over the disturbed area and counting all squares in which more than 50 % of the area was disturbed (Figure 3, left).

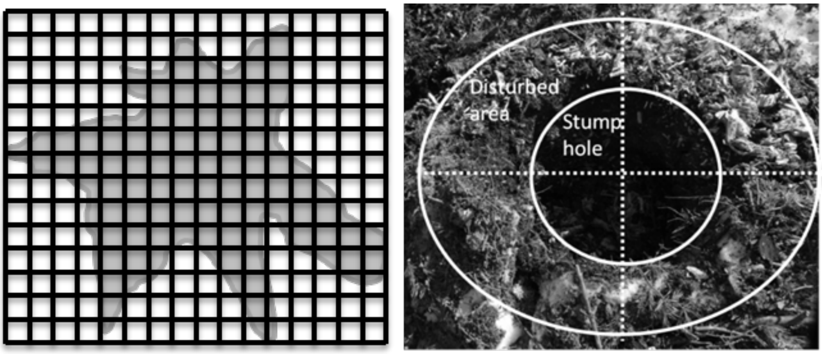

Figure 3. A schematic diagram of the net placed over the area of disturbed ground after a stump removal in Study I and Study IV (left) and a photograph showing a hole and the disturbed area after using the stump drill in Study IV, with dotted lines showing the measurement points (right).

The root breakage diameter was measured in Study I on one, randomly chosen, stump piece in every heap on the plots. The root breakage diameter was measured at the tip of the remaining root. Between 15 and 329 roots (70 on average) were measured per stump piece. Both the arithmetic mean and BAW mean root breakage diameter were calculated for every stump piece.

ANOVA followed by Tukey's (pairwise comparison of means) tests was used to detect significant differences between the two sites. ANCOVA was applied when the response variable in the ANOVA was correlated to a measured variable, which was then used as a covariate. Least square regression functions ($y=a+b\times x...$) were constructed for the area of disturbed ground with DSH as predictor. Data acquired were pooled before the regression analysis if no significant difference was found between them. To assess these distributions the Shapiro-Wilk normality test was applied to the residuals from the ANOVA, ANCOVA and regression analysis (Royston, 1982), while the Kruskal-Wallis rank sum test was used to assess differences between treatments if the residuals from the ANOVA or ANCOVA were not normally distributed (Hollander & Wolfe, 1973). The response variables in the regression functions were logarithmically transformed if necessary to achieve normal distributions of residuals. For all statistical tests a significance level of 0.05 was used. RStudio version 0.97.511 was used for the statistical analysis

2.2 Paper II

Study II was conducted in a clear-cutting area in the Swedish municipality of Vindeln (Table 9). The area had sandy sedimentary soil and flat, even, dry ground; the bearing capacity, ground roughness and slope all Class 1 according to the Swedish terrain classification scheme (Berg, 1992). In this study a stump-twisting rig (ca. 300 kg) capable of twisting stumps through an entire revolution (360°) was developed and used (Figure 4).

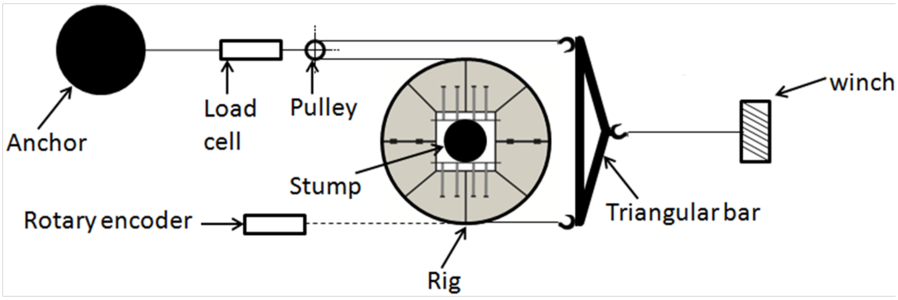

Figure 4. The trial setup in Study II, cables shown as lines and strings as broken lines.

There were two treatments: twisting stumps (n = 6) (T1) and cutting lateral roots around stumps (n = 20) by rotating one or two knives around the stumps (T4). In T1 the variable torque required to twist stumps was measured, while in T4 the torque required to cut the lateral roots was measured. In addition, the torque needed to overcome the rig-to-stump resistance (n = 2) (E) was measured by twisting the rig without any knives or chains around stumps. This torque was then subtracted from measurements for T4 to exclude the rig-to-stump resistance from the results. Trees that were twisted in the trials were cut to 1-1.5 m high stumps. To apply T1 four 1.5 m long chains were fastened (one in each corner) to the rig's frame (Figure 4). Holes were then dug under four major roots, a chain was placed around each of them and then reconnected to the rig. The rig rotated with the stump. To apply T4 one or two knives were attached to the rig (Figure 4), near the roots (within 10-50 mm). The rig was sufficiently heavy to push the knives into the soil when it was placed around a stump, and the rig rotated around the stump.

The applied force was measured with a load cell, and the distance the rig turned was measured with a modified rotary encoder. The data acquired from the load cell and the rotary encoder were recorded at a resolution of one measurement per second. The rotation of the rig and the maximum torque were calculated after the trails.

A linear equation ($y=k\times x+m$) expressing the torque of E as a function of DBH were constructed. To investigate differences in effects of the treatments (T1 and T4) ANOVA followed by Tukey's (pairwise comparison of means) tests was used. ANCOVA was applied when the response variable in the ANOVA was correlated to a measured variable, which was then used as a covariate. Least square regression functions ($y=a+b\times x...$) were constructed for the maximum torque with DBH as predictor. For all statistical tests a significance level of 0.05 was used. Minitab 16 (Minitab Ltd.) was used for the statistical analysis.

2.3 Paper III

Study III used data collected by Herlitz (1975) on eight Norway spruce - dominated clear-cutting type stands (Table 9). For all the trees in each of the stands the Cartesian coordinates were known. Trees with a smaller DBH than 80 mm were considered unsuitable for producing saleable wood, and were assumed to be pre-cleared before the harvesting. As the cost of the pre-clearing operation would be equal for both systems, it was not considered in the analysis. The type stands were assumed to have a bearing capacity, ground roughness and slope of Class 1 according to the Swedish terrain classification scheme (Berg, 1992). Two harvesting systems were modelled and simulated using discrete event simulation. System 1 (Figure 5) was the current conventional harvesting system: a standard roundwood harvester (17 – 19 t) (H), a standard forwarder (16 – 18 t) (FH), a stump harvester (20 – 23 t excavator) (SH) and a standard stump forwarder (forwarder, 14 t) (SF). System 2 (Figure 6) was an integrated three-machine system: a wheel-based feller-buncher (22 – 25 t), here named feller-puller (FP); a standard harvester (17 – 19 t) used as a processor (P) to delimb and buck the trees in the stand and a standard forwarder (16 – 18 t) (FFP) for transporting the normal and extended logs. The FP was equipped with a theoretical felling head able to harvest trees with the central part of the stump still attached to them, the side roots were cut in the soil and the trees were bunched along the driving path. The stump centre was handled as an extension of the butt-log. The harvesting of logging residues was assumed to have equal cost in both systems and was therefore not considered. Only PM_0 was considered in the simulations and the machines in both systems were assumed to have sufficient buffer volume to avoid affecting each other's work, i.e. no interactions were considered. Site preparation was not considered and assumed to be conducted with a separate machine in both systems, as this is standard current practice in Sweden (L-E Brantholm, TL Grot AB, pers. comm., 2012) and Finland (Kärhä, 2012).

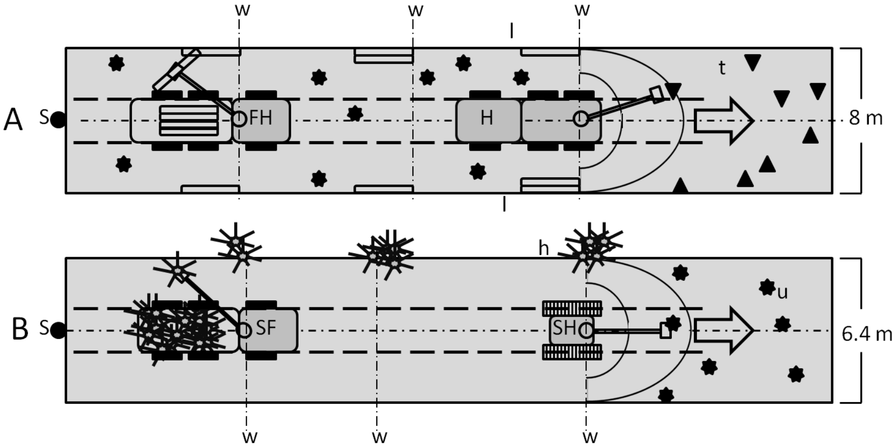

Figure 5. Sketch of the conventional harvesting system in Study III, consisting of: a harvester (H), a forwarder (FH), shown in A, a stump harvester (SH) and a stump forwarder (SF), shown in B. A and B have the same strip road but with a time delay between the operations. (S) indicates a random starting position, the arrow indicates the machine movement direction. (w) indicates the machine's working points where the H cut all trees, indicated by dark filled triangles (t). The distance between working points depended on the positions of the trees. The FH then drove along the same path as the H stopping at and loading the piles indicated by (l) from the working points used by H. The SH thereafter drove along the same path, but having other working points depending on the positions of the stumps. The SH uprooted the stumps indicated by dark filled "stars" (u) and placed them in one heap indicated by (h). The SF then drove along the same path as the SH stopping at and loading the heaps from the working point used by the SH. Both the FH and SF were restricted to only load the heap/pile produced by the SH/FP at a specific working point even if it could reach heaps/piles produced at other working points.

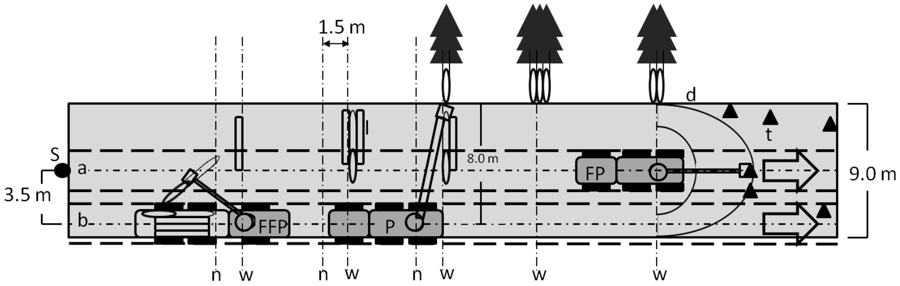

Figure 6. Sketch of the integrated harvesting system in Study III, consisting of: a feller-puller (FP), a processor (P) and a forwarder (FFP). The FP's path is indicated with (a) and the P's and F's path is indicated with (b). (S) indicates a random starting point, the arrow indicates the machine movement direction. (w) indicates the machine's working points for the FP and FFP, where the FP uprooted the trees indicated by dark filled triangles (t) and placed them perpendicular to the driving path in bunches indicated by (d). (n) indicates the machine's working point for the P which were set by the FP's work. The P was restricted to only processing the bunch produced from a specific working point even if it could reach other bunches. The FFP moved along the same path as the P stopping at working points parallel to those of the FP. The FFP was restricted to only load the piles indicated by (l) produced by the P at a specific working point even if it could reach other piles.

The PM_0 time of the machines and harvested volume were calculated for each simulation, and 100 simulations were conducted for each stand. Site variables and the productivity (m^3o.b./PMh_0) for the H, SH, FP and P were calculated for every simulation. The productivity of the FH, SF, FFP was calculated for every simulation but the biomass was repeatedly loaded until the equivalent of a 5 ha site had been forwarded, in order to reduce the effect of half-filled loads.

The harvested stem volumes for Scots pine, Norway spruce and birch trees were calculated using functions presented by Näslund (1947; 1940). The attached stump centre was assumed to have an OD mass of 32 % of the whole stump mass according to Nilsson and Danielsson (1976) and Hakkila (1972). The OD mass of the whole stumps was calculated using biomass functions presented by Marklund (1988) (deciduous stumps were assumed to have the same function as Scots pine). The OD mass of Scots pine, Norway spruce and deciduous stumps was converted to m^3 solid by dividing it by 0.45, 0.41 and 0.51, respectively (Karlsson, 2007).

Times for most work elements for the H, SH, FP and P were based on published data (Nakagawa *et al.*, 2010; Hedman, 2008; Nurminen *et al.*, 2006; Nylinder, 1977). The times from old time studies were multiplied by 0.82 to account for technical developments (Athanassiadis *et al.*, 2011a; Nylinder, 1977). However, some were constructed for the study. The number of pieces produced per stump and the FP's time consumption for felling a tree with the stump centre attached. Most input parameters were taken from the literature

(Jundén, 2011; Bergström *et al.*, 2007; Karlsson, 2007; Nurminen *et al.*, 2006) and company information (Cranab AB; Sweden, Hitachi Construction Machinery Co. Ltd., Japan; T. Persson, Eurologi Inc, pers. comm., 3 October 2011). However, the following inputs were assumed: all times for acceleration and retardation; time for crane rotation with loaded head; and time for dropping the biomass for the SH and FP.

The work elements of the FH, SF and FFP were based on published studies (Laitila *et al.*, 2008; Nurminen *et al.*, 2006). The input parameters for the forwarder's work were taken from the literature (Laitila *et al.*, 2008; Karlsson, 2007; Nurminen *et al.*, 2006). To use the functions, the following assumptions were made: two saw-log assortments and one pulpwood assortments were loaded at the same time and a mixed load of saw-logs (main assortment) and pulp-logs, when unloading. The grapple size was set to 0.25 m^3 for unloading stumps.

System analysis

System analysis was carried out by creating productivity functions for the machines based on the simulations from which the cost of stump wood (€/ODt), time consumption per cubic meter (PMh_0/m^3), and volume (m^3/ha) were calculated. To analyse the stump wood cost (€/ODt), it was assumed that the costs of harvesting roundwood were equal in both systems, i.e. the cost for harvesting roundwood in the conventional system was used as the cost in the integrated system. The calculations were based on the hourly machine costs given in Table 10 and the type stands (Table 9) using the mean values for the type stands as inputs for the productivity and biomass functions (Marklund, 1988; Näslund, 1947; Näslund, 1940).

Several models were made for the two systems as there were uncertainties about the productivity of the SH and the yield of stump wood in the integrated system. The cleaning work of the SH was assumed to be done during 80% of the crane movement, and the stumps were split over the heap (CH & MS model), as skilled operators usually work that way. The SH worked by cleaning and splitting the stumps over the uprooting point and then moving the pieces to the heap (basic model) to investigate a work method with minimal impact. The SH's productivity functions were changed to a function presented by Athanassiadis *et al.* (2011a) for stump harvesters as some of the work elements were based on old studies. The yield of the stump centre in the integrated system should be 32 % of the whole stump volume according to Nilsson and Danielsson (1976) and Hakkila (1972) (Svol 32% model). Fryk (1975) estimated the volume of the stump extension to be 8.5 % of the stump volume (basic model). The main analysis in the thesis is based on the CH & MS and Svol 32% models, as they were deemed to be the most realistic.

Table 10. *Hourly costs calculated in Study III for the harvester (H), forwarder in the conventional system (FH), stump harvester (SH), stump forwarder (SF), feller-puller (FP), processor (P) and forwarder in the integrated system (FFP).The exchange rate was 9.18 SEK per €*

	H & P	FH & FFP	SH	SF	FP
Cost (€/PMh_0)	119.82	98.04	95.86	91.51	141.61

Least square regression (y=a+b×x...) functions were constructed for the simulated machines using the productivity (m^3/PMh_0) as the response variable with stand variables as predictors. For all statistical tests a significance level of 0.05 was used. Minitab 16 (Minitab Ltd.) was used for the statistical analysis and the simulation in Study III was conducted in MatLab R2009b (The MathWorks Inc.).

2.4 Paper IV

Study IV was conducted on a clear-cutting in ditched peatland in Lappajärvi municipality, Finland (Table 9). A conventional stump splitting-type harvesting head, the Terosa KK-900 (Figure 2, right), was compared to an Ellettari stump drill with an inner diameter of 40 cm (Figure 2, middle). Most of the snow had thawed when the harvest was conducted, but the ground was still frozen. It was not possible to connect individual stumps to disturbed areas in this study. The holes created by the conventional stump splitter were measured in the same way as in Study I. The diameter of the area disturbed by the stump drill was measured in two directions (Figure 3, right). Measurements were taken the same year as harvest and the year after harvest.

To investigate differences in effects of the treatments ANOVA followed by Tukey's (pairwise comparison of means) tests was applied to detect significant differences in the area of disturbed ground and depth of the holes created by the two stump harvesting heads on both measurement occasions. To assess these distributions the Shapiro-Wilk normality test was applied to the residuals from the ANOVA (Royston, 1982), while the Kruskal-Wallis rank sum test was used to assess differences between treatments if the residuals from the ANOVA were not normally distributed (Hollander & Wolfe, 1973). For all statistical tests a significance level of 0.05 was used. RStudio version 0.97.511 was used for the statistical analysis.

3 Results

3.1 Results from Paper I

No significant difference between the “Old” and “New” sites in areas of disturbed ground (p-value = 0.670, cov = 0.136, R^2 = 36.4), depth of the holes (p-value = 0.639, R^2 = 0.0), arithmetic root breakage diameter (p-value = 0.084, R^2 = 31.9) and BAW root breakage diameter (p-value = 0.157, R^2 = 18.7) was detected. The average area of disturbed ground per stump was 6.06 m^2 (SD 3.14), average depth of the holes was 39.8 (SD 11.4) cm, average arithmetic root breakage diameter was 4.6 (SD 2.2) mm and average BAW root breakage diameter 29.5 (SD 17.9) mm. The data sets acquired from measurements on the two sites were pooled before the regression analysis, as no significant difference was found between them. A regression function was created for the area of disturbed ground (m^2) (Table 11 and Figure 7). When the value from the function was retransformed the constant 1.091 had to be applied to correct logarithmic bias according to the ratio correction procedure presented by Snowdon (1991).

Table 11. *Least square regression functions for the ground disturbed area depending on DSH. The standard deviation of the estimated variable (SD), the p-value for the estimated variable (p-value), the residual standard error of the function (RMSE) and the adjusted (R^2) are shown*

Predicted variable		Independent variables					Model’s	
	Area		Unit	Parameter	SD	p-value	RMSE	R^2
LN(Area)	m^2	Constant		0.9720	0.1332	<0.001	0.419	23.6
		DSH	mm	0.002203	0.0003902	<0.001		

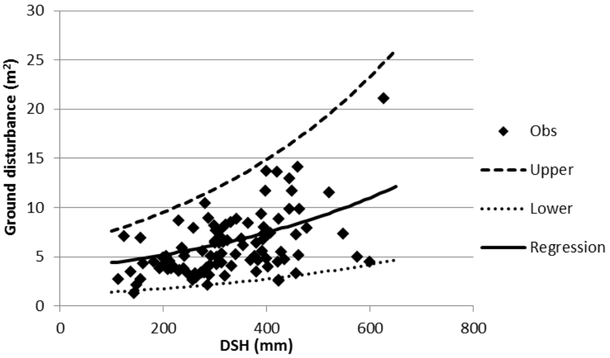

Figure 7. Dependence of the measured area of ground disturbance (Obs) on DSH, showing regression functions (Regression) for predicting ground disturbance (1.091×e^(0.9720+0.0022026×DSH)) and the Upper (e^(1.805+0.002238×DSH)) and Lower (e^(0.1392+0.002167×DSH)) boundaries for the 95 % confidence intervals.

3.2 Results from Paper II

The DBH variable was correlated to the maximum torque and used as a covariate in the ANCOVA analysis. T1 required a significantly higher torque than T4 (p-value <0.001, covariate <0.001, $R^2 = 71.1$). Thus, twisting stumps required higher maximum torque than cutting lateral roots around stumps. DBH was used as a predictive variable in the least square regression functions for the torque in treatments T1 and T4 (Table 12 and Figure 8).

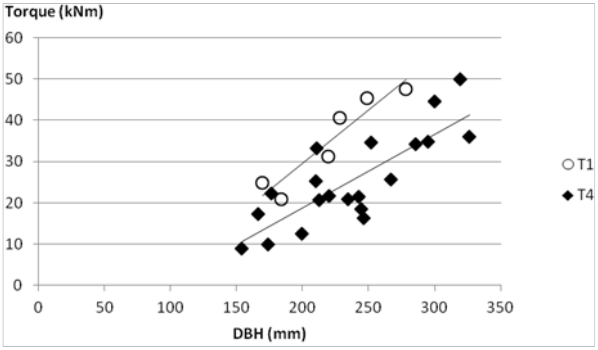

Figure 8. Torque needed to cut roots around stumps (-16.896+0.178×DBH) (T4) and the torque needed to twist stumps (-22.270+0.259×DBH) (T1) as functions of DBH in Study II. The lines shown are least squares regression lines.

Table 12. *Regression functions for the torque required to twist stumps (T1), to cut lateral roots around stumps (T4) and the linear equations for the rig-to-stump resistance (E) depending on DBH. The standard deviation of the estimated variable (SD), the p-value for the estimated variable (p-value), the residual standard error of the function (RMSE) and the adjusted (R^2) are shown*

Predicted variable		Independent variables					Model's	
	Torque		Unit	Parameter	SD	p-value	RMSE	R^2
E	kNm	Constant		-2.844				
		DBH	mm	0.027				
T4	kNm	Constant		-16.896	7.729	0.032	6.656	64.3
		DBH	mm	0.178	0.030	<0.001		
T1	kNm	Constant		-22.270	10.330	0.097	4.142	86.0
		DBH	mm	0.259	0.046	0.005		

3.3 Results from Paper III

The productivity generally increased with increasing tree size for all machines. However, the productivity of the FH, SF and FFP levelled out after an initial increase, while it continued to increase for the other machines (Table 14). The two systems produced different volumes of stump-wood (Table 13). The Svol 32% model for the integrated system produced stump-wood from trees with a DBH > 160 mm more cheaply than the CH & MS model for the separate system (Figure 9).

Table 13. *The productivity and harvested volume of the harvester (H) and forwarder in the conventional system (FH), stump harvester (SH) and stump forwarder (SF), feller-puller (FP), processor (P) and forwarder in the integrated system (FFP) in Study III. Also shown is the round-wood volume harvested per hectare (RW); the stump wood volume harvested in the conventional system (SC); and the stump volume (SI) harvested in the integrated system*

	Volume (m^3/ha)			Productivity (m^3/PMh_0)						
	RW	SC	SI	H	FH	SH	SF	FP	P	FFP
	51	34	11	18.44	16.37	7.35	7.99	29.90	32.48	20.04
	78	42	13	20.04	16.70	7.79	8.07	33.00	34.72	20.33
	88	45	14	15.49	15.63	6.41	7.81	23.53	28.17	19.41
	88	46	15	18.18	16.31	7.28	7.98	29.38	32.12	19.99
	109	51	16	19.50	16.59	7.64	8.04	31.97	33.97	20.24
	131	70	22	31.54	18.38	10.12	8.46	51.40	49.89	21.77
	461	131	42	98.93	20.89	16.56	8.80	115.72	154.17	23.53
	689	178	57	65.10	20.55	14.07	8.88	89.60	95.10	23.50
Mean	*212*	*75*	*24*	*35.90*	*17.68*	*9.65*	*8.25*	*50.56*	*57.58*	*21.10*

Table 14. *Least squares regression models for estimating the productivity of the stump harvester (SH) in the CH & MS model and the productivity of the feller-puller (FP), processor (P) and integrated forwarder (FFP) in the Svol 32% model. The standard deviation of the estimated variable (SD), the p-value for the estimated variable (p-value), the residual standard error of the function (RMSE) and the adjusted (R^2) are shown*

Predicted variable		Independent variables					Model's	
	Productivity		Unit	Parameter	SD	p-value	RMSE	R^2
SH	m^3/PMh_0	Constant		-64.313	2.107	<0.001		
		DBH	mm	-0.020712	0.002033	<0.001	0.694416	96.2
		LN(DBH)	mm	14.8309	0.4826	<0.001		
FP	m^3/PMh_0	Constant		-69.488	1.389	<0.001		
		DBH	mm	0.75249	0.01282	<0.001	4.76412	98.3
		DBH^2	mm	-0.00074168	0.00002389	<0.001		
P	m^3/PMh_0	Constant		118.68	18.85	<0.001		
		DBH	mm	0.59598	0.01812	<0.001	7.15035	97.5
		LN(DBH)	mm	-35.480	4.318	<0.001		
FFP	m^3/PMh_0	Constant		-43.122	2.875	<0.001		
		DBH	mm	-0.038146	0.002763	<0.001	1.09051	77.6
		LN(DBH)	mm	13.6867	0.6585	<0.001		

3.3.1 Sensitivity analysis

The basic model for the integrated system produced stump wood more cheaply than the basic model for the conventional system for trees with a DBH >210 mm. The basic model for the integrated system produced stump wood more cheaply than the CH & MS model for the conventional system for trees with a DBH >280 mm, and more cheaply than the model presented by Athanassiadis *et al.* (2011a) for trees with a DBH >420 mm. The Svol 32 % model for the integrated system produced stump wood more cheaply for trees of all sizes than both the basic model and the model presented by Athanassiadis *et al.* (2011a) for the conventional system.

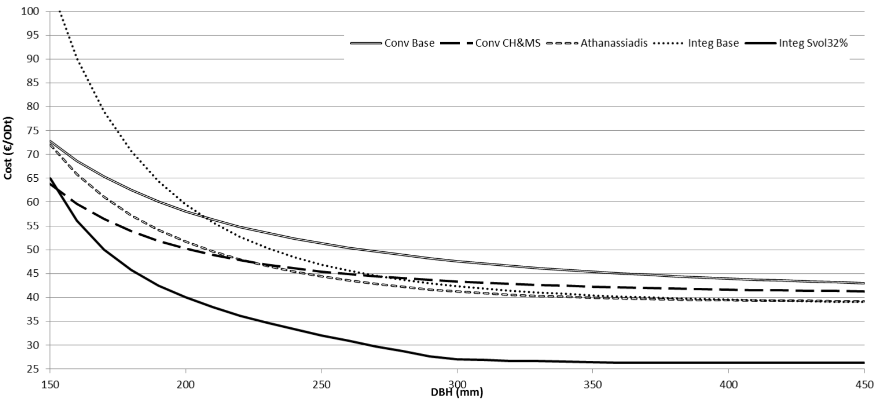

Figure 9. Costs (€/ODt) of stump-wood as a function of breast height diameter (DBH) in Study III. Legend abbreviations indicate: conventional stump harvest (Conv base) and integrated (Integ base) harvesting system in the simulation's basic scenario; when stumps were cut over the heap and part of the cleaning was carried out while moving the stump (Conv CH&MS); when the productivity model by Athanassiadis *et al.* (2011) was used for the stump harvester (SH); and when the stump-wood yield from the integrated system was assumed to be 32 % of the yield from the conventional system (Integ Svol 32 %). All calculations are based on the assumption that the cost for round-wood from the integrated system equals the cost from the conventional system.

3.4 Results from Paper IV

The area of ground disturbed per stump harvested by the conventional stump splitter was 9.0 (SD 4.01) m^2 in Year 0, ten times more than the area disturbed by the stump drill, 0.9 (0.17) m^2 (Kruskal-Wallis test <0.001). The difference decreased to 8-fold larger in Year 1 (p-value <0.001, $R^2 = 93.7$) when the areas disturbed by the harvest was to 7.60 (SD 2.62) m^2 and 0.93 (0.20) m^2, respectively. The depth of the holes created by the conventional stump splitter and stump drill in Year 0 were 36.4 (SD 7.6) cm and 39.3 (SD 7.1) cm, a non-significant difference (p <0.090, $R^2 = 2.7$). The corresponding values in Year 1 were 29.3 (SD 5.5) and 31.9 (SD 6.0) cm, respectively, again a non-significant difference (p <0.057, $R^2 = 3.8$).

4 Discussion

The demand for biomass will determine the price of biomass and whether or not stump harvesting is economically viable in the future. A political goal of the EU is to replace use of most fossil fuels by 2050 (European Commission, 2011b), which should create a large demand for renewable energy sources and bio-based products. Thus, high demand is expected for stump wood, for example in Finland the use of stump wood is expected to double or triple by 2020 (Kärhä, 2012). Scots pine stump wood, especially, is likely to become more attractive in the future, as it has a high extractives content (Eriksson *et al.*, 2012) and thus could be used for manufacturing chemicals. The magnitude of the demand will depend on how firmly the politicians follow the goals and the proportion of the supply that will be met by imported biomass.

4.1 Technical possibilities and system development

It is desirable to reduce the ground disturbance and increase the root breakage diameter in stump harvesting (Studies I and IV). This will probably require improvement of harvesting technologies, as delaying harvest had no positive effect on these variables (Study I). It is possible to develop heads similar to the conventional Nordic harvesting heads, stump drills, new harvesting methods, or further investigate possibilities for integrated harvests. However, the only apparent way to reduce the ground disturbance is to harvest a smaller part of the stump and root system, which would also increase the root breakage diameter, and reduce the harvested stump volume by 47-68 % according to (Nilsson & Danielsson (1976). Future harvesting systems based on such methods will need to be more profitable than the machines used today for contractors to replace them. It is however possible that future regulations or certification criteria could limit the permitted ground disturbance. If so heads that harvest a smaller part of the root system will probably be used first in cases where the limits could be exceeded, at least until new technologies that cause less disturbance are developed.

4.1.1 Twisting stumps

Study II investigated novel means to harvest stumps; using torque to twist them, or cut roots around them. The results showed that stronger torques are required to twist or cut free Scots pine stumps (10-50 kNm) than a normal rotator can generate (L. Eriksson, Indexator AB, pers. comm., May 12, 2010). It could be possible to use the wrist of a feller-buncher's felling head, which can generate greater torque (D. Barlow, Tigercat Inc., pers. comm., May 27, 2011). However, Norway spruce stumps generally have thicker lateral roots than Scots pine stumps (Hakkila, 1972), and thus probably require even higher torques. Stumps anchored in coarse soils may also require higher torque. Thus, use of harvesting heads based on twisting would probably be restricted to certain harvesting sites and/or species (thereby restricting the machine owners' annual work base, scope to bid for contracts and degree of machine utilization). If the market is small investments in harvester head development will be limited. In Sweden about 2.4 million ha of Scots pine forest (with >70 % pine basal area) is growing on peat or sedimentary soil that is classified as productive forest land (P. Nilsson, Swedish Forest Inventory, SLU, pers. comm., 12 Sept 2014). The total area of productive forest land is about 22.4 million ha, so roughly 10 % of the forest area is covered by pine-dominated forests on sediment or peatland. Hence, it seems unlikely that such heads will be competitive with current harvesting technologies in a foreseeable Swedish market. There are also environmental concerns associated with peat soils and fine-textured sedimentary soils that make them less suitable for stump harvest (Egnell *et al.*, 2007).

The effect of the twisting on the stems was not measured in Study II, but cracks in the stems were visually observed after both treatments. Therefore, neither twisting stumps nor application of torque to cut roots around stumps should be used in an integrated stem and stump harvesting system, such as the one examined in Study III. The knives used also bent after cutting a few roots, although they were quite sturdy and made from high quality steel. If such heads are developed they would likely require a lot of material and therefore be quite heavy or constructed from new lighter, stronger materials. In summary, twisting is probably not the best option for future development of stump harvesting technology, regardless of whether it is implemented in conventional or integrated harvests. A possible alternative for integrated harvests could be to cut off the roots by vertical movement (from above). Such root severing does not reportedly damage the attached stem, but the stem may be damaged when the tree is lifted out of the ground (Grillot, 1976; Koch & Coughran, 1975).

In order to develop functional stump harvesting heads knowledge of the variation in forces required to lift (uproot) stumps is required. Current lack of such knowledge has led to heads being oversized, and consequently greater than necessary material consumption in their construction, higher prices and requirements for bigger/heavier/more expensive base machines.

4.1.2 Conventional stump harvest technology

There are some ongoing efforts to develop the heads currently used in Scandinavia. One prototype head that could be developed further is the Järvinen head (Kärhä, 2012). This head has a ring that is placed around the stump, the stump is then gripped and pulled upwards while the ring remains on the ground, breaking the roots around the stump. The device can cut off 50-100 mm diameter roots, which should lead to 25-36 and 45-55 % reductions in the harvested volume and N removal, respectively (Table 16), compared to harvesting all roots down to 5 mm. The prototype has several drawbacks that would have to be resolved before use in practical operations: it cannot harvest all stumps, split stumps or clean the stumps at all. Another head that could be developed further is the Brantholm head, which can cut the roots close to the stump and reduce ground disturbance by approximately 50 % compared to the disturbance recorded in Study I, but due to current limitations it is difficult to use and needs to be redesigned (H. von Hofsten, The Forestry Research Institute of Sweden, pers. comm., 22 Oct 2014).

Stump drills, such as the one used in Study IV, can already be used at sites on peatlands and fine-textured mineral soils. However, they may be more challenging to use on coarse glacial till soils, as the teeth will quickly be worn out against the stones. In Sweden about 6.6 million ha of productive forest land is located on peat or sedimentary soil (P. Nilsson, Swedish Forest Inventory, SLU, pers. comm., 15 Sept 2014), which means that ca. 30 % of the forest land could be potentially suitable to harvest using stump drills. The estimates in this thesis indicate that stump drills are 30-60 % more expensive than the conventional system in Nordic conditions. This difference is consistent with results presented by von Hofsten *et al.* (2012b) and von Hofsten (2010). The productivity of the stump drill has to be improved to similar levels to those reached in Mediterranean conditions on agricultural land (Spinelli *et al.*, 2005), to be as cost-effective (5 % lower to 17 % higher costs) as the conventional system. However, the stump drills used in the Mediterranean countries have a clear drawback in that they cannot split or clean the stumps, which facilitates drying during storage, but on a positive note unsplit material is less bulky

(Anerud & Jirjis, 2011). In addition, the latest version of the Nordic stump drill has been equipped with a splitting knife, so it can split stumps and to some extent clean them (von Hofsten *et al.*, 2012b).

The base machine used for stump harvesting and forwarding could also be improved. This would probably not reduce the ground disturbance, but could improve the profitability of the operations. The time spent on cleaning stumps by shaking them during harvest accounts for 11-25 % of conventional Nordic stump harvesters' effective work time (Hedman, 2008). In a best case scenario separate cleaning could eliminate this work element. Separate cleaning is especially important if stump drills are used as they have limited cleaning ability (von Hofsten *et al.*, 2012b). Vibrations, chain-flails, water, or large rotating drums could be used for cleaning (Anerud *et al.*, 2013; Spinelli *et al.*, 2005; Jonsson, 1985). Separate chain-flail cleaners are used in the Mediterranean countries (Spinelli *et al.*, 2005). Vibrations are also effective, and can reduce stumps' ash content as much as ordinary cleaning during harvest and then storing the stumps for three summer months (Anerud *et al.*, 2013). The cleaning could be done by: adding a device to the harvester for cleaning (e.g. a vibrating platform) with a possibility to handle a number of stumps before dumping them in a heap; a cleaning device mounted on the forwarder; or a cleaning device at the landing. Alternatively, the stumps could be cleaned at a terminal or industrial site, but this would increase costs as the contaminants would also be transported. The stump-splitting could also be automated and done simultaneously with lifting, or at the same places as listed for the cleaning, or by the forwarder when loading or unloading. Splitting accounts for 8% of the total work time for a conventional Nordic stump harvester (von Hofsten *et al.*, 2012a), so the gains would be smaller than for automatic cleaning. Lifting the whole stump with a harvesting head would probably increase ground disturbance to higher levels than those observed in Study III, which is not desirable. von Hofsten *et al.* (2012b) showed that 9 % of the effective work time of stump drills that can split stump centres is spent on splitting. This is an important feature, as split stumps dry better than unsplit stumps during storage (Anerud & Jirjis, 2011).

4.1.3 Integrated stump harvests

A first step towards integrated harvests would be to integrate the harvest of trees and stumps and to cut off the stump part in the forest or at the landing. Estimates in this thesis show that cutting off the stumps at the landing could be economical, but not to transport them to industrial sites with the roundwood (Figure 11). There are also fewer hurdles to overcome before stump centres could be cut off at the landing. After a stump has been cut off from the roundwood more options are available for cleaning and splitting. Integrated whole stump harvesting systems in which stumps are cut off in the stand have been trialled on peatlands (harvested to allow peat harvest) and were found to be profitable for small trees (Laitila *et al.*, 2013). However, the results of Study IV indicate that whole stump harvests could cause substantial ground disturbance on peatland. This disturbance is not a problem when the site is converted for peat harvests, but would likely be problematic in sites that will be kept as forest land in the future. Cutting off the stump extensions would also probably be more difficult in stands on mineral soil, which could damage the saw and reduce the machine's productive time or require specialised saws with high durability. Integrated whole stump harvests would probably not reduce the ground disturbance.

Estimates in this thesis are based on assumptions that the stump extensions would be used as fuel wood. However, if the stump centres were transported to industrial sites still attached to the butt-logs, saw logs could be extended 1-2 dm to the point where the fibres start to change angle (Jonsson, 1985), and the rest of the stumps could be used as fuel wood. These extensions would have higher value than fuel wood and could be economically viable to utilize. The cost at mill gate should be 112-150 €/ODt (Figure 11) for the entire extension. Removing the part of the extensions that could not be used as saw timber would then incur additional costs. However, the following problems have to be considered: logs with a stump wood extensions are bulkier (Grillot, 1976), which reduces the number of logs that can be loaded on a truck or forwarder; and stump extensions harvested from mineral soil will be contaminated. Grillot (1976) noted that the soil contamination of stump extensions was problematic for the processing industries and prohibited wider use of the method. I also think that contaminating soil could fall off during transportation with normal roundwood trucks, which is not desirable so they would have to be cleaned before transportation. The same methods as mentioned for conventional stump harvests could be used to clean the extensions.

Integrated harvest has been successfully conducted with 20 cm of ground frost (Fryk, 1975), indicating that it should be possible to conduct year-round. However, there will be seasonal problems during the winter wherever the stumps are cut off as contaminating matter is difficult to remove when it is frozen onto stumps (Anerud & Jirjis, 2011). This problem would probably be exacerbated if stumps were transported to industrial sites as extensions of the butt-logs. However, if the stumps were cut off at the landing the rest of the process could be delayed until conditions were more favourable. In previous studies of integrated harvests stems were also sometimes damaged when they were lifted from the soil (Grillot, 1976; Fryk, 1975). This is a problem that must be satisfactorily solved before any kind of integrated harvest can occur.

It is also important to have the option to only cut the trees and leave the stump centres in the ground when integrating stump harvesting. Harvesting all available stump centres is unlikely to be desirable, e.g. close to streams. In the analysis of the integrated system in Study III the processor could be used to cut and process the remaining trees. Integrated harvests would also enable stump harvests while leaving the logging residues at the site. This option could be attractive as logging residues have higher nutrient contents than stumps (Iwald *et al.*, 2013).

4.2 Productivity

Several models for integrated and conventional systems were constructed, compared and found to have differing productivity in Study III**.** However, only the Svol 32% model for the integrated system and CH & MS model for the conventional system were used in this thesis as they were assumed to be more realistic. In the conventional system the productivity of the stump harvester was uncertain. The CH & MS model for the conventional system, where the splitting and part of the cleaning is not done over the stump hole, is more realistic than the basic model for the conventional system, as skilled operators work in that manner. The work in the basic model was done in a way that minimized the impacts of stump harvesting on the site, so the 18-23 % lower productivity can be seen as a cost of minimising the harvest impact.

In addition to the comparisons in Study III, the productivity of the feller puller can also be compared to the productivity of the American TX-1600 tree extractor (Figure 10) as reported by Grillot (1976). The comparison indicates that the FP can harvest trees 13-40 % faster than the TX-1600, and the difference is largest for small trees. As stated in Paper III, technical improvements have led to a 20 % reduction in the time required for stump harvesting (Athanassiadis *et al.*, 2011a; Nylinder, 1977). Hence, the FP's productivity may be over-estimated for small trees, but should be accurate for larger trees.

The stump drill also has interesting potential as it causes low ground disturbance on peatland (Study IV), but its productivity on peatland has not been evaluated in any in-field time studies. The productivity of the stump drill and forwarding stump drill on mineral soil in Nordic conditions has been evaluated, but unfortunately it seems to be about 60 % and 30 % lower than that of conventional technology, respectively (von Hofsten *et al.*, 2012b). The low productivity of the stump drill is mainly due to the reduction in harvested volume (47-68 % (Nilsson & Danielsson, 1976)), while the reduction in forwarder productivity is partly due to the reduction in stump wood concentration and partly due to the stump centres falling off and being difficult to pick up. The productivity could probably be improved if stakes on the load bunk were set closer to prevent stump centres from falling off, and the grapple could perhaps be redesigned to facilitate gripping. The Mediterranean system has similar productivity to conventional Nordic stump harvesting, but cleaning is done with a separate machine and no splitting is done (Spinelli *et al.*, 2005).

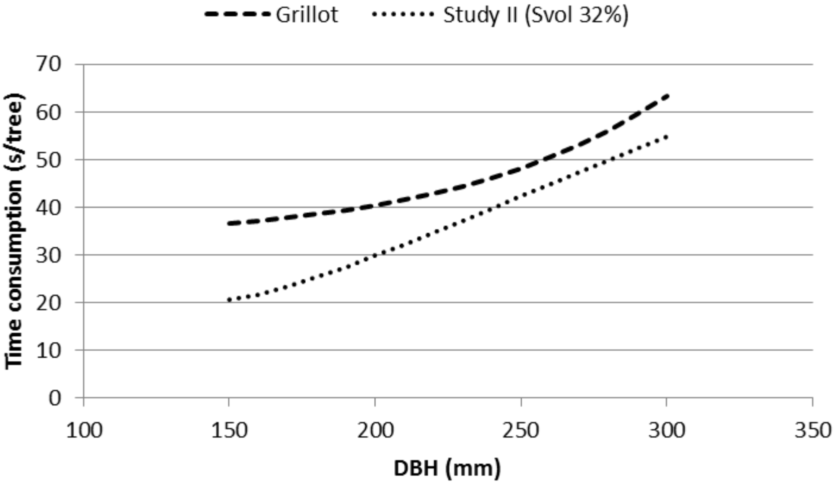

Figure 10. Comparison of the PM_0 required for lifting a tree as function of DBH in Study III based on the Svol 32 % model and using a TX-1600 tree extractor for clear cutting in Grillot (1976).

4.3 Economics

It was concluded in Study III that the integrated system could be cheaper than the conventional system for harvesting and transporting stump wood from trees over 420 mm DBH to the landing, and in best-case scenarios could be lower for trees over 160 mm DBH. Conflicting results were reported by Laitila *et al.* (2013), who investigated integrated whole stump harvesting on peatland that was to be converted for peat harvesting. They found that integrated harvests could be cheaper for trees below 200 mm DBH. The integrated harvest studied by Laitila *et al.* (2013) was done by a normal roundwood harvester which gripped and lifted the trees with their root systems out of the soil and then cut off the stumps before processing the trees as normal. The roundwood and stumpwood were then forwarded separately. This approach differs from the approach in Study III, which makes it difficult to compare them. Grillot (1976) showed that integrated harvests of stump centres with the TX-1600 could produce pulpwood at competitive costs in clear cuttings, but not thinnings, compared to the prevailing feller-buncher system used in the southern USA. These observations underline the conclusions in Study III that more research is needed to investigate the potential profitability of integrated harvests.

However, the cost for the whole chain from forest to industry is more important than the cost for the part of the chain ending at landings, as this is the cost that must be covered by the price the end-user pays. Transportation and comminution costs were not empirically investigated in Study III. However, some estimations were made in this thesis for the integrated system when cutting off stumps and comminuting them at the landing and then transporting the hog fuel to industry, and for cleaning the stumps at the landing, transporting them as butt-log extensions to industrial sites, where they were cut off and comminuted. These costs were then compared to those of a conventional system in Study III. In addition, the cost of using a stump drill similar to the one used in Study IV to harvest the stump centres on mineral soil was estimated (Figure 11). In both systems that only harvest stump wood, it was comminuted at the landing then transported as hog fuel. These estimations were based on the cost and productivity data shown in Table 15. The estimated cost of conventional stump harvest is 77.1-99.5 €/ODt or 14.5-21.4 €/MWh (Figure 11). This is within the range of 10.6-30.0 €/MWh estimated by Eriksson *et al.* (2014a) for the conventional supply chain, indicating that the cost estimates are reliable. The estimates indicate that the integrated system is 0-90 % more expensive than the conventional system if it includes cutting off stump extensions at the landing, and 60-100 % more expensive if it includes cutting them off at the industrial site (Figure 11). Based on these findings it seems unlikely that integrated harvesting would be profitable if stumps were transported as butt-log extensions, but could perhaps be viable if they were cut off at the landing. The estimates also indicate that stump centre harvesting is 30-60 % more expensive than conventional stump harvesting. If stump drills were used on peatland the productivity would probably be higher (Table 15), which would make them less costly, but still 20-30 % more expensive than the conventional technology.

Table 15. *Productivity, costs and fuel consumptions (based on 50 km trucking distance). Abbreviations: H, harvester; FH, roundwood forwarder; SH, stump harvester; SF, stump forwarder; C+S, comminution and sawing; SLT, transport of comminuted stumps; FP, feller puller; P, processor; FFP, roundwood and stump extension forwarder; C, cleaning stump extensions at the landing; IT, transport of timber with stump extensions; CTI, cutting stump extensions at industrial sites; CI, comminution at industrial sites; CTL cutting of stump extensions at landing; SD, stump drill harvesting; SDF, stump drill forwarder;(C), stump centre or stump extension; and (P), on peatland*

		Operational cost		Fuel consumption		
Machine	Productivity functions	Levels	Source	Levels	Source	Payload
H	CH & MS model		Study III	12.73 l/ PMh$_0$	(Brunberg, 2013)	
FH	CH & MS model		Study III	9.45 l/PMh$_0$	(Brunberg, 2013)	
SH	CH & MS model		Study III	12 l/PMh$_0$	(Eriksson-Näslund & Gustavsson, 2008)	
SF	CH & MS model		Study III	9.5 l/PMh$_0$	(Eriksson-Näslund & Gustavsson, 2008)	
C+S	-	7.79 €/ODt	(Eriksson *et al.*, 2014b)	4.1 l/PMh$_0$	(Eliasson *et al.*, 2012)	
SLT	-	10.13 €/ODt	(Eriksson *et al.*, 2014b)	5.73 l/10 km	Same as IT	30 ton
FP	Svol 32% model		Study III	41.4 l/PMh$_0$	(Ghaffariyan *et al.*, 2012)	
P	Svol 32% model		Study III	12.73 l/PMh$_0$	Same as H	
FFP	Svol 32% model		Study III	9.45 l/PMh$_0$	Same as FH	
C	(Spinelli *et al.*, 2005)	119.82 €/PMh$_0$	Same as H and P	12.73 l/PMh$_0$	Same as H	
IT	-	55.63 €/ODt	(Lindström, 2014)	5.73 l/10 km	(Lindström, 2014)	32 ton
CTI.	-	45.84 €/ODt	50 % CTL	-	-	
CI.	-	6.23 €/ODt	(Eriksson *et al.*, 2014b)	-	-	
CTL	-	91.67 €/ODt	Based on P and H in Study III	12.73 l/PMh$_0$	Same as H	
C+S(C)	-	29.6 €/ODt	(von Hofsten *et al.*, 2012b)	4.1 l/PMh$_0$	(Eliasson *et al.*, 2012)	
SD	(von Hofsten *et al.*, 2012b)	95.86 €/PMh$_0$	Same as SH	12 l/PMh$_0$	Same as SH	
SD(P)	(Spinelli *et al.*, 2005)	95.86 €/PMh$_0$	Same as SH	12 l/PMh$_0$	Same as SH	
SDF	(von Hofsten *et al.*, 2012b)	91.51 €/PMh$_0$	Same as SF	9.5 l/PMh$_0$	Same as SF	

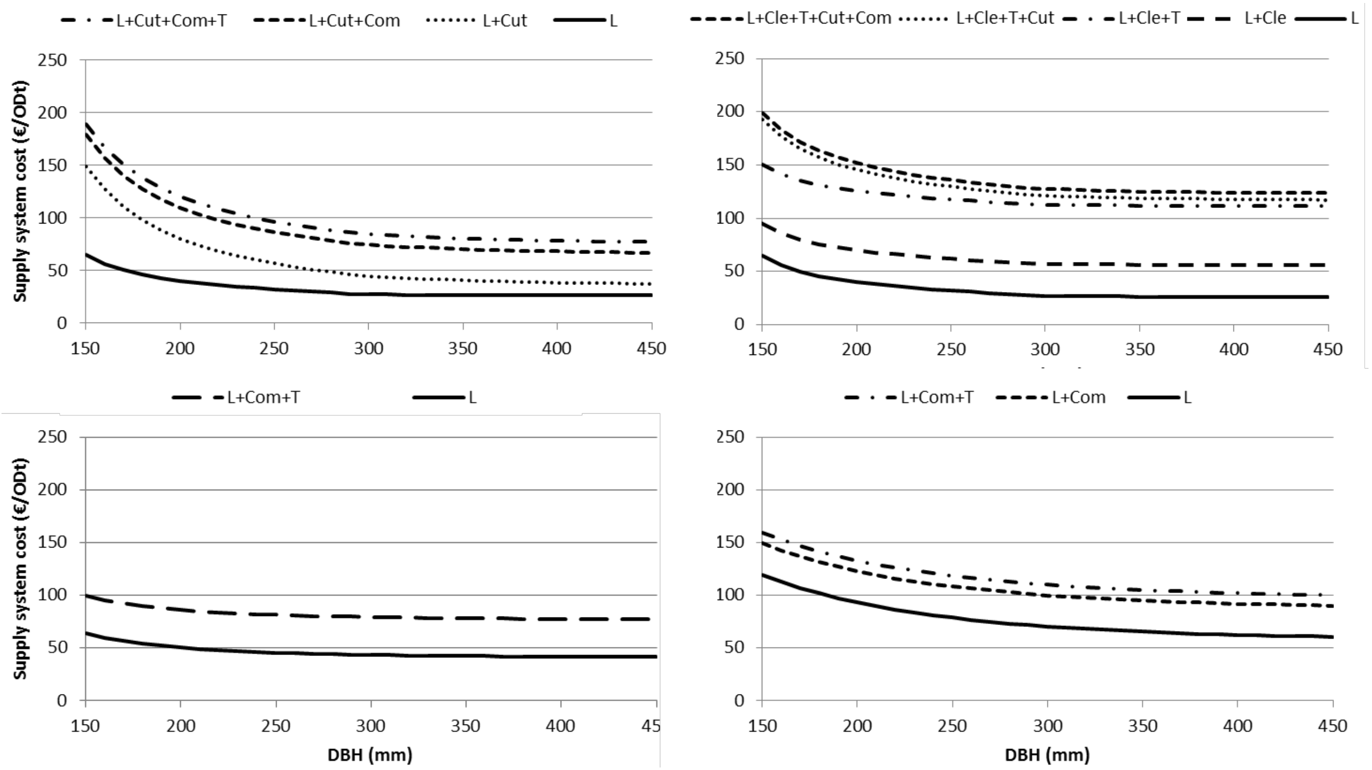

Figure 11. The cost of stump wood as function of DBH in the integrated system in Study III when stump extensions are cut off and comminuted at the landing before transport (top left) and when cleaned and then transported to industrial sites and cut off and comminuted there (top right), the conventional system (bottom left) in Study III and a system for stump drill harvesting (bottom right). Calculations are based on 50 km transport distance. The costs are estimated for harvesting and forwarding (L), cutting off the stump extension (Cut), cleaning the stump extension (Cle), comminution (Com) and transport (T).

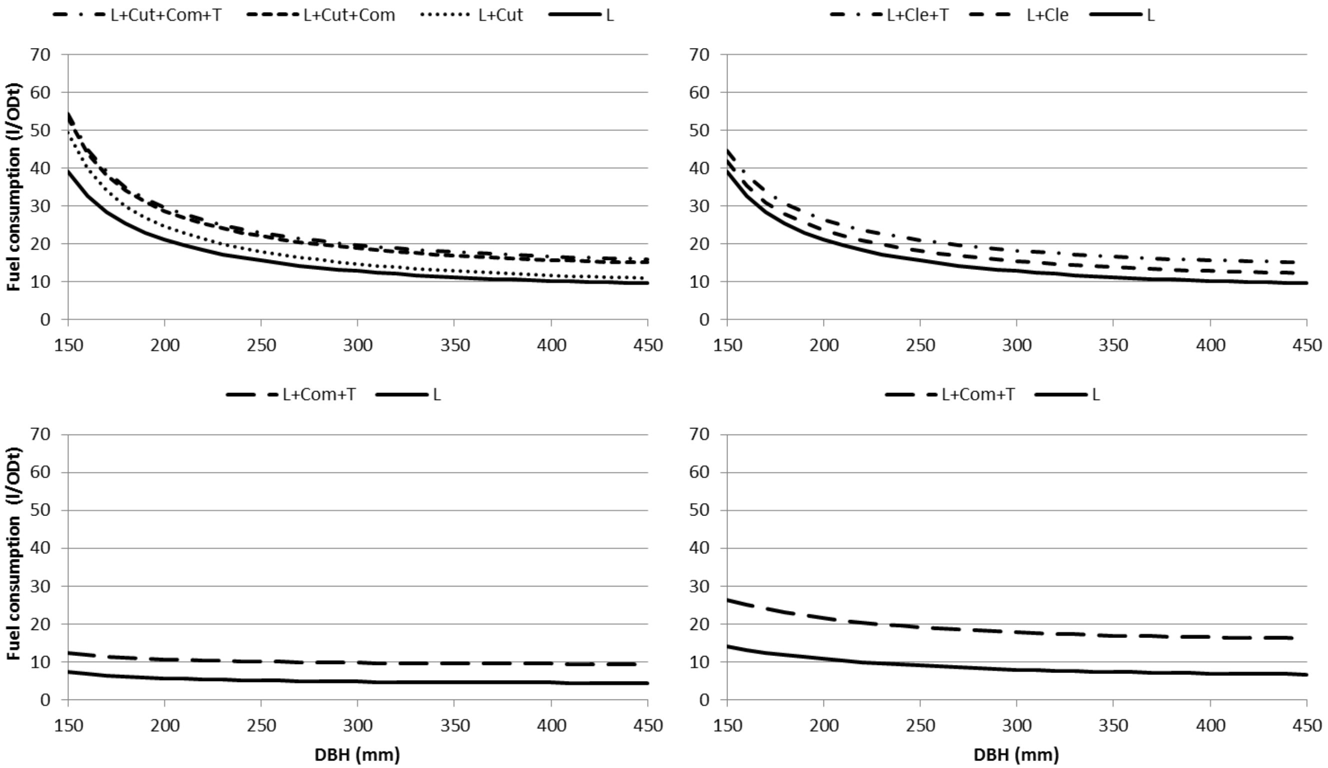

Figure 12. Fuel consumption per ODt of stump wood as function of DBH by machines in the following systems: the integrated system examined in Study III when extensions were cut off at the landing (top left) and when they were transported to and cut off at industrial sites (top right), the conventional stump harvesting system examined in Study III (bottom left) and a system for stump drill harvesting on mineral soil (botton right). All at 50 km transportation distance. The fuel consumption is estimated for harvesting and forwarding (L), cutting off the stump extension (Cut), cleaning the stump extension (Cle), comminution (Com) and transport (T).

4.4 Fuel consumption of the machines

Fuel consumption of the machines was estimated for the integrated system addressed in Study III when cutting off stump extensions at the landing or industrial sites, the conventional system addressed in Study III, and stump drill harvesting on mineral soil (Table 15). The fuel consumption per ODt stump wood was found to be higher in the integrated system than in the conventional system (Figure 12). Cutting off the stump extensions at the landing in the integrated system required 68-339 % more fuel than the conventional system, and 59-261 % more when transporting them to industrial sites (Figure 12). The integrated system examined in Study III harvests a smaller amount of stump wood per ha than the conventional system (47-68 % reduction (Nilsson & Danielsson, 1976)) so higher fuel consumption was expected. However, in most cases it also consumed more than the stump drill system, which consumed 71-114 % more fuel than conventional stump harvesting.

4.5 Ground disturbance

The results of Studies I and IV indicate that the ground disturbance caused by stump harvesting depends on the soil and harvesting head used, but not on the time since clear-cutting. The conventional heads used for harvesting on the mineral soil (Study I) and peatland (Study IV) were different, so the results cannot be rigorously compared. According to the results from Study I the ground disturbance increases with stump size and should therefore have been larger in Study I than in Study IV, but instead it was 35 % lower. The stands used in Study I were pure Norway spruce stands while those used in Study IV were Scots pine-dominated (Table 9). Norway spruce root systems are approximately twice as wide as pine root systems (Hakkila, 1972). Thus, the area of disturbed ground should be smaller after harvesting Scots pine. This also implies that the recorded disturbance areas should have been larger in Study I than in Study IV if there was no difference between the soil types. In conclusion, the area of disturbed ground is probably larger after stump harvesting using the conventional Nordic technique on peatland than on mineral soil.

In Study IV the stump splitter clearly caused much more disturbance (8-10 times more) than the stump drill. Roots and vegetation provide most of the bearing capacity on peatlands (Uusitalo & Ala-Ilomaki, 2013), thus conventional stump harvests on peatlands would probably severely reduce the bearing capacity, making forwarding difficult. It is therefore unlikely that conventional stump harvesting heads could be used on peatlands. However, stump drills could prove to be an environmentally-friendly option for winter harvesting of stumps on peatlands. This could prolong the stump harvesting season, but could lead to contractors needing two types of harvesting heads, with financial implications that require analysis. Stump harvesting and forwarding in winter conditions would also affect the procurement system as heavy snow falls can cover stumps and heaps, making them impossible for operators to locate, likely requiring the operations to be conducted close in time.

Delaying stump harvests did not reduce the ground disturbance in Study I. A longer delay probably would, but this would not be desirable, as even after a single summer stumps have been colonised by 3.1 insect species, on average (Jonsell & Hansson, 2011). Lengthening the delay would also delay the regeneration work. This strengthens the conclusion that harvesting technology must be developed to reduce the ground disturbance.

In Study I a regression equation describing the disturbed area as a function of harvested stump size was constructed, enabling estimation of the ground disturbance in similar areas if they are harvested with a Ecorex30 head and the coordinates of the stumps are known. Estimates in this thesis for the sites in Study I indicate that roughly 37 % of the area would have been disturbed by conventional stump lifting if all the stumps had been harvested, taking into account overlaps (41 % otherwise), and the area of overlaps would have increased with increases in the number of stumps per ha. In contrast, the stump drill would have disturbed only 7 % of the area, assuming that it would have caused similar ground disturbance on mineral soil as it did on peatland in Study IV. This difference indicates that stump drills could reduce ground disturbance by 80-85 % at site level. It was assumed that the integrated system in Study III also reduces ground disturbance by the same amount as the stump drill.

The Brantholm head would probably disturb ca. 15-20 % of the total area at site level (H. von Hofsten, The Forestry Research Institute of Sweden, pers. comm., 22 Oct. 2014), which would be a step in the right direction if it could be profitable.

The results can be compared to the disturbance after soil preparation. Disc trenching disturbs 40-60 % and mounding 14-21 % of the total area (Roturier *et al.*, 2011; Roturier & Bergsten, 2006). These values indicate that the disturbance caused by conventional stump lifting is intermediate between that caused by mounding and disc trenching, and the stump drill causes less disturbance than mounding. However, the current practise is to scarify soil separately after stump harvest (Kärhä, 2012), which probably results in disturbance being higher after stump harvest and soil preparation than when stumps are not harvested, and only soil preparation is performed.

Study II investigated the possibilities of harvesting stumps by twisting them or cutting them loose by twisting knives. However, if stumps are twisted some roots will break while others will be uprooted intact (and dragged around the stump, causing ground disturbance). Visual observations during the trial suggest that the ground disturbance after twisting is similar to the disturbance after the conventional harvest observed in Study I, and somewhat lower when knifes are twisted around stumps. The twisting techniques would therefore most likely lead to similar levels of ground disturbance to those observed in Study I, making them less attractive.

The total disturbance caused by the harvest also depends on whether the machines have tracks or wheels. Wheeled machines are likely to cause more rutting (Jansson & Johansson, 1998) and increase the bulk density more than tracked machines (Jusoff, 1991). Thus, tracked machines should be preferred when possible in forestry, and a tracked feller-buncher may have been a better choice as a feller-puller than the wheeled feller-buncher used in Study III.

4.5.1 Possible carbon emissions from soil due to ground disturbance

The ground disturbance caused by harvesting stumps can in some cases, on mineral soil, lead to higher carbon emissions from the forest soil than normal roundwood harvest and soil scarification (Grelle *et al.*, 2012; Kataja-aho *et al.*, 2012; Strömgren & Mjöfors, 2012). The relative effects of stump harvesting on peatland soils are uncertain: soil scarification has been found to slightly reduce CO_2 emissions and slightly increase NO_x emissions from them (Pearson *et al.*, 2012), but the effects of the ground disturbance caused by stump harvesting have not been measured. Thus, it was not possible to consider any emissions from the soil due to ground disturbance in Study IV.

However, differences in emissions from the soil caused by differences in the ground disturbance associated with conventional and stump drill harvests on mineral soil can be estimated, using data acquired from previous publications and Studies I and IV. Grelle *et al.* (2012) measured emissions after stump harvesting over 3 years and estimated that they could continue for 10 years while two other studies assumed that emissions are proportional to the disturbed area (Kataja-aho *et al.*, 2012; Strömgren & Mjöfors, 2012). The carbon emissions from soil can therefore be assumed to be proportional to the disturbed area, which should be about 5 times larger following conventional harvesting than following stump drill harvesting per stump on mineral soil. It should be noted that the reduction in ground disturbance when stump centres are harvested rather than whole stumps is smaller per MWh than per ha, as a larger area has to be harvested to generate the same amount of energy. The area of disturbed ground was on average 4.6 m^2 per MWh (45.4 m^2/ODt) when using the stump drill and 8.0 m^2/MWh (79.3 m^2/ODt) when using a conventional head, indicating that use of the drill can reduce the disturbance and soil carbon emissions per MWh by about 43 %. Corresponding values for pine may be substantially different, as a larger part of the root system is close to the centre, and the roots cover a smaller area (Hakkila, 1972).

4.6 Root breakage diameters

According to Study I one can assume that most roots down to 5-30 mm diameter are harvested with current technology, resulting in low fuel quality and undesirably high nutrient removal from the site. Delaying the harvest did not significantly change the breakage diameter, it is therefore desirable to increase the root breakage diameter through technological changes. A reduction from harvesting roots down to 5 mm diameter to only harvesting stump centres would reduce the harvested volume by 68 % according to Study I, and substantially reduce nutrient removal. For instance, it would reduce N removal by ca. 77 %, equivalent to removing 84-113 kg/ha less N (Table 16). If only roots with diameters exceeding 100 mm were removed, as could be roughly expected if the Järvinen head was developed and used (Kärhä, 2012), nutrient removal would be reduced by ca. 55 % and the harvested biomass by ca. 37 %. These estimates favour systems for harvesting the central part of the stumps, like the integrated system used in Study III and the stump drill used in Study IV. The estimated N content of stumps and root systems per ha at the site used in Study I (Table 16) is somewhat higher than the estimate by Finér *et al.* (2003) of 90 kg/ha in stump and root systems, and differences between the sites used to obtain the estimates can explain the difference in estimates. Finér *et al.* (2003) also showed that logging residues at a site have ca. two times higher N contents than the stumps. In the current system the logging residues are harvested before the stumps at a site, but the residues could be left on-site if an integrated harvest system was used, which would be beneficial.

However, the ash content of stumps harvested with the stump drill from mineral soil could be higher than that of conventionally harvested stumps, due (probably) to insufficient cleaning and soil being pushed into them (von Hofsten *et al.*, 2012b). However, an earlier study did not find such an increase in ash content (Anerud & Jirjis, 2011). These differences indicate that not only the part of the stump that is harvested, but also the ability to clean the wood and the operator's work practices significantly influence the ash content.

Table 16. *The nitrogen (N) (Hellsten et al., 2013) content and oven dry mass (OD) (Repola, 2009; Petersson & Ståhl, 2006; Marklund, 1988; Hakkila, 1972) of indicated root and stump fractions based on measurements in Study I (Table 9). The total stump mass and its N content per ha were 67-91 ODt and 110-147 kg, respectively*

	Root fraction (mm)						
	5-10	10-50	50-100	100-200	>200	Stump	Total
N content (% OD)	0.350	0.225	0.145	0.115	0.155	0.115	-
Stump mass (%)	12	13	11	19	13	32	100
N mass (%)	27	18	10	13	9	23	100

An increase in the root breakage diameter while harvesting stumps could also lead to a reduction in the area of disturbed ground. Root spans are inversely correlated with their breakage diameter (Hakkila, 1972). Thus, increasing the breakage diameter should reduce ground disturbance, and data provided by Hakkila (1972) can be used to calculate the area likely to be disturbed by harvesting roots down to 5 or 10 cm. However, estimates based on Hakkila's (1972) spans would generally give a much larger area than the regression function obtained in Study I (Figure 13). This indicates that the true area of ground disturbance could be larger than the visually observed area. That would favour heads that have low disturbance potential, such as the stump drill used in Study IV, or the integrated system in Study III, which cut the roots at a set distance from the stump centre. How much the root breakage diameter could be increased by different technology cannot be estimated with current knowledge. To acquire the knowledge needed, heads that do not harvest the whole root system have to be developed (thereby increasing the root breakage diameter) and then tested

Reducing the part of the root system that is harvested would likely have several beneficial effects, but also some negative. If more stump wood is left in the soil the harvest will be less effective for reducing root rot (Gibbs *et al.*, 2002), which would be a drawback. Possible benefits include the following. Firstly, it could reduce nutrient removal as small roots have higher nutrient contents than coarse roots and stump centres (Hellsten *et al.*, 2013; Gordon & Jackson, 2000). The harvested volume could possibly be reduced by 68 % while N removal could be reduced by 78 % if only spruce stump centres are harvested (Table 16). The latter reduction would also improve the fuel quality as the wood would have lower ash contents. Secondly, it would reduce ground disturbance, which would have several benefits, notably reducing soil carbon emissions, which are assumed to be proportional to the disturbance (Kataja-aho *et al.*, 2012; Strömgren & Mjöfors, 2012). For harvests of spruce stumps on mineral soil this should reduce the soil carbon emissions by 43 % per MWh. Lower ground disturbance should also reduce leaching and erosion risks

(Walmsley & Godbold, 2010). Thirdly, leaving more stump wood would mitigate site-level reductions of habitats for fungi, mosses, bryophytes and insects, but more sites would need to be harvested to generate the same amount of energy. However, the wood that remains could have lower habitat quality than stumps that are not harvested as only the side roots would be left. The remaining roots could also be affected by the harvest, as it could change their habitat quality.

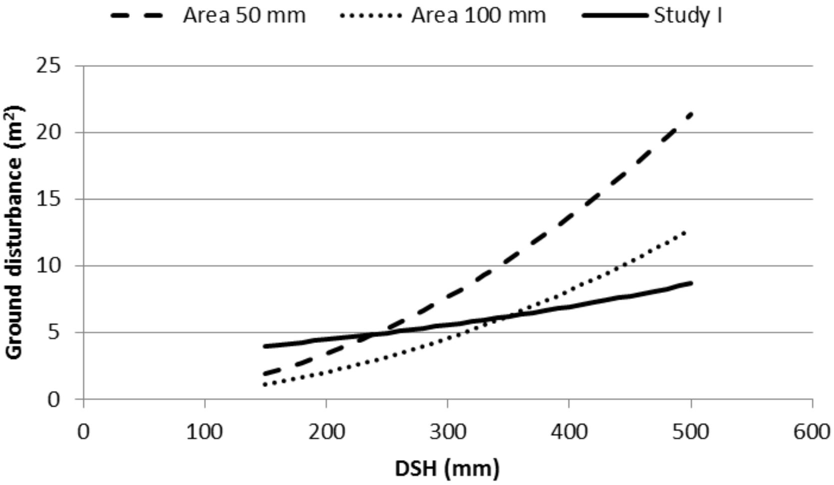

Figure 13. The area around stumps corresponding to the longest span of 50 (Area 50 mm) and 100 mm (Area 100 mm) roots according to Hakkila (1972) as function of DSH compared with the function for disturbed area from Study I.

5 Conclusion

It is already possible to decrease the ground disturbance caused by stump harvesting by using stump drills, at least on peat and fine texture mineral soils, but it is not profitable. In the future, integrated stem and stump centre harvests could potentially be profitable for large trees if the stumps are cut off at the landing. However, currently there are no strong financial incentives to reduce ground disturbance caused by stump harvesting, regulations may be required to limit it.

The studies underlying this thesis indicate that: the ground disturbance depends on the type of harvesting head, as harvesting the whole stump creates more disturbance than harvesting the central part of the stump; the ground disturbance is also larger on peat soil than on mineral soil, but does not depend on time since clear cutting; and the root breakage diameter is surprisingly small (5-30 mm) after whole stump harvests and is not affected by the time since clear-cutting.

Improvements are therefore dependent on development of new technologies and/or methods for stump harvesting. Twisting stumps loose cannot be considered a viable way to remove stumps *per se* or for extracting them while still attached to the butt-log in an integrated harvest system.

Whether or not stump harvests will be integrated with roundwood harvest is difficult to predict, but it is unlikely to occur in the near future and the possible problems of lifting causing damage to the stems have to be solved. However, if implemented the initial system is likely to involve integrated harvest, separation of stumps and butt-logs at the landing, then separate transportation to industrial sites. Estimates presented in this thesis show that it is not economical to transport stump extensions with the butt-logs to industrial sites if the stump wood is used as fuel wood, but if parts can be used as extensions to the saw log results could change. Hence the price of the wood will determine its fate.

The fraction of the stump and root system that should ideally be harvested is difficult to determine as all of the options have pros and cons (Table 17). Harvesting whole stumps is favourable from both economic and diesel consumption perspectives, but not from either ground disturbance, soil carbon or nutrient perspectives. There are also other ecological drawbacks that should be decreased if smaller parts of stumps are harvested. I therefore believe that harvests will be limited to the central part on most sites to reduce the environmental consequences of stump harvesting to an acceptable level. However, as stump removal is the only current way to reduce root rot, I believe that complete stump harvests will continue in stands infected by root rot in order to reduce damage in future forest generations.

Table 17. *Summary of effects of indicated systems for separate and integrated harvests of stumps and roundwood. Landing and Industry indicates where the stump extension are cut of is done*

	Integrated stump harvest		Separate stump harvest	
	Landing	Industry	Conventional	Drill
Cost (€/ODt)	77-189	124-199	77-100	100-159
(% of conventional system)	100-190	160-199	100	130-160
Stump mass (ODt/ha)	22.5-29.1	22.5-29.1	67.3-90.8	22.5-29.1
(% of conventional system)	32	32	100	32
Ground disturbance (m^2/MWh)	4.6	8.0	4.6	4.6
(% of conventional system)	57	57	100	57
Ground disturbance (% of area)	7	7	37	7
(% of conventional system)	19	19	100	19
N removal (kg/ha)	25-33	25-33	109-147	25-33
(% of conventional system)	23	23	100	23
Fuel (L diesel/ODt stump wood)	15.9-54.2	15.1-44.6	9.5-12.4	16.3-26.4
(% of conventional system)	168-439	159-361	100	171-213

6 Future research

Several aspects of stump harvesting considered in this thesis warrant further study. Studies I and IV included some initial observations of the ground disturbance caused by various heads, and it would be interesting to study effects of different harvesting heads in other conditions (e.g. when harvesting at sites with different soil types and soil moisture contents), and risks of rutting due to movements of stump harvesters and forwarders during conventional stump and stump centre harvests. The empirical data acquired could be used to simulate the ground disturbance in different conditions after stump harvesting and determine when, where and how stump harvests should be performed to minimize rutting and ground disturbance. The feasibility of hypothetical automatic cleaning and splitting devices could also be simulated, if detailed time studies are conducted as the present studies do not provide sufficiently detailed information about the work elements.

Ground disturbance seems to release some of the carbon stored in forest soils. However, both the degree of disturbance (and thus emissions per unit disturbed area) caused by using conventional stump harvesting heads and stump drills, or similar devices, probably differs for several reasons. For example, other authors have concluded that more carbon is emitted when humus and mineral soil are mixed (Kataja-aho *et al.*, 2012). Thus, since stump drills cause less mixing of these soil layers than conventional harvesting heads, their effects on emissions could be weaker than estimated in this thesis.

Several aspects related to the simulation of the integrated system in Study III also need to be investigated more thoroughly before further developments, for example, the effectiveness of possible methods for separating stump centres from the roots, and lifting trees without damaging their stems. Possible effects of stump extensions on machines used in later processes in the supply chain also need further attention, notably if the logs are more difficult to pick up and handle than normal logs and if they are bulkier when stacked.

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