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Abstract

The EU renewable energy policies will likely be dependent on all renewable energy sources to meet set climate goals. In forest-rich countries like Sweden, primary residues following harvest operations, such as slash and stumps, could serve as additional biomass sources since secondary residues from the industry are already used. However, harvesting these residues might harm site productivity and stand production due to nutrient loss. This thesis investigates the effects of slash and stump harvest on carbon (C) and nitrogen (N) pools in soil and forest stands across Sweden. Results show no negative impact on site C and N pools or stand production, even with more intense soil disturbance levels. Although deep soil cultivation, not used in practical forestry, had a negative impact on the soil C at one site out of two, it did not affect total C and N pools due to increased tree growth. There was no stump harvest effect in another field experiment designed with a lower soil disturbance more similar to practical forestry, underlining the importance of taking differences between the experimental design and practical operations into account when results are interpreted and used to guide practical forestry. Initial height growth matched stand production trends, seedling survival remained stable, and natural regeneration significantly increased with slash harvest. The findings emphasize the importance of analyzing the total C pool rather than soil and tree C-pools separately when making claims about climate impacts, and advocate for more practical experimental designs in future research. Long-term studies should include real-world factors like site preparation, timing of planting, supplementary planting, and pre-commercial thinning to better reflect forest management practices. This thesis suggests that logging residues like slash and stumps can provide a renewable energy source without depleting future forest C and N pools, and stand production, aiding climate goal.

Keywords: sustainability, logging-residues, environmental impact, bioenergy, stump-harvest, boreal forest, carbon, nitrogen, soil, forest stand, biomass, site productivity, natural regeneration, seedling survival

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EU:s politik för förnybar energi kommer sannolikt att vara beroende av alla förnybara energikällor för att uppnå de uppsatta klimatmålen. I skogrika länder som Sverige kan prima avverkningsrester, såsom ris och stubbar, utgöra ytterligare en biomassaresurs för generering av bioenergi då sekundära restprodukter från industrin redan används fullt ut. Dock kan skörd av dessa rester påverka skogsmarkens produktionsförmåga och skogsproduktionen på grund av det ökade uttaget av näring. Denna avhandling undersöker effekterna av ris- och stubbskörd på kol (C) och kväve (N) pooler i mark och skogsbestånd över hela Sverige. Resultaten visar ingen negativ påverkan på markens C- och N-pooler eller skogsproduktionen, även vid mer intensiva markstörningsnivåer. Även om djupplöjning med en nyodlingsplog, som inte används i praktisk skogsbruk, hade en negativ påverkan på markens C pool på en av två försökslokaler, påverkade det inte de totala C- och N-poolerna på grund av ökad trädtillväxt. I ett annat fältexperiment med en markstörning liknande den som uppstår vid praktisk skogsbruk påvisades ingen effekt av stubbskörd, vilket understryker vikten av att ta hänsyn till skillnader mellan experimentell design och praktiska verksamhet när resultat tolkas och används för att vägleda praktisk skogsbruk. Initial höjdtillväxt matchade skogsproduktionstrenden, plantöverlevnad förblev stabil, och naturlig föryngring ökade signifikant med risskörd. Resultaten betonar vikten av att analysera den totala C-poolen snarare än mark- och trädpooler separat när man gör påståenden om klimatpåverkan och förespråkar mer praktiska experimentella designer i framtida forskning. Långtidsstudier bör inkludera verkliga faktorer som markberedning, planteringstid, hjälpplantering och röjning för att bättre återspegla skogsskötselpraxis. Denna avhandling visar att avverkningsrester såsom ris och stubbar kan bidra till en förnybar energikälla utan att äventyra framtida skogars C- och N-pooler och skogsproduktion, vilket bidrar till klimatmålet.

Keywords: hållbarhet, avverkningsrester, miljöpåverkan, bioenergi, stubbskörd, boreal skog, kol, kväve, mark, skogsbestånd, biomassa, bonitet, naturlig föryngring, plantöverlevnad

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Abstract

Lai sasniegtu izvirzītos klimata mērķus, ES atjaunojamās enerģijas politika, visticamāk, būs atkarīga no visiem atjaunojamās enerģijas avotiem. Mežiem bagātās valstīs kā, piemēram, Zviedrijā, primārie atlikumi pēc mežizstrādes operācijām – zari un celmi, var kalpot kā papildu biomasas avoti, jo rūpniecībā jau tiek izmantoti sekundārie atlikumi. Tomēr šo atlikumu novākšana var kaitēt augsnes un koku stādījumu ražībai, barības vielu zuduma dēļ. Šis promocijas darbs pēta zaru un celmu izstrādes ietekmi uz oglekļa (C) un slāpekļa (N) krājumiem augsnē un mežu stādījumos visā Zviedrijā. Rezultāti neliecina par negatīvas ietekmes uz C un N krājumiem vai stādījumu ražību, pat pie intensīvākas augsnes sagatavošanas metodes. Lai gan dziļā augsnes sagatavošana, kas netiek izmantota praktiskajā mežsaimniecībā, negatīvi ietekmēja augsnes C vienā no diviem izmēģinājuma laukumiem, tā neietekmēja kopējos augsnes un audzes C un N krājumus, straujākas koku augšanas dēļ. Citā eksperimentā, kurš tika sagatavots ar mazāku augsnes sagatavošanas intenistāti, kas vairāk līdzinās praktiskajā mežsaimniecībā lietotajai, nebija novērojama celmu izstrādes ietekme, uzsverot, cik svarīgi ir ņemt vērā atšķirības starp eksperimentu dizainu un praktiskajām operācijām, kad rezultāti tiek interpretēti un izmantoti praktiskās mežsaimniecības vadlīnijās. Sākotnējais koku augstuma pieaugums atbilda stādījumu ražības tendencēm, stādu izdzīvošana saglabājās stabila, un dabiskā atjaunošanās ievērojami palielinājās ar zaru novākšanu. Rezultāti uzsver, cik svarīgi ir analizēt kopējo C krājumu, nevis atsevišķi augsnes un koku C krājumus, veicot apgalvojumus par klimata ietekmi, un ierosina plānot pētījumus, kur mežsaimniecības darbības un operācijas ir līdzīgas praktiskajā mežsaimniecībā lietotajām. Ilgtermiņa pētījumos būtu jāietver šādi faktori: vietas sagatavošana, stādīšanas laiks, papildu stādīšana un agrotehniskā un jaunaudžu kopšana, lai labāk atspoguļotu meža apsaimniekošanas praksi. Šis darbs norāda, ka mežizstrādes atlikumi, piemēram, zari un celmi, var nodrošināt atjaunojamu

enerģijas avotu, nesamazinot nākotnes mežu C un N krājumus un stādījumu ražību, kas dod ieguldījumu klimata mērķu sasniegšanā.

Keywords: ilgtspējība, mežizstrādes atlikumi, ietekme uz vidi, bioenerģija, celmu izstrāde, boreālie meži, ogleklis, slāpeklis, augsne, mežaudze, biomasa, augsnes ražība, produktivitāte, dabiskā atjaunošanās, bonitāte

Photo: Gustaf Egnell

Dedication

To all the children, both those who are guided by the loving arms of their parents and those who must go through life without them. May you always find the love and support you need to shine brightly in this world. I believe in you, and I know that you can make your life great.

Contents

List of publications

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

I. Egnell, G. *, Jurevics, A., & Peichl, M. (2015). Negative effects of stem and stump harvest and deep soil cultivation on the soil carbon and nitrogen pools are mitigated by enhanced tree growth. Forest Ecology and Management, 338, 57-67. https://doi.org/10.1016/j.foreco.2014.11.006

II. Jurevics, A.*, Peichl, M., Olsson, B. A., Stromgren, M., & Egnell, G. (2016). Slash and stump harvest have no general impact on soil and tree biomass C pools after 32-39 years. Forest Ecology and Management, 371, 33-41. https://doi.org/10.1016/j.foreco.2016.01.008

III. Jurevics, A.*, Peichl, M., & Egnell, G. (2018). Stand Volume Production in the Subsequent Stand during Three Decades Remains Unaffected by Slash and Stump Harvest in Nordic Forests. Forests, 9 (12), 770. http://www.mdpi.com/1999-4907/9/12/770

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The contribution of Arnis Jurevics to the papers included in this thesis was as follows:

I. Developed the research idea, hypothesis, and objectives together with co-authors. Conducted the fieldwork, data sampling, and sample preparation, as well as performed the data compilation and statistical analysis, and data interpretation, with the help of co-authors, and participated in the writing of the manuscript in collaboration with the co-authors.

II. Is the main author. Developed the research idea, hypothesis, and objectives together with co-authors. Performed the data compilation and statistical analysis, and data interpretation, with the help of co-authors, and wrote the manuscript in collaboration with the co-authors.

III. Is the main author. Developed the research idea, hypothesis, and objectives together with co-authors. Performed the data compilation and statistical analysis, and data interpretation, with the help of co-authors, and wrote the manuscript in collaboration with the co-authors.

Abbreviations

BECCS	Bio-energy with carbon capture and storage
C	Carbon
CCS	Carbon capture and storage
CO_2	Carbon dioxide
dbh	Diameter at breast height
GHG	Greenhouse gas
N	Nitrogen
RED	Renewable Energy Directive
SS-DSC	Stem and stump harvest and deep soil cultivation
S-PS	Conventional stem-only harvest and manual patch scarification
UNCOP	United Nations Conference of the Parties
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

1.1 Climate change and bioenergy

1.1.1 Current policies and targets to reduce CO_2 emissions as drivers for increased use of biomass for bioenergy

Climate change and the associated risks are major global challenges facing humanity today. The "Rio Earth Summit", held in Rio de Janeiro, Brazil, in 1992 was followed by the first United Nations Conference of the Parties (UNCOP 1) in Berlin, Germany 1995. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in Kyoto, Japan, in 1997 (UNCOP 3) and it entered into force in 2005. The United Nations Conference of the Parties (UNCOP) 21 was held in Paris in 2015, and a historic agreement was reached that entered into force in 2016 (UNFCCC, 2015). The participating states agreed to reduce greenhouse gas emissions to limit global warming to less than 2°C. Since 56.6 % of the net greenhouse gas (GHG) emissions are a result of using coal, gas, and oil energy sources (IPCC, 2011), several international and local energy policies have been put in place to promote the development of green and renewable energy sources (International Energy Agency, 2016). The most relevant policy document in Europe is the Renewable Energy Directive (RED, Directive 2009/28/EC). Given the need to speed up the EU's clean energy transition, the Renewable Energy Directive EU/2018/2001 was revised in 2023. The amending Directive EU/2023/2413 entered into force on 20 November 2023. The set targets for the share of renewable energy sources have increased gradually and now they are binding for member states. Although concern about the consequences of a changing climate has been an important political driver for this development, security of energy supply has also been important as Europe is highly dependent on imported coal, gas, and oil (Grubb, 1994). Moreover, following Russia's invasion of Ukraine, European countries have reduced their energy import from Russia (International Energy Agency, 2022). However, reducing total GHG emissions will be a challenge as global energy consumption is increasing and is projected to increase also in the future (Energy Information Administration, 2016 and 2023, e.g., Figure 1). Moreover, coal, gas, and oil are fossil fuels standing for 88 % of the anthropogenic GHG emissions (Friedlingstein et al., 2023). Renewable energy sources are solar energy, wind energy, hydropower, bioenergy, geothermal energy, and ocean energy (Ang et al., 2022), which are gradually increasing, as these energy sources are associated with clean energy.

During recent years, political and scientific debate on climate benefits of bioenergy has developed - not the least from long-rotation forestry. On one hand, forest-based biomass is associated with forest harvest that may have negative effects on the climate, and it is argued for reduced forest harvest. On the other hand, biomass is the largest renewable energy source (Figure 2), and it will be difficult to phase out coal, gas, and oil without the contribution of biomass. It will be even harder to reduce the use of both fossil fuels and biomass simultaneously. In a European context, forest-based biomass for energy is rarely the driver for forest harvest and most of the biomass used for energy comes from residue streams in the forest industry and following harvest. Good examples exist with the Nordic countries decisively progressing towards a carbon (C) neutral economy with the potential of preparing the rest of Europe for this step (IEA and Nordic Energy Research, 2016).

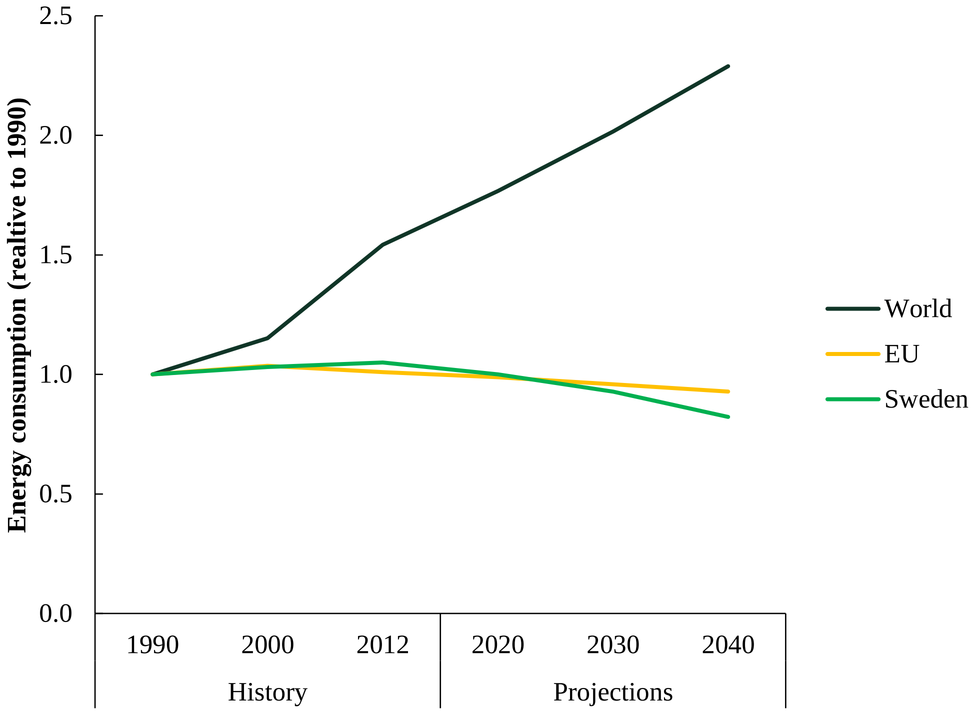

Figure 1. Historical energy consumption and projections relative to the year 1990 in Sweden, Europe and Global. Sources: Eurostat, 2016; Energy Information Administration, 2016 and 2023; Gustavsson et al., 2011.

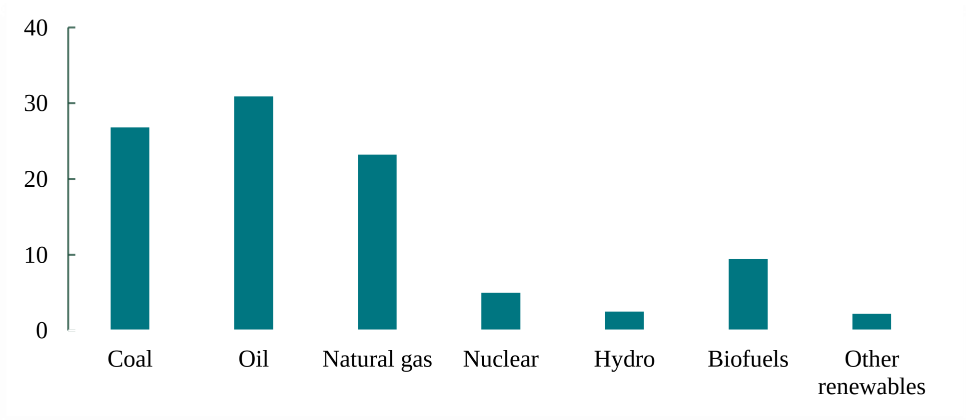

Figure 2. Total global primary energy supply by source in 2019 expressed as a share in percentages; total is 606 EJ. Source: IEA, 2021.

1.1.2 Biomass-related climate change mitigation strategies

Climate change can be mitigated by carbon dioxide (CO_2) removal from the atmosphere combined with reducing GHG emissions from anthropogenic sources (Lenton, 2010). Carbon capture and storage (CCS) has been suggested to be one strategy to reduce CO_2 in the atmosphere (Gibbins and Chalmers 2008; Hepple and Benson, 2005; Pires et al., 2011) and even more powerful in combination with the combustion of biomass (BECCS, Azar et al., 2010). In several of IPCCs pathways toward the 1.5-degree target, BECCS has a large share (IPCC, 2018). However, this strategy requires considerable investments and is associated with high risks in case of a major disturbance that may result in a release of captured and stored CO_2 back into the atmosphere (Bachu, 2008; IPCC, 2005; Rochon, 2008).

Another climate mitigation strategy is to capture C in living biomass, for example, in algae (Packer, 2009; Sayre, 2010) or forests with a large potential C sink (Canadell and Raupach, 2008; Myneni et al., 2001; Pan et al., 2011). However, C capture and storage in living biomass is also challenged due to risks associated with natural disturbances (Seidl et al., 2014). Another limitation is that C storage in biomass also has its limits with signs of saturation in European forests (Nabuurs et al., 2013).

The third strategy to achieve reduced GHG emissions and mitigate climate change is to substitute coal, gas, and oil by increasing the share of renewable energy (Panwar et al., 2011; Sims, 2004). Renewable energy sources are hydro-, solar-, wind-, ocean power, geothermal, and bioenergy. In the European Union (EU), biomass constituted 57.6 % of total renewable energy consumption in 2019, followed by wind power and hydropower, 15.7 % and 14.7 % respectively (Bioenergy Europe, 2021). Thus, biomass is currently the largest renewable energy source in the EU and Sweden, with biomass from forests as the dominant and most important source, mainly due to a well-established infrastructure and market (Mantau et al., 2010; Pelkonen et al., 2014). Forest biomass for energy generation within the EU is expected to increase from 346 million m^3 in 2010 (3.1 EJ) to 752 million m^3 in 2030 (6.6 EJ) (Mantau et al., 2010). There are also political ambitions towards a future bioeconomy that will further increase demand for forest biomass – not least within the EU (European Commission, 2018). This implies increased pressure on biomass resources in the future and has raised concerns about sustainability of these practices (Schulze et al., 2012). To reduce negative and empower positive impacts of increased biomass utilization on C-balance and stand production in the forest, the development towards increased biomass utilization must be knowledge-based.

1.2 Biomass in slash and stumps

Although Sweden has decreased its GHG emission, while at the same time maintaining total energy consumption and increasing its gross domestic product (Swedish Energy Agency, 2016), the Swedish parliament has committed to becoming C-neutral by 2045. In Sweden, biomass supplied 554.4 PJ of total energy supply (1864.8 PJ) in 2023 (Swedish Energy Agency, 2023). In forest-rich countries with a large forest industry like Sweden, biomass comes mainly from forest. As the residues from the forest industries are fully utilized, other forest biomass sources have already been targeted, for example, slash (i.e., tree branches and tops), small-diameter trees, and tree stumps (Routa et al., 2013). Most of the increase in renewables in district heating between 1980 and 2014 was based on slash and to some extent small-diameter trees and stumps (Swedish Energy Agency, 2015).

Indeed, slash and stumps, previously left in the forest following stem wood harvest, provide a large biomass potential. The stump biomass, including coarse roots, constitutes roughly 20% of the total biomass (Figure 3). The proportion of slash biomass decreases with tree size but constitutes another 15 and 20% of the total tree biomass on trees with a breast height diameter of 30 cm for pine and spruce, respectively. Consequently, a harvest of slash and stump biomass increases the total biomass potential by 40 % (cf. Richardson et al., 2002). The current annual harvest level in Sweden is around 90 million m^3, suggesting an additional biomass potential in stumps and slash of 60 million m^3. However, technical, economic, and environmental constraints will reduce that theoretical potential (de Jong et al., 2017). Based on data from the Swedish National Forest Inventory the future potential harvest levels are forecasted regularly by the Swedish Forest Agency. The latest forecast suggests that for a "business as usual scenario", annual harvest levels will increase from currently 90 million m^3 per year to 115 million m^3 by 2100 (Swedish Forest Agency, 2022). Thus, if policymakers will not demand forest owners to sequester more C in growing forests, available slash and stump biomass is likely to increase during the next 100 years.

Slash and small-diameter trees are available in both clear-cuts and thinnings and are already utilized in Sweden and other Nordic countries (Ericsson et al., 2004). While the harvest of slash and small-diameter trees is already implemented, the expansion of stump harvest is still relatively slow due to high procurement costs (Eriksson et al., 2015; Lundmark et al., 2015), with extraction operations requiring additional expensive machinery to get decent quality biomass without mineral soil and stone admixture (Anerud, 2012; Berg, 2014; von Hofsten, 2014). Furthermore, the environmental constraints with stump harvest tend to be stronger (Persson and Egnell, 2018), and, not the least, the Forest Stewardship Council (FSC) National Forest Stewardship Standard of Sweden does not allow stump harvest without approval by FSC Sweden (Forest Stewardship Council, 2020).

In conventional forestry, slash and stumps, with its nutrient and C, were left in the forest and only the commercial stem-wood was harvested. Harvest of slash and stumps increases the harvest intensity and may have effects on future forest production and the C-balance. For example, stump harvest causes soil disturbance that may change nutrient availability (Becker et al., 2016), while slash harvest substantially increases the nutrient export with the harvested slash and alters microclimate and growing conditions for seedlings and understory vegetation (Thiffault et al., 2011). Additionally, biodiversity needs to be considered in all forest management activities including slash and stump harvest (Shevlin et al., 2017; Snall et al., 2017). This has raised questions about the long-term sustainability of the increased harvest intensity.

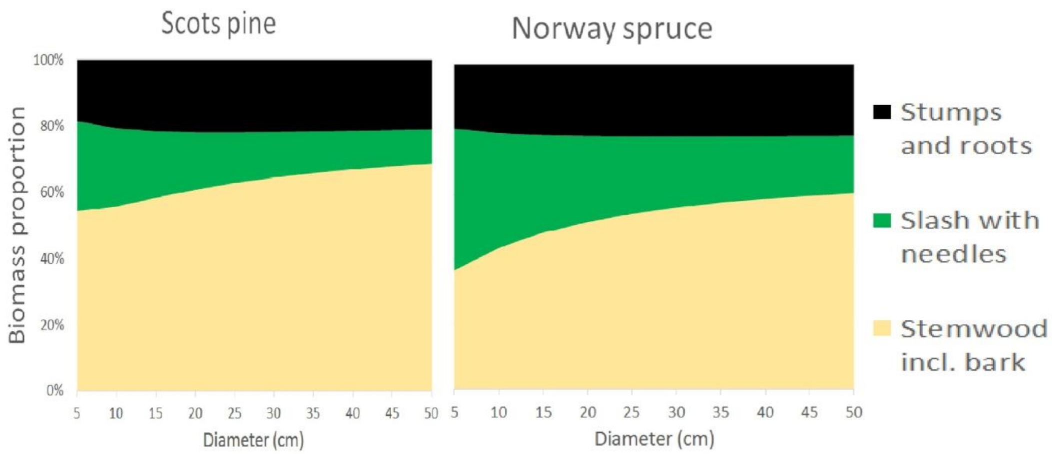

Figure 3. Biomass distribution (%) of Scots pine and Norway spruce trees with increasing diameter (at breast height, 1.3 m) according to biomass equations by Marklund (1988).

The biomass distribution in slash and stump is different between Norway spruce and Scots pine (Figure 3.); slash biomass is relatively two-fold higher in Norway spruce than in Scots pine stands. The difference between species is even more important for foliage, which is also two-fold higher for Norway spruce in younger stands with smaller diameters and threefold higher in older forest stands with higher tree diameter. Additionally, Norway spruce stumps are easier to extract with less force needed in comparison to Scots pine. Possible explanations for differences may be more shallow root architecture for Norway spruce or more wet sites where Norway spruce is predominantly growing. Therefore, the species composition of a forest stand is a factor that needs to be considered, when sites for slash and/or stump harvest are selected, as Norway spruce and Scots pine that are main tree species in Sweden (Figure 4.), may result possibly in different effects.

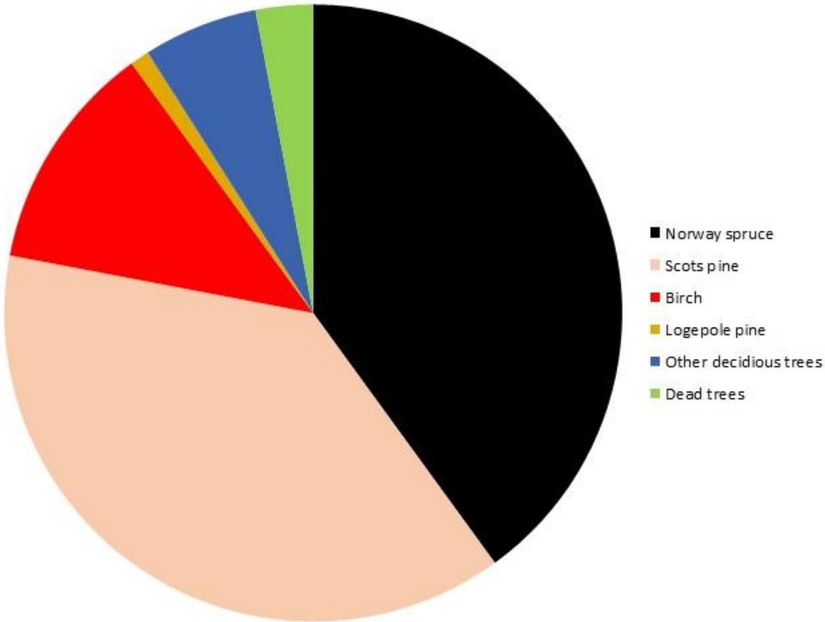

Figure 4. Species distribution in Swedish forests by standing volume. Source: The Swedish National Forest Inventory 2010–2014.

1.3 Effects of slash and stump harvest on sustainability and forest ecosystem services

To ensure long-term sustainability, new and more intensive forest management practices should be based on empirical evidence regarding their potential impacts on ecosystem services. There are many ecosystem services provided by forests, for example, fibers, wood, drinking water, prevention of soil erosion, climate regulation, and air purification, not the least personal and cultural enrichment services (Aznar-Sánchez et al., 2018; Bennett et al., 2009). While during recent years several studies on ecosystem service effects of slash harvest have been published (Brandtberg and Olsson, 2012; Bouget et al., 2012; Palviainen and Finer, 2011; Repo et al., 2012; Alam et al., 2011; Mason et al., 2012; Tamminen and Saarsalmi, 2013; Routa et al., 2011), the number of studies on effects of stump harvest is limited (Walmsley and

Godbold, 2010). Moreover, there are no studies investigating the separate and combined effects of slash and stump harvest on C-balance, N-balance, and stand production in the forest. Thus, there is a need to address these issues related to stump and/or slash harvest for all potential effects and to understand treatment effect differences at the regional and forest stand scale on C-balance and stand production in the forest.

1.3.1 Slash and stump harvest impacts on soil C and N pools

Changes in C pools are important in the context of climate as net CO_2 emissions are reduced when C is sequestered. Slash and stump harvest may impact soil C and N pools by (1) affecting C and N mineralization, (2) affecting the establishment of field- and bottom vegetation and natural regeneration, and (3) export of N and C with harvested slash and stumps. Current knowledge related to these potential impacts suggests that (1) soil disturbance caused by stump harvest may increase soil N mineralization of organic matter at some sites (Becker et al., 2016; Kataja-aho et al., 2012a). Other studies suggest no significant change in CO_2 emissions after stump harvest, at least in the short-term (Kaarakka et al., 2016; Strömgren and Mjöfors, 2012; Strömgren et al., 2017), suggesting no change in C mineralization rates. (2) Slash may function as mulch on the site resulting in reduced competition from vegetation (Bai et al., 2014; Emmett et al., 1991), and slash harvest, thus, results in higher vegetation growth, subsequently resulting in higher vegetation competition to planted trees that may reduce forest growth. However, vegetation may store C, as its growth is enhanced. (3) Direct C loss from the forest occurs due to the export of C stored in stumps. While this C is immediately emitted into the atmosphere as the biomass is combusted, stumps decompose at a slower rate when left in the forest, resulting in some recalcitrant fractions which are added to the soil C pool (Berg et al., 2009). From a soil C point of view, effects from slash harvest are less severe compared to stump harvest, due to the higher decomposition rate when slash is left in the forest, and a major part of N in the slash is expected to be mineralized upon decomposition within the first 10-15 years after clear-cut (Hyvönen et al., 2000). In addition to direct N removal, a consequence of leaving the stumps is that N is immobilized in the stumps for a long time and consequently not available for the following tree generation, but stored in the soil N pool (Palviainen et al., 2010). This effect has also been proposed from modeling (Hyvönen et al., 2012) and from N mass balance studies of a clear-felling (Bergholm et al., 2015). Thus, any negative effect due to the moderate export of N with the harvested stumps may be counteracted by reduced N immobilization in stumps – at least in the short to medium term. This could explain the higher soil N concentrations and lower C:N ratio following slash and stump harvest as compared to mounded and slash harvested plots 1-5 years after harvest in Finland reported by Kataja-aho et al. (2012a). In contrast, Butnor et al. (2012) reported a lower total soil N pool 50 years after stump harvest and soil cultivation of southern pine sites in the south-eastern USA suggesting that stumps are important for long-term N retention. However, in this experiment, in addition to stump harvest, slash was removed, intensive mechanical site preparation was applied, and soil C and N pools were measured in soil samples from 0-10 cm depth. It may be that topsoil, with its C and N pools, due to stump harvest and site preparation, was buried deeper than 10 cm, and therefore was not included in the soil samples collected. Thus, there is a need for knowledge of slash and stump harvest effects on soil C and N pools in deeper soil layers.

1.3.2 Slash and stump harvest impacts on nutrient availability and site productivity

Site productivity is the key driver for forest stand production and depends mainly on N availability as the primary growth-limiting factor in boreal forests (Tamm, 1991). Site productivity may be affected after slash and stump harvest by changes in nutrient availability. Slash harvest with removal of nutrient-rich branches and needles has the potential of decreasing tree growth as a result of reduced amount of available nutrients for plants (Berg, 1986; Johansson, 1995; Näsholm and Ericsson, 1990; Ring et al., 2015; Smaill et al., 2008), while nutrient export with harvested stumps is much lower due to lower nutrient concentration in stump biomass (Hellsten et al., 2013; Ouro et al., 2000; Uri et al., 2015). In many studies, slash harvest has decreased tree growth after thinning (Mälkönen & Sarkkola, 2012; Mannerkoski & Smolander, 2000; Tolvanen et al., 2015; Valinger et al., 2005; Wallertz et al., 2014), however, results after slash harvest following clear cut are not that unequivocal, as long-term studies do not always reveal a significant negative effect of slash harvest (Thiffault et al., 2011). On the other hand, stump harvest has a potential to increase nutrient availability and thus stand production in the forest, if soil organic matter mineralization will increase due to disturbance after stump harvest, as discussed in previous section. However, the effect of mineralization after stump harvest on tree growth might be overestimated and other factors might be equally important, for example, reduced competition from vegetation (Egnell, 2016; Kaye, et al., 2008). Height development of planted seedlings has been used as a measure of site productivity following Monserud (1984). An increased height of planted seedlings has been reported after stump harvest by Piri et al. (2020) and by Aosaar et al. (2020) after six and eight growing seasons, while Zeglen and Courtin (2019) revealed no effect of tree height growth after stump harvest. Stump harvest might increase available nutrients due to reduced vegetation competition, as stump harvest works like mechanical site preparation and leaves patches with bare mineral soil without competing vegetation. Disturbance and effects of stump harvest is similar to mechanical site preparation, which is often included as an additional treatment in stump harvest experiments. Thus, the potential positive effect of stump harvest might be leveled out by the positive effects of mechanical site preparation that is widely used in forest management in Nordic countries (Nilsson et al., 2010; Örlander et al., 1990; Sikström et al., 2020).

1.3.3 Slash and stump harvest impacts on seedling survival

Forest stand production is determined by site productivity and silvicultural success, for example, seedling survival and contribution or competition from natural regeneration. Changes in water availability, light and micro-climatic conditions following slash and stump harvest might affect not only site productivity but also seedling survival which might further affect C-balance and stand production. After stump harvest, bare mineral soil is exposed, which limits competing ground vegetation and thereby enhances tree seedling establishment (Nilsson and Örlander, 1999) and seed germination (Winsa, 1995). Stump harvest might therefore promote planted and naturally regenerated seedling establishment and survival (Karlsson and Tamminen, 2013; Tarvainen et al., 2015) and subsequent stand production in the forest (Kataja-aho et al., 2012b; Örlander et al., 1996). Furthermore, some studies suggest no effect of slash harvest on seedling survival in spruce stands (Egnell and Valinger, 2003; Sikström, 2004.), while others report higher seedling survival after slash harvest in pine stands (Egnell and Leijon, 1999).

This is possibly due to a better microclimate after slash harvest (Proe et al., 2001) and better conditions for site preparation and planting when following slash and stump harvest (Saarinen, 2006). Thus, increased seedling survival might have a positive effect on the stand production and tree biomass C pools, as the number of stems in the forest stand might be increased from the survival of planted seedlings and natural regeneration as well.

1.3.4 Slash and stump harvest impacts on natural regeneration

The establishment of pioneer tree species such as birch, aspen, pine, and alder are favored by disturbances, while secondary tree species such as spruce are negatively affected by this disturbance. A few studies suggest that the abundance of natural regeneration could be changed with slash and stump harvest (Saksa, 2013). The main driver for natural regeneration after stump harvest might be exposed mineral soil providing good conditions for seed germination (Winsa, 1995) and facilitating the establishment of natural regeneration, primarily pioneer species (Hyvönen et al., 2016). Slash harvest might favor natural regeneration as physical obstacles (slash) are removed and microclimate might be improved (McInnis and Roberts, 1994), resulting in higher stem numbers with positive effect on stand production in the forest. As researchers often strive for “clean” experiments, natural regeneration is more likely to be removed in multiple pre-commercial thinnings in experiments than in practical forestry. Furthermore, supplementary planting is also more likely to happen in experiments as compared to in practical forestry, which may mask effects on seeding survival if not properly recorded. Thus, the interpretation of experimental results should involve thorough analysis of experimental design, and it is important to study the effects of slash and stump harvest in the long term, as forest management is a long-term business in the boreal zone, with a rotation period extending over several decades up to more than a century.

1.3.5 Slash and stump harvest impacts on stand production and tree biomass C pool

Since site productivity might be affected after slash and stump harvest, stand production and subsequently tree biomass C pools might also be affected by slash and stump harvest. Negative effects following slash harvest on tree growth have been reported by Egnell and Leijon (1999) and Egnell (2011). These growth reductions seem to be more evident for Norway spruce than for Scots pine (Egnell and Leijon, 1999; Helmisaari et al., 2011). In addition, several reviews have drawn attention that the medium- and long-term effects of slash and stump harvest on stand production need to be addressed (Clarke et al., 2015; Thiffault et al., 2011). In most studies, stump harvest has increased site productivity which indicates that stump harvest may have a potentially positive effect on stand production. Slash harvest, however, might have negative effects on site productivity and, thereby on stand production and the tree biomass C pool, as the removal of nutrients is increased when nutrient-rich slash is harvested and is likely to result in reduced nutrient availability (as described in Section 1.3.2.).

The effects of slash and stump harvest on the total (soil, field, bottom vegetation, and stand) C pool will depend on the combined impact on the soil, vegetation, and tree biomass C pools. This is more critical for the stump harvest as soil disturbance has the potential of reducing the soil C pool, while stump harvest might have a positive effect on the tree biomass C pool due to increased nutrient availability. If only one C pool is considered (soil or tree biomass), the effects of slash and stump harvest might be over- or underestimated. As tree C pool is associated with stand production in the forest, it is crucial to investigate potential drivers behind the change of stand production in the forest following slash and stump harvest. Forest owners are, however, usually more interested in stand production rather than in the soil C pools.

1.4 Knowledge gaps

Effects of slash and stump harvest have been studied, particularly environmental aspects, however, effects on site C and N, and productivity of the subsequent forest stand are equally important. Research needs to address knowledge gaps for informed decisions based on soil C, stand C, site and stand productivity, and on long-term effects (over a rotation).

Biomass and Bioenergy: The utilization of slash and stump biomass for bioenergy production presents both opportunities and challenges. In Sweden, stump biomass is used for energy production, unlike in the USA and Canada where stumps are usually harvested to reduce root rot disease (Bloomberg and Reynolds, 1988; Cleary et al., 2008; Cleary et al., 2013; Norris et al., 1998; Shaw et al., 2012; Sturrock et al., 2006). There is a lack of comprehensive research on the implications of intensive forest harvest for bioenergy production and its potential effects in the context of C sequestration and stand production.

Soil C: It is crucial to understand the impact of slash and stump harvest on soil C dynamics, as current studies have shown conflicting results. Examining the long-term changes in soil C pools and their response to harvest practices can improve our understanding of the overall C balance in forest ecosystems.

Stand C: While the impacts of slash and stump harvest on stand C have been studied, there is room for further investigation. Research focusing on the allocation and changes in C pools within forest soil and forest stand can provide insights into the mechanisms driving changes in stand C and the overall C dynamics in forests.

Site Productivity: Despite some studies into the effect of slash and stump harvest on site productivity, there is a notable gap in comprehensive understanding. Further research is needed to describe the mechanisms by which harvest activities affect soil C, nutrient dynamics, and overall site productivity in forests.

Stand Production: While studies have explored the direct effects of slash and stump harvest on stand production, there is a need for more in-depth analyses. Research focusing on the relationships between harvest intensity, seedling survival, and natural regeneration, can provide valuable insights into optimizing forest management strategies for sustainable stand production.

Long-Term Effects: Forest soils contain large C pools (Lal, 2005), and forest management and harvest are suggested to have the potential of decreasing this pool (James and Harrison, 2016). While existing research has shed light on the immediate consequences of slash and stump harvest on forest C pools and stand production, to date, there exists a significant gap in understanding their long-term effects. We need studies that look at what happens over a long time after the harvest to understand how these practices affect the forest in the long run. It is important to continue to monitor existing long-term experiments.

In summary, while progress has been made in understanding the effects of slash and stump harvest on various aspects of forest ecosystems, significant knowledge gaps persist. Addressing these gaps through long-term research efforts will be crucial for sustainable forest management practices and climate mitigating strategies.

This thesis attempts to study slash and stump harvest effects based on mid-term (up to 39 years) experimental studies, thus, contributing to filling these knowledge gaps.

2. Thesis aim and research objectives

The overarching aim of the thesis was to assess the effects of slash and stump harvest relative to stem-only harvest on the total (soil and stand) C and N pools, stand production, seedling survival, and natural regeneration in the subsequent forest stand (Figure 5).

The main thesis objectives were to:

1. Investigate the effects of stump harvest and subsequent intensive soil disturbance on forest soil and stand carbon and nitrogen pools (Paper I);
2. compare the effect of slash and stump harvest with moderate soil disturbance (a common practice) on the soil and stand production carbon pool in the subsequent forest stand (Paper II);
3. determine slash and stump harvest effects on stand production, seedling survival, and natural regeneration in the subsequent forest stand (Paper III).

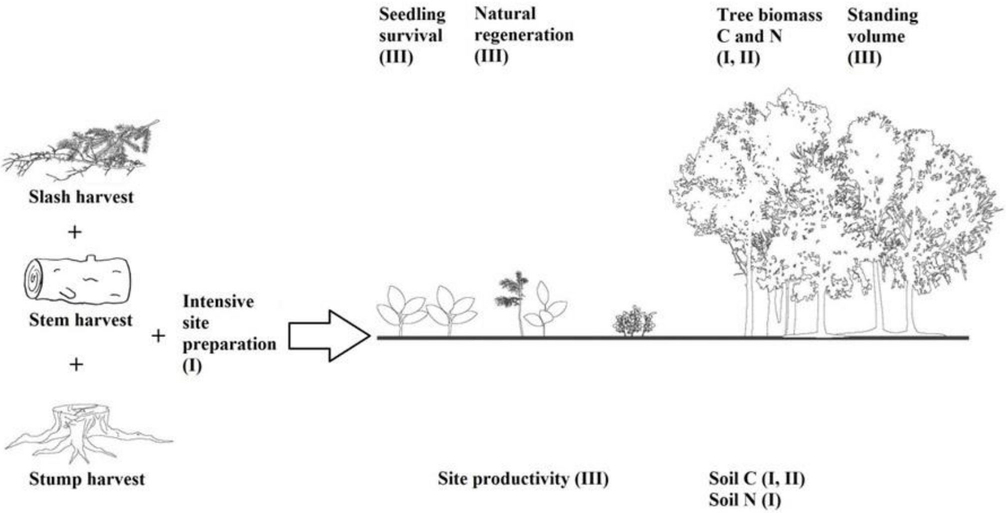

Figure 5. Schematic illustration of the effects of harvest intensity and regeneration practices on key ecosystem services and properties including site productivity, stand production, seedling survival, natural regeneration and C and N pools. Roman numbers correspond to the three papers included in this thesis.

2.1 Hypotheses

The main hypotheses were that:

1. Stump harvest combined with intensive soil disturbance do not reduce total C and N pools because reduction in soil pools is compensated by increased stand C and N pools (Paper I).
2. Conventional slash and stump harvest reduces neither soil C pool, nor stand C pool (Paper II).
3. Stand production increases after stump harvest, but decreases after slash harvest, due to their different impacts on site productivity, survival of planted seedlings, and recruitment of trees through natural regeneration (Paper III).

2.2 Highlights

- Stem and stump harvest and deep soil cultivation reduced soil C and N pools. However, the total (soil and stand) pools were not affected, because soil losses were compensated for by increased tree growth. Therefore, claims on C and N balance effects should be based on both the soil and the stand C and N pools (Paper I).
- Extreme intensive soil preparation is not common in practical forestry in the Nordic countries, where more moderate mechanical site preparation is used. Slash and/or stump harvest with moderate site preparation did not reveal general effects on soil and stand C pools (Paper II) or stand production after 32–39 years (Paper III).
- Silviculture measures to maintain experiments could deviate from practical forestry and may therefore mask treatment effects that likely occur in practical forestry. On the other hand, "clean" field experiments with distinct treatments and a lot of maintenance measures may deviate from practical forest management, possibly leading to exaggerated effects, conclusions, and practical implications.

3. Material and Methods

3.1 Study sites

This thesis is based on two experimental series with study sites representing different climates and site productivity located across Sweden. Paper I is based on experimental series I and Paper II and III are based on experimental series II (Figure 6). The experimental series in Paper I included two sites, Degerön and Norrekvarn, which were established between 1988 and 1990. Degerön is situated in northern Sweden, and Norrekvarn in southern Sweden. The soil at Degerön is dry sand, and the vegetation type is lichen. The soil at Norrekvarn is mesic silt with some sand and clay, with a hardpan at 50-60 cm depth, and the field vegetation type is grass (Hägglund and Lundmark, 1977).

Figure 6. Site locations of the experimental series I (A, B; Paper I) and II (1-8; Paper II-III).

Papers II and III are derived from experimental series II, carried out between 1978 and 1980. The dominant soil types at the study sites were mesic sandy-silty tills with an established haplic podzol (spodosol). It is worth noting that the E-horizons were found to be poorly developed at Tagel, Remningstorp, and Ekenäs.

3.2 Experimental design

In experimental series I (Paper I), the Degerön forest stand was clear-cut in 1987, with stump harvest, soil treatment, and new planting in 1988. At Norrekvarn, clear-cutting occurred in 1983, followed by stump harvest, soil treatment, and planting in 1990. Treatments were replicated on 30 x 30 m plots in a randomized block design with four blocks. Treatments included control plots with stem-only harvest and manual patch scarification (S-PS; 40 x 40 cm), and stem and stump harvest with deep soil cultivation (SS-DSC), displacing the organic layer 50-60 cm into the mineral soil.

In experiment series II (Papers II-III), treatments occurred one year post-clear-cutting, with planting completed within one to four years. Treatments were assigned to 30 x 30 m plots within blocks, surrounded by a 10 m buffer, except at Tagel, where plots were 30 x 40 m. The treatments were: (i) stem-only, (ii) stem and stump, (iii) stem and slash, and (iv) stem, stump, and slash harvest. Paper II initially had two blocks per site, but soil sampling was limited to one block. Paper III used the same series with two replicates, but omitted one at Norduppland, Remningstorp, and Tagel due to extensive damages from frost and browsing.

3.3 Measurements of soil C and N pools

3.3.1 Soil sampling

In the experimental series I (Paper I), soil samples, including field vegetation, were collected along two diagonal transects per plot. Each plot had 21 samples, spaced 4 m apart, with starting points randomly selected. Samples were grouped into three composites per layer. Sampling locations were adjusted if obstructed, and stump areas were avoided at Degerön. A plastic pipe (Ø 0.1 m) was used for field vegetation, litter, and humus sampling (Figure 7), while a soil probe (Ø 1.5875×10^{-2} m) was used for mineral soil sampling in four layers (0-0.15, 0.15-0.3, 0.3-0.5, 0.5-0.7 m; Figure 8). Samples were frozen at -20°C and then dried for 48 h at 65°C. It was not possible to distinguish cultivated from uncultivated strips on the two plots at Norrekvarn. Therefore, sampling on these plots was performed as described above, meaning that some of the sample positions may have been taken on uncultivated strips. In further analysis, the fully cultivated plots and the plots cultivated in strips were considered as the same treatment. Bulk density samples were taken from three random pits per plot using steel cylinders at various depths. Bulk densities were calculated after drying (72 h at 65°C) and adjusted using the equivalent soil mass (ESM) method (Lee et al., 2009).

Figure 7. Field vegetation, litter, and humus sampling with a plastic pipe. Photo: Gustaf Egnell


Figure 8. Mineral soil sampling with a soil probe. Photo: Gustaf Egnell

In the experimental series II (Paper II), soil sampling occurred in the autumn 2012 at Garpenberg and Ekenäs, and in 2013 at other sites. Each plot had 25 sampling spots in a regular grid pattern, with the starting spot randomly chosen near a corner. Cores from the humus layer (Ø 100 mm) and mineral soil (down to 10 cm) were collected with a steel auger. Samples were limited to the upper 10 cm due to stony soil challenges. Sampling spots near tree stems (≤50 cm) were replaced randomly, ensuring accurate organic matter estimation. Samples were pooled by layer, kept cool (4°C), and sifted through steel mesh to remove gravel and roots > 2mm.

3.3.2 Chemical analyses and estimates of soil C and N pools

In the experimental series I (Paper I), dry mineral soil samples (containing fine roots) and humus samples (with field vegetation, fine roots, and litter) underwent grinding in a UNIMEG rolling mill for 48 hours before chemical analysis. After grinding, the material was mixed and homogenized to produce representative sub-samples for laboratory analysis. C and N concentrations in different soil layers were measured using an automated elemental analyzer isotope ratio mass spectrometer (EA-IRMS, Thermo Fisher), following calibration techniques outlined by Ohlsson and Wallmark (1999).

In the experimental series II (Paper II and III), soil samples were processed differently. One portion underwent drying at 105°C for 24 hours to determine fresh/dry mass ratios, while another was dried at 60°C for 24 hours and analyzed for C content using a LECO elemental analyzer (St Joseph, MI, USA). Humus layer dry mass per unit area was derived by dividing plot sample dry mass by plot sample area. The bulk density (BD) of mineral soil for <2 mm fractions was determined. Initially, <2 mm mineral soil volume in the 0–10 cm horizon per plot was estimated by subtracting stone and boulder volume via the Stendahl et al. (2009) method. Subsequently, BD of <2 mm mineral soil in each 5 cm layer was computed using plot average volume and the Nilsson and Lundin (2006) pedotransfer equation, considering C content influence on BD:

$$BD_{(<2\ mm)} = 1546.3 * EXP(-0.313*C^{0.5})+0.00207*d$$

where C denotes C content (%) and d represents soil depth below the mineral soil surface in cm. The gravel (2–20 mm) fraction wasn't accounted for in the Stendahl et al. (2009) method, potentially causing a slight overestimation of mineral soil BD due to unquantified gravel content.

However, this systematic error likely pales in comparison to the uncertainty associated with volume and boulder content estimation using the penetration method. Many study sites exhibited notably high stone and boulder contents, resulting in an estimated root mean square error of 9.2-9.5% for stoniness estimation at specific sites, primarily due to method limitations and errors (Eriksson and Holmgren, 1996).

3.4 Carbon pool in residual stumps

In experimental series II (Paper II), stumps and coarse roots were excluded from the soil sampling, omitting residual C in stumps after harvest on stem-only and slash plots. Without individual tree data, residual C pools in stumps and roots >5 cm were estimated using biomass expansion factors from standing volume (Lehtonen et al., 2004). The remaining stump C was estimated based on a 4.6% annual decomposition rate (Melin et al., 2009) and added to the soil C pool for analyses.

3.5 Stand measurements

In the experimental series I and II, all trees were measured for diameter at breast height (dbh, 1.3 m) and sample tree heights were recorded 22-24 and 32-39 years post-planting. The heights of the remaining trees were estimated using diameter-height equations. Seedling height was used as a site productivity proxy (Monserud, 1984). Thinned trees were included in stand production estimates, using Brandel's volume equations (1990).

Figure 9. Sixteen trees (2 per plot) were felled at Degerön for data collection purpose. Photo: Gustaf Egnell

Biomass of tree components was estimated using Marklund's equations (1988) for Norway spruce and Scots pine. At Degerön Sixteen trees (2 per plot) were felled (Figure 9), and four stumps with coarse roots up to 1 m were excavated in fall 2012 (Figure 10). In addition, 4 stumps including coarse roots within a 1 m radius from the center of the stump were excavated. Fresh weights were taken in the field, and samples were cleaned and sub-sampled for fresh and dry weight measurements. Branches with needles and cones were bulk-weighed and separated after drying to determine dry weights from the fresh-dry weight ratios.

Figure 10. Four stumps with coarse roots within 1 m from the center of the stump were excavated in fall 2012 at Degerön for data collection purpose. Photo: Gustaf Egnell

3.5.1 Biomass equations for lodgepole pine at Degerön in Paper I

In Paper I at Degerön, 16 sample trees were used to create biomass equations for lodgepole pine, as no prior equations existed for Sweden. Regression analysis on the dry weights of tree fractions and dbh led to the development of biomass functions. Logarithmic bias was corrected using Baskerville's method (1972). A subsequent equation by Elfving et al. (2017) incorporated data from this study.

3.6 Statistical analyses

Analysis of variance was used to evaluate general treatment effects on all dependent variables in Papers I-III, covering experimental series I and II. The final model comprised block (nested within species and site) as a random effect, with fixed effects for treatment, species, site (nested within species), and the interaction between species and treatment. Site index and stem number were included as covariates in the models.

In the experimental series I in Paper I, analyses of variance were also performed at the site level, as there were more replicates at each site. The site-level model included fixed effects of treatments and random effects of blocks. To separate significant differences between treatment means, Tukey's pairwise comparisons test was used as a post hoc test ($p \leq 0.05$). In the experimental series II described in Papers I and II, site-level analysis was limited, allowing only for a general treatment analysis of the entire country of Sweden.

4. Results and discussion

4.1 Carbon and nitrogen pools in forest stands after stump harvest and intensive soil disturbance (Paper I)

4.1.1 Effects of stump harvest and deep soil cultivation on soil C and N pools

In experimental series I (Paper I), the average soil C pool was 18% lower, though not statistically significant, after stump harvest with extreme soil disturbance compared to stem-only harvest with moderate soil preparation (Figure 11). At Degerön, which experienced more intense site preparation, there was a significant 25% lower C pool. This site had 100% soil disturbance due to deep soil cultivation to a depth of 50 cm. Studies have indicated that soil C loss occurs following tillage. For instance, in a survey study covering extensive areas of Finland, Simola (2018) observed a decrease in the C pool within the humus layer. It seems that the sampling method in that study focused primarily on litter and the topsoil, potentially overlooking buried C deeper in the soil. It has been suggested that forest harvest and soil disturbance increase decomposition and mineralization resulting in reduced C and N pools (Achat et al., 2015; Grelle, et al., 2012; Johnson, 1992; Kishchuk et al. 2016; Piirainen et al., 2015) and some studies suggest that harvest intensity should be reduced (Buchholz et al., 2014; Zummo and Friedland, 2011). Prescott et al. (2017) studied the decomposition rates of humus on the soil surface and humus buried in the mineral soil. They found that decomposition was higher when humus was buried suggesting that soil disturbance might increase decomposition. This has, however, been contradicted by Kaarakka et al. (2016), who reported no effect of stump harvest on C and N pools. These results imply that soil disturbance following stump harvest and site preparation does not result in short-term increases in CO_2 emissions. Thus, it is hard to detect and complicated to explain a decreased soil C pool. It has also long been believed that higher temperature would increase decomposition rates, however, this has also been disputed by Giardina and Ryan (2000) suggesting that temperature alone will not increase decomposition. Moreover, Nave et al. (2010) did an extensive meta-analysis of forest harvest effect on soil C pools and suggested that changes in C pool might be explained by species composition and soil taxonomic order. Additionally, Yanai et al. (2000) concluded that changes in the organic humus layer may be attributed not solely to harvest treatment, but also to harvest technology or changes over time. Thus, there is evidence that soil C pool is not solely linked to the disturbance followed by decomposition and mineralization; rather it is a more complex relationship and could not be explained with only one single variable. It's important to note that deep soil cultivation is not commonly practiced in practical forestry due to legal restrictions. Instead, less intensive methods like harrowing, mounding, and patch scarification are typically used in the Nordic countries (Nilsson et al., 2010). These methods typically result in soil surface disturbances of approximately 50%, 25%, and 25%, respectively, to depths of 10-20 cm (Bäcke et al., 1986). Furthermore, in the Nordic countries, stump harvest results in less soil disturbance, since stumps are lifted employing an excavator equipped with a special stump extraction-splitting device that was developed to reduce soil disturbance and mineral soil contamination of harvested biomass (Berg et al., 2012; Laitila et al., 2008; Persson 2012, 2017). Although soil disturbance caused by stump harvest could replace mechanical site preparation, to have sufficient planting spots, additional site preparation may be needed (Laitila et al., 2008). Therefore, stump harvest complemented with a site preparation method used in practical forestry may have less negative effects on the soil C and N pools than the deep soil cultivation in this study.

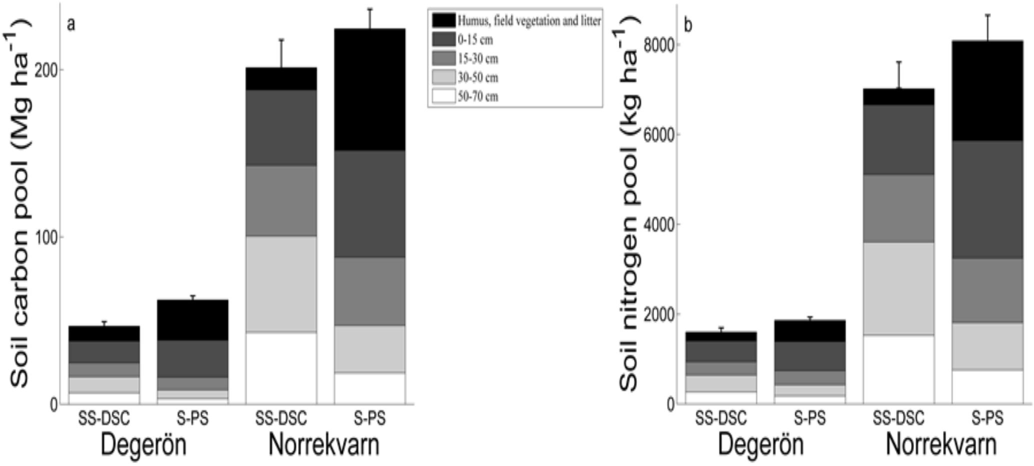

Figure 11. Soil a) carbon pools (Mg ha^{-1}) and b) nitrogen pools (kg ha^{-1}) in different soil layers at Degerön (24 years after treatment) and Norrekvarn (22 years after treatment) after stem and stump harvest and deep soil cultivation (SS-DSC) in comparison with conventional stem-only harvest and manual patch scarification (S-PS). Error bars indicate standard error (n=4) of the total soil pool means.

4.1.2 Effects of stump harvest and deep soil cultivation on tree biomass C and N pools

Paper I demonstrated a 33% higher tree biomass C pool following stump harvest and deep soil cultivation compared to stem-only harvest and manual patch scarification (Figure 12). The tree biomass N pool also increased significantly following stump harvest and deep soil cultivation. Mechanical site preparation has been shown to support seedling establishment and growth (Boateng et al., 2009; Hawkins et al., 2006). Örlander et al. (1998) found that 10 years after site preparation, tree biomass was 4 to 11 times higher in lodgepole pine stands and 4 to 8 times higher in Norway spruce stands. Seedling survival rates also improved, with inverting proving to be the best site preparation method. In a recent study, Mjöfors et al. (2017) compared site preparation methods and found that tree biomass C pool was higher after ploughing in comparison to the control with no treatment. However, they recommended using mounding and harrowing as it causes less soil disturbance and still has positive effect on tree growth. Thus, increased tree growth with accompanying C sequestration could be gained with lower intensity site preparation than deep soil cultivation, possibly with reduced soil disturbance and soil C loss.

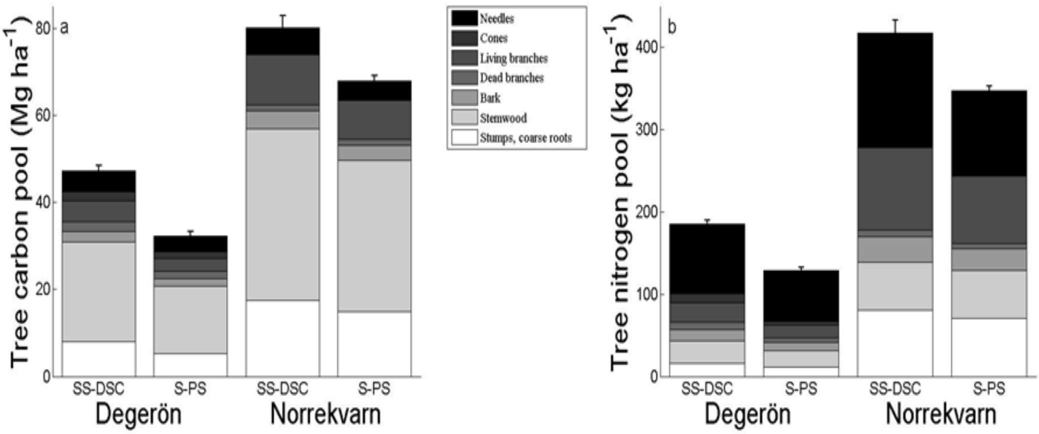

Figure 12. Tree biomass (a) carbon pools (Mg ha^{-1}) and (b) nitrogen pools (kg ha^{-1}) in different tree fractions 24 years at Degerön and 22 years at Norrekvarn after stem and stump harvest and deep soil cultivation (SS-DSC) in comparison to conventional stem-only harvest and manual patch scarification (S-PS). Error bars indicate standard error (n=4) of the tree biomass pool means.

4.1.3 Effects of stump harvest and deep soil cultivation on total C and N pools

Treatment effects on the total C pool (soil and stand) is more relevant in a climate impact context than effects on the soil or stand C pool separately. Claims on climate impacts therefore must be based on the total C pool rather than on the soil or tree C-pool only. The C stored in soil is a considerable part of the terrestrial ecosystems, which can be potentially released into the atmosphere and become a C source. On the other hand, growing trees convert CO_2 from the atmosphere into tree biomass C and have potential to work as C sink from the atmosphere and CO_2 sequestration. The total C pool (soil and tree biomass) showed no significant changes due to stump harvest treatment (Figure 13). Though N pools are not directly related to C sequestration, they might be important if soil N mineralizes and supports tree growth, leading to increased C sequestration. The total N pool was, on average, 11% lower following stump harvest and deep soil cultivation compared to stem-only harvest and manual patch scarification, though this was not statistically significant (Figure 13). After 22-24 years, the study found no effect on the total C pool from stump harvest and intensive soil disturbance, as the increases in tree biomass C and N pools balanced out the negative effects on soil pools.

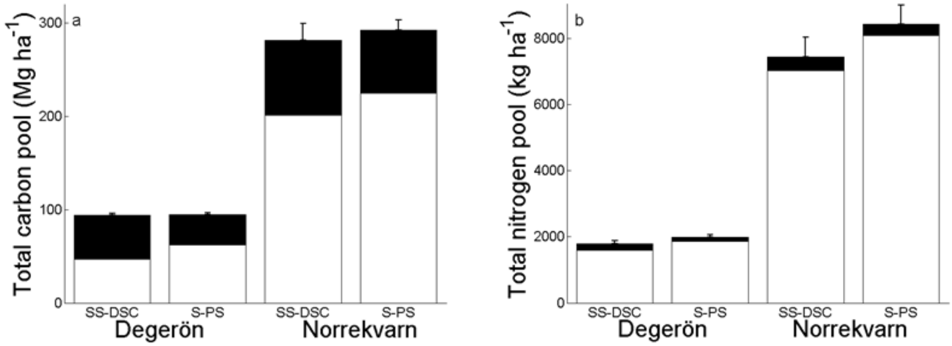

Figure 13. Total (a) carbon pools (Mg ha^{-1}) and (b) nitrogen pools (kg ha^{-1}) 24 years at Degerön and 22 years at Norrekvarn after stem and stump harvest and deep soil cultivation (SS-DSC) in comparison to conventional stem-only harvest and manual patch scarification (S-PS). White bars represent soil pools and black bars - tree biomass pools. Error bars indicate standard error (n=4) of the total pool means.

These results clearly show the link between the forest soil and tree C pools. These C pools are linked to net CO_2 emissions through respiration and photosynthesis and will affect climate mitigation strategies. Thus, forest management should be optimized for a harvest with smallest possible climate impact (Lamers et al., 2013; Repo et al., 2012), aiming for possibly the highest tree growth in consecutive forest stand and the lowest C released from soil after soil disturbance. Both soil and tree C pools can be used as storage with soil C being more secure since tree C could be easily released in case of ecosystem disturbances, for example, biotic and abiotic disturbances or a combination of the two (Schelhaas et al., 2003). Although the tree C pool is not as stable while being in the forest stand, tree C pool could be transported from the forest site and stored in different tree products i.e. timber houses, furniture, and other wooden products (Börjesson and Gustavsson, 2000; Nabuurs, 1996). Additionally, biomass can displace coal, gas and oil burning, while timber and wood could be used to substitute materials that are associated with large C footprint (Moroni, 2013). Thus, the full picture of climate impact includes product C pools as well as positive substitution effects of all wood products on the global C balance in the atmosphere. After trees are harvested and transported from the forest site, regeneration commences, and additional CO_2 can be sequestered in the new forest stand. Furthermore, the soil C pool might be amplified by increased forest production and thereby additional input to the soil C pool (Jandl et al. 2007). Well-informed decisions might reduce the disturbance of different harvest operations like stump harvest. The results of Paper I challenge the current paradigm and present evidence that stump harvest does not decrease soil C pools. Mjöfors et al. (2017) found no effect of soil disturbance on soil C pool 25 years after harrowing, mounding, and ploughing in comparison to control with no treatment. However, as previously discussed in section 4.1.1., deep soil cultivation is not permitted in Swedish forestry. Thus, the results obtained from the ploughing experiment in this study and the deep soil cultivation in Paper I may not fully reflect potential effects in practical forestry. Therefore, experimental series II including stump harvest and complementary mechanical site preparation that were more similar to practical forestry operations was analyzed in Paper II and III.

4.2 Slash and stump harvest effects on soil and stand C pool across Sweden (Paper II)

In Paper II, results are from an experimental series with treatments closer to practical stump and slash harvest operations. The total soil and stand C pool for the different harvest intensities at the eight sites showed an irregular pattern (Figure 14) suggesting a site-specific treatment response although no statistically significant effect was detected for any of the pools. In practical harvest operations, stumps are rarely harvested without slash as slash is readily available biomass in a clear-cut. Trees are delimbed in forest with the harvester in conventional forest management operation, where slash are piled in larger piles, waiting to be picked up, forwarded and transported to the end user, resulting in less costly harvest operations for slash in comparison to stumps (Lundmark et al., 2015). Additionally, slash harvest will facilitate the stump harvest operation, as there will be more tree branches and tops that may cover stumps in the forest and make it hard for stump harvest operator to find all stumps. In Paper II, the statistical analyses for the ANOVA models did not reveal any significant general treatment effects of slash and stump harvest on total C, tree C, or soil C pools, which was in line with hypothesis 2. Similarly, no stump harvest effect was found on the C pool in humus and mineral soil 1 and 10 years after stump harvest at three sites in interior BC (Hope, 2007). Also, Karlsson and Tamminen (2013) reported no stump harvest treatment effect on C and N pools after 30 years in a Norway spruce stand in Finland. Similarly, Persson et al. (2017) discovered a lower C pool in the humus layer after stump harvest with no slash harvest, but no difference in the total soil profile down to 20 cm in the mineral soil. Additionally, the amount of C in the mineral soil tended to be larger following stump harvest (Persson et al., 2017). Thus, it is likely that the stump harvest has buried more of the organic layer in the mineral soil than patch scarification, and conclusions on C-loss following stump harvest must be based on total soil C in the whole impacted soil profiles.

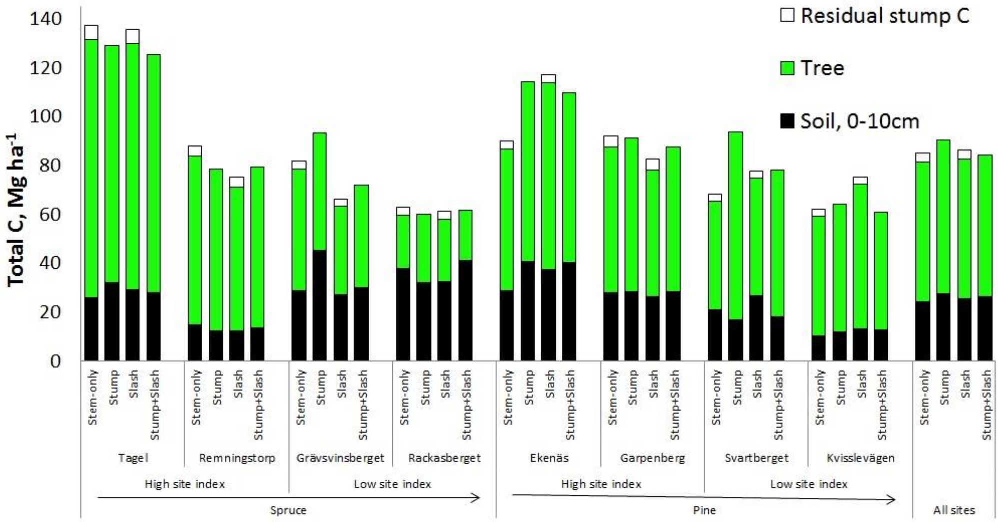

Figure 14. Carbon pools (Mg ha^{-1}) in the total, soil (0 to 10 cm depth), residual stumps, and tree biomass 32 – 39 years after stem-only harvest in combinations with slash and stump harvest. The experimental sites are split into Norway spruce and Scots pine sites and within species sorted in fertility order (site index based on top height).

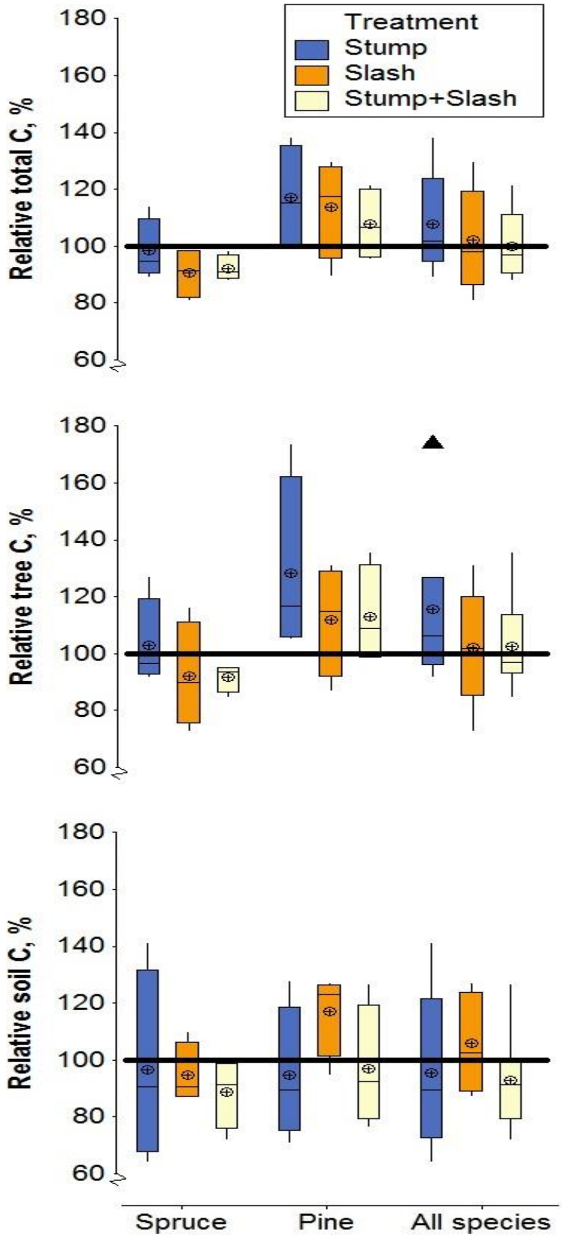

Figure 15. Box plot showing the total carbon (C) including soil C (down to 10 cm depth in the mineral soil and humus) and tree C, 32 – 39 years after stem and stump harvest and/or slash harvest in relation to stem-only harvest (100 %) based on data from eight experimental sites in Sweden (four planted with Norway spruce and four with Scots

pine). Box width extends to the 25th and 75th percentile, circles indicate averages, and horizontal lines - medians. The triangle represents outlier data outside the ±1.5 interquartile whisker range.

Based on the design and scope of the experiment in Paper II, it could be assumed to be representative of the managed forests in Sweden suggesting, that slash and stump harvest would not change the C pools in Swedish forests over a 32-39 year period after harvest. However, there is a variation between sites in the treatment response indicating a positive tree growth response in Scots pine stands after stump harvest and a negative response in Norway spruce stands after slash harvest. This is in line with two reviews for the soil C pool (Clarke et al., 2015) and for the stand C pool (Thiffault et al., 2011), suggesting that slash and stump harvest effects might be site- and species-specific. In Paper II, the impact of tree species on C pools was evaluated using an ANOVA model, but no significant effect was detected. However, it is notable that treatments involving slash harvest in Norway spruce stands yielded the lowest average C pools (Figure 15). Conversely, Scots pine stands exhibited a different trend, with generally higher total C pools observed for slash harvest, stump harvest, and combined slash and stump harvest. This was mainly due to increased tree C pools after stump and/or slash harvest and higher soil C pools following slash harvest. Therefore, targeted forest management practices that avoid slash and stump harvest on sites susceptible to C losses could enhance C sequestration. For instance, Strömgren et al. (2013) discovered a decreased total C pool 25 years after slash and stump harvest when comparing stem-only harvest and stump harvest in two Norway spruce stands and two Scots pine stands. In their study similarly as in paper II, treatment effect differed between the individual sites and only low fertility sites were significantly affected, indicating risk sites with potential to suffer C losses due to decreased tree growth. The sites Svartberget in Paper II and Northern Pine in Strömgren et al. (2013) are similar as they are both in northern Sweden and both have pine stands, where both stump harvest and slash+stump harvest showed a positive effect on the stand C pool. One potential reason for the differing growth responses between pine and spruce after slash harvest could be the lower nutrient content in pine stands' slash, primarily due to less nutrient-rich needle biomass (Alriksson and Eriksson, 1998), resulting in lower nutrient export with slash harvest operation. As boreal forest growth on mineral soils is primarily limited by nitrogen (N) (Tamm, 1991), fresh carbon added in slash and stumps may cause a higher rate of immobilization of available soil N compared to its release from slash and stumps (Berg and Ekbohm, 1983; Vitousek and Matson, 1985). However, the contribution of N-mineralization from soil and slash to plant uptake in the boreal zone is challenging to assess, as plants in harsh climates tend to use also organic N (Näsholm et al., 2009; Inselsbacher and Näsholm, 2012). Moreover, soil disturbance caused by stump harvesting opens bare mineral soil, reducing vegetation competition. Thus, soil disturbance from stump harvest could facilitate early seedling establishment (Vasaitis et al., 2008; Menkis et al., 2010) that could be the case at Svartberget in Paper II and Northern pine in Strömgren et al. (2013). However, reports indicate that soil compaction leading to a poor drainage occurs when slash and stumps are harvested, especially under wet conditions (Strömgren et al., 2012). Thus, soil compaction caused by heavy machinery reduces root penetration ability and can hinder tree growth (Page-Dumroese et al., 1998). Alternatively, these factors could contribute to the observed differences between sites at Svartberget in Paper II and Northern pine in Strömgren et al. (2013) and other sites, as variations in climate, tree species, N dynamics, soil compaction, and early seedling establishment may all together influence the growth responses. The results presented in Paper II suggests that slash and stumps are a biomass resource that can be utilized without depleting the total C pool in the forest.

As discussed in Paper I and II, tree biomass C pool increased following stump harvest mainly due to increased tree growth and stand production. Currently, forest owners however have little interest in C markets and C sequestration as these markets are not well developed and thus not profitable. Although, there is some effort to make the C market more attractive by creating a C banking system as suggested by Bigsby (2009). Nevertheless, forest owners still get most of their revenue by providing feedstock to the traditional forest industry, that depends on tree growth at the stand level, a largely regulated by site productivity and regeneration success. Thus, stand production changes after slash and stump harvest could be explained by changes in site productivity, but also by effects on seedling establishment and natural regeneration. Therefore, the focus of paper III was to identify drivers of change in stand production after slash and stump harvest, which is a critical issue for forest owners.

4.3 Stand production in the forest (Paper III)

4.3.1 Site productivity

As stated before, in boreal forests, tree growth is limited by nutrient availability, primarily N (Tamm, 1991). Consequently, stand production is heavily influenced by nutrient availability, emphasizing the importance of site productivity (Helmisaari et al., 2011; Wall, 2012). In Paper III, height growth served as an indicator of site productivity (Hägglund and Lundmark, 1977). Although the statistical model revealed a significant treatment effect on mean tree height, post hoc comparisons did not detect significant differences between treatment means. Nonetheless, mean tree heights tended to be 11%, 2%, and 8% higher after stump, slash, and stump+slash harvest, respectively, compared to stem-only harvest (Figure 16). The results of the potential positive effect of stump harvest in Paper III might be overshadowed by mechanical site preparation that is common practice before planting in Sweden (Örlander et al., 1990, 1996, 1998) as disturbance caused by site preparation is similar to stump harvest effects, with harrowing disturbing 40-60 % of the soil surface and mounding 14-21 % (Roturier et al., 2011; Roturier and Bergsten, 2006). To verify stump harvest effects on site productivity and analyze data closer, treatment response was compared at Svartberget, where site preparation method was manual patch scarification that caused lower soil disturbance, in comparison to all other sites that had mechanical site preparation by harrowing. The study conducted at Svartberget demonstrated that the mean height exhibited a notably higher value in comparison to the control treatment relative to the treatment effects at the other study sites. This observation further substantiates the proposed positive impact of stump harvest, particularly when the site preparation method involves lower intensity than harrowing. Overall, the results suggest that slash and stump harvest have no negative effect on site productivity with the potential of a positive effect of stump harvest, when it is complemented with lower intensity site preparation methods such as patch scarification or others.

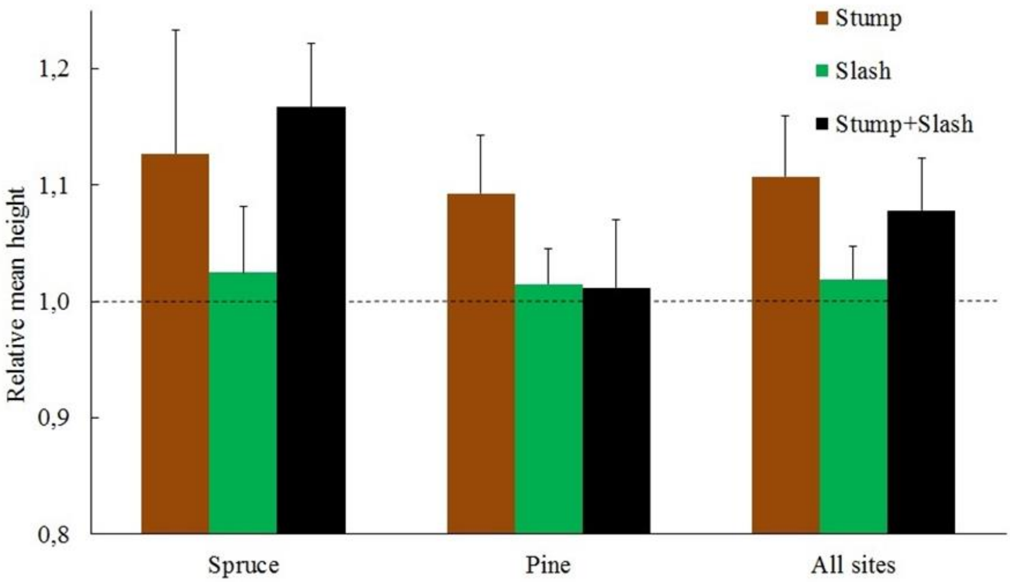

Figure 16. Relative mean height 10-19 years after stump, slash and stump+slash harvest treatments relative to the control with stem-only harvest (horizontal dashed line) that is set to 1. Error bars show standard error.

4.3.2 Seedling survival

In addition to site productivity, seedling survival is possibly equally important for stand production, as slash and stump harvest could also affect seedling survival resulting in changes in the recruiting of new trees (Egnell, 2017). As the number of trees in the final stand is affected by regeneration success, one of the possible explanations for lower stand production after slash harvest could be reduced seedling survival. In paper III, seedling survival after 5 years for the initially planted seedlings was, however, not significantly different among the harvest treatments. This agrees with other studies (Egnell, 2017; Fleming et al., 2014; Morris et al., 2014). Nevertheless, aligning with hypothesis 3, there was an observable trend indicating a higher seedling survival rate after stump, slash, and stump+slash harvest compared to stem-only harvest, with rates 24%, 16%, and 28% higher, respectively (Figure 17). While data from Paper III showed no significant differences between species, the treatment effect on seedling survival seemed more pronounced at spruce sites. This could be attributed to data from the spruce site Remningstorp, where seedling survival was remarkably low across all treatments, ranging from 13% to 56%, with the stem-only harvest treatment recording the lowest rate (13%) due to frost damage. The exclusion of Remningstorp data from the analysis resulted in marginal differences in seedling survival between spruce and pine stands. Even a small increase in seedling survival could offset the negative effect of slash harvest on stand production due to reduced nutrient availability and site productivity (Morris et al., 2014). In practical forest operation, seedling survival could be improved simply because of better quality of the regeneration measures taken when obstructing slash and stumps have been removed (Saarinen, 2006). Several supplementary plantings were done in the experiment presented in paper III to assure high seedling survival for long-term study purposes. Multiple supplementary planting may have hidden relevant treatment effects in Paper III, as it is not common in practical forest management; seedling survival might be more important for stand production in practical forestry in comparison to experimental conditions.

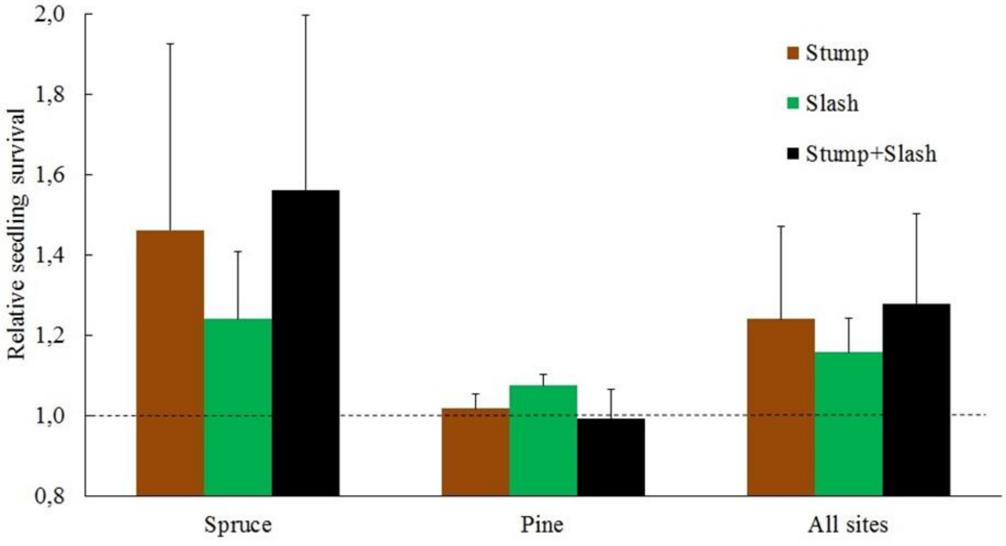

Figure 17. Relative tree seedling survival (i.e. number of seedlings) after stump, slash and stump+slash harvest treatments relative to the control with stem-only harvest (horizontal dashed line) that is set to 1. Error bars show standard error.

4.3.3 Natural regeneration

Much like seedling survival, natural regeneration stands as a potentially vital factor influencing forest stand production. The statistical analysis revealed a treatment effect on the number of naturally regenerated seedlings (p=0.002). Relative to stem-only harvest, the number of naturally regenerated seedlings notably increased following slash and stump+slash harvest treatments by 89% and 96%, respectively (Figure 18). These results are in line with Karlsson et al. (2002) study in which natural regeneration increased after slash harvest, and with Hyvönen et al. (2016) where natural regeneration of birch seedlings was higher after stump harvest. One could argue for partial slash-harvest effects in practical forestry, as slash is harvested (redistributed) also on sites without slash harvest to reinforce strip roads to reduce soil compaction and rutting. Although not significant, the number for naturally regenerated seedlings tended to be higher also after stump harvest (34 %). A possible explanation for no significant stump harvest effect on natural regeneration is not that stump harvest has no effect, but rather that soil was mechanically prepared and disturbed in all treatments including the control treatment. Thus, soil disturbance of mechanical site preparation could have overshadowed the positive effect of stump harvest. In practical forestry, pre-commercial thinning procedures are often less stringent compared to those implemented in long-term field experiments. Consequently, this may result in a greater number of naturally regenerated trees in practical forestry, leading to diverse responses to the effects and outcomes of slash and stump harvesting. Over the extended tree rotation cycle, the consequences of slash and stump harvest may be moderated or obscured by silvicultural strategies, not the least pre-commercial thinnings.

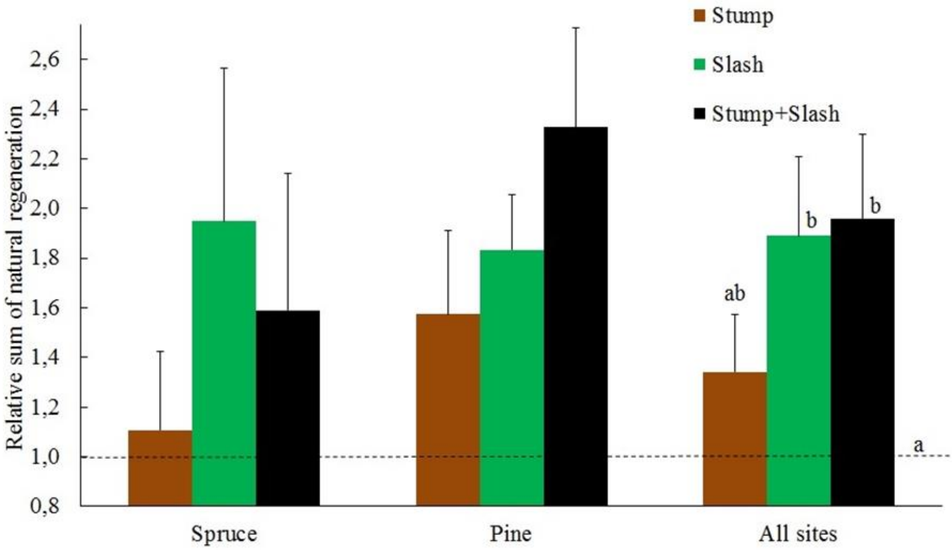

Figure 18. Relative number of naturally regenerated seedlings five years after stump, slash and stump+slash harvest treatments with stem-only harvest (horizontal dashed line) before pre-commercial thinning and without supplementary planting relative to the control with stem-only harvest that is set to 1. Error bars show standard error. Different letters denote statistically significant treatment effects between treatment means ($p<0.05$). There are no letters for spruce and pine, because the statistical model did not suggest species effect.

4.3.4 Stand production

Despite negative impacts on site productivity, seedling survival, and natural regeneration, Paper III revealed a significant treatment effect on stand production. Notably, stand production was higher after stump harvest compared to slash harvest, aligning with hypothesis 3. Compared to stem-only harvest, total stand production tended to be higher after stump (20 %) and stump+slash harvest (15 %), and lower after slash harvest (- 4 %) (Figure 19). However, no other statistical differences were observed. Tree height trends following stump harvest mirrored those of stand production, suggesting increased site productivity after stump harvest and decreased productivity after slash harvest. These results suggest that stumps should be harvested preferably over slash to achieve the highest stand production. However, in practical forestry, slash is harvested before stumps as it is cheaper (Lundmark et al., 2015). In Paper III, although not significant, trends for species differences could be observed. Stand production tended to be reduced after slash harvest in Norway spruce stands, but there was no negative effect in Scots pine stands. No additional tree species-level analysis was done as there was no interaction between treatment and tree species (p=0.583). However, species-level data were in line with studies suggesting negative effect of slash harvest on stand production in spruce stands, no effect of slash harvest in pine stands, and positive effect after stump harvest in pine stands (Egnell, 2017). A possible explanation for species differences in response to slash harvest could be that nutrient removal often is larger on spruce sites due to the larger mass of branches and foliage (Repola, 2009), which results in lower nutrient availability for consecutive stand growth. To verify this, two sites were examined more closely: the spruce stand planted on a formerly pine-dominated stand at the Norduppland and the pine stand that was planted on a formerly spruce-dominated stand at Svartberget. However, former forest stand species did not explain the response to slash harvest at these sites suggesting that the effect of the larger foliage and nutrient removal at spruce sites is not the only explanation for the results. Another possible explanation for differences in treatment response between pine and spruce could be that pioneer species like pine are adapted to the disturbance caused by slash and stump harvest (Linder et al., 1997). Additionally, the study conducted by Palviainen et al. (2010) revealed an observable increase in N content in stumps following harvest, suggesting the accumulation of exogenous nitrogen in these substrates. After 40 years of decomposition, the nitrogen content exhibited respective increments of 1.7 and 2.7-fold compared to the initial quantities within pine and spruce stumps, thereby highlighting a substantial accrual of N throughout decomposition within these organic remnants. As pine trees are typically planted on less fertile sites, the immobilization of nutrients in slash and stumps might impact the initial growth of newly planted seedlings. In terms of sustainable stand production, it is crucial to carefully assess slash harvest at spruce sites, while this appears to be less of an issue in pine stands.

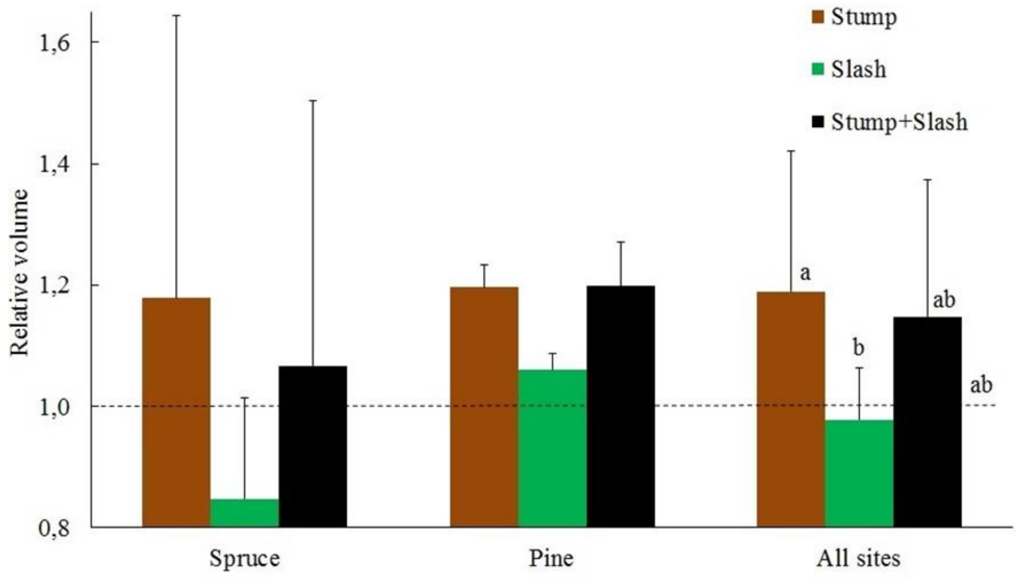

Figure 19. Relative stand production 32-39 years after stump, slash and stump+slash harvest treatments relative to the control with stem-only harvest (horizontal dashed line) that is set to 1 (total stand production + thinning volume). Error bars show standard error for spruce (n=5), pine (n=8) and all sites (n=13). Different letters denote statistically significant treatment effect between treatment means (p<0.05). There are no letters for spruce and pine, because the statistical model did not reveal any species-specific effects.

4.4 Climate impact of slash and stump harvest

In Paper I and Paper II harvest intensity could be increased without negative effect on total (soil C and stand C) pools. These results suggest that stump and slash biomass is a sustainable source that could be utilized for bioenergy. However, the utilization of logging residues, such as slash and stumps, for energy production has raised concerns about its climate impact, particularly regarding soil disturbance and nutrient depletion (Hannam, 2012). There is concern that increasing harvest intensity to include these residues may lead to decreased organic matter, forest C, and nutrients, posing challenges to forest ecosystem sustainability (Zanchi et al., 2012). In the context of climate change mitigation, strategies aim to enhance C storage in soil and tree biomass (Bonan, 2008; Canadell & Raupach, 2008). This involves maintaining soil C pools (Lal et al., 2015; Ontl & Schulte, 2012) and promoting tree biomass growth (Bäckstrand & Lövbrand, 2006; Dewar & Cannell, 1992) to sequester atmospheric carbon dioxide (CO_2) (Gustavsson et al., 2015, 2017; Haus et al., 2014). Soils are also recognized as potential carbon sinks, sequestering CO_2 into the soil C pool (Lal, 2004). Forest stands can also work as a C sink with the help of increased tree growth through forest management, fertilization (Templer et al., 2012), and supporting soil microorganisms with added organic material (Insam & Domsch, 1988; Sparling, 1992). However, there is a dilemma in the trade-offs between storing C in soil versus increasing stand production (Janzen, 2006). Increased stand production following stump harvest may lead to decreased soil C levels, indicating a transfer of C from soil to forest stand (Gustavsson et al., 2006; Sathre & O'Connor, 2010). This transfer suggests a shift in C allocation, potentially affecting the overall C balance. Immediate actions are imperative, as highlighted by the IPCC, which advocates for reducing harvest levels to increase C sequestration in forests (IPCC, 2022). This is also suggested as a short-term and fast option to mitigate climate change in forestry (e.g. Skytt et al., 2021). Yet, it is vital to consider the risk of C leakage, where limiting harvest in one location might lead to increased harvest and, thereby, emissions in another (Zanchi et al., 2012).

In a recent review, Cowie et al. (2021) argue that policy decisions must be based on a comprehensive understanding of the bioenergy system and the linkages to other forest product markets. Emphasizing short-term emission reduction goals alone can hinder the achievement of long-term climate objectives (Cowie et al., 2021). Thus, prioritizing biomass production may be more crucial than focusing solely on carbon storage (Hall and House, 1994). Additionally, fertilization presents an option to enhance tree growth and carbon sequestration, although its environmental impacts and long-term sustainability require careful consideration (Lal et al., 2015; Ontl & Schulte, 2012). Managing the climate impact of slash and stump harvest requires a comprehensive understanding of the trade-offs between soil C pools and stand C. By integrating strategies to conserve soil C, promote biomass growth and stand production, and mitigate potential adverse effects, forest management can contribute to climate change mitigation while supporting sustainable bioeconomy development.

5. Conclusion and management implications

This thesis demonstrates that slash and stump harvest do not negatively impact site carbon (C) and nitrogen (N) levels or stand production. Even deep soil cultivation, used as a site preparation method after stump harvest in one experiment, did not affect the total C and N pools as losses in the soil were compensated for by increased tree growth. Although deep soil cultivation can reduce soil C and N pools, it is an extreme practice not used in practical forestry in Sweden. The findings highlight the importance of assessing total carbon pools in the context of climate change and greenhouse gas dynamics, as isolated evaluations of soil and tree biomass C may not fully capture the forest's adaptive responses to harvesting and silviculture. Additionally, varying site preparation intensities in combination with slash and stump harvests did not significantly affect the total forest soil and stand C pools. Nor did it affect site productivity, subsequent stand production, and seedling survival. In the future, research should aim to also use more practical experimental designs that reflect real-world forest management practices. When conducting experiments, it is common to clear-cut forests and replant them shortly after, but in practical forestry, the clear-cut area often remains resting for a year or more before regeneration measures commence. Therefore, it's important to also incorporate factors such as the timing of site preparation, planting, supplementary planting, and pre-commercial thinning. Thus, experimental designs should also adopt more practical methodologies and be monitored over the long term.

Furthermore, future investigations should explore other crucial aspects of slash and stump harvest. To ensure holistic decision-making, it is essential to also consider studies of slash and stump harvest impacts on i.e. biodiversity, wildlife populations, reindeer herding practices, vegetation dynamics, economic feasibility, recreational values, climate resilience, landscaping, societal acceptance soil erosion, water quality.

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Popular science summary

The European Union (EU) is looking to forests as a key player in meeting its climate goals. In Sweden, this means using every part of the tree, not just the main wood. Residues like slash (branches and leaves) and stumps can also be turned into energy. But there's a concern: could removing these parts harm the soil and reduce future forest growth? This thesis explored whether harvesting slash and stumps affects the carbon (C) and nitrogen (N) pools in soil and trees, and the overall forest growth. This thesis summarizes conducted studies across various sites in Sweden. The good news? The results showed no negative impact on total C and N pools (soil + trees) or forest growth, even when the soil was heavily disturbed. Deep soil cultivation, a method never used in practical forestry in Sweden, didn't harm total pools because losses in the soil was compensated for by boosted tree growth. Interestingly, the growth of planted and naturally generated seedlings were not affected, and sometimes even improved when the stumps were harvested. This means that using slash and stumps for energy purposes does not seem to hurt the forest's ability to bounce back and keep growing. The study highlights the importance of looking at the overall C pool (both in soil and trees) to understand how forest management impacts climate change. Future research should also include practical, real-world approaches, considering factors like the intensity and timing of different silvicultural measures following final cut to get a true picture. In short, the thesis suggests that using slash and stumps for energy can help meet climate goals without jeopardizing future forest growth and carbon storage in the forest. It's a win-win situation for renewable energy and sustainable forest growth and yield.

Populärvetenskaplig sammanfattning

Europeiska unionen (EU) ser skog som en nyckelspelare för att uppnå sina klimatmål. För svensk del innebär detta att varje del av trädet ska användas, inte bara stamveden. Avverkningsrester som grenar, barr och löv samt stubbar kan omvandlas till energi. Men det finns en oro: kan uttag av dessa delar påverka skogsmarkens produktionsförmåga och därmed minska framtida skogstillväxt och kolinlagring? I arbetet bakom denna avhandling undersöktes om skörd av ris och stubbar påverkar kol- (C) och kväveförrådet (N) i mark och träd, samt skogstillväxten. Avhandlingen sammanfattar genomförda studier på olika platser i Sverige. De goda nyheterna? Resultaten visade ingen negativ inverkan på totala C- och N-förrådet (mark + träd) eller skogstillväxten, inte ens när marken var kraftigt störd. Djupplöjning med en nyodlingsplog, en metod som aldrig används i praktiskt skogsbruk i Sverige, påverkade inte poolerna eftersom förluster i markpoolen kompenserades av den ökade trädtillväxten. Intressant nog påverkades inte tillväxten av planterade och naturligt föryngrade plantor, och ibland förbättrades den till och med när stubbarna skördades. Det innebär att användning av ris och stubbar för energiändamål inte verkar påverka skogens förmåga att återhämta sig och fortsätta växa. Studien understryker vikten av att titta på den totala C-poolen (både i mark och träd) för att förstå hur skogsbruk påverkar klimatförändringarna. Framtida studier bör också ta hänsyn till praktiska, verklighetsbaserade metoder och beakta faktorer såsom tidpunkten och intensiteten för olika skogsskötselåtgärder efter föryngringsavverkning för att på så sätt få en rättvisande bild. Sammanfattningsvis visar avhandlingen att användning av avverkningsrester för energi kan bidra till att uppfylla klimatmålen utan att skada framtida tillväxt och kolinlagring. Det är en win-win-situation för förnybar energi, uthållig skogstillväxt och avkastning.

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Negative effects of stem and stump harvest and deep soil cultivation on the soil carbon and nitrogen pools are mitigated by enhanced tree growth

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ABSTRACT

New energy policies in many forest rich countries have promoted the utilization of industrial and logging residues for energy purposes. This practice is, however, questioned from a climate change mitigation point of view, particularly when it comes to the harvest of coarse woody biomass like stem wood and stumps.

Stump harvest removes slowly decomposing biomass with its carbon (C) and nutrients. The harvest operations also cause soil disturbance that may stimulate mineralization of the soil organic pool, and thereby further increase the C and nutrient loss from the site. However, increased mineralization and expected decrease in amount of competing vegetation could make more nutrients available that stimulates growth of the new tree generation and thereby compensates for the soil C loss.

Based on two field experiments, located in southern and northern Sweden, we present C and nitrogen (N) pool data in soil (0–70 cm depth) and tree biomass 22 and 24 years after stem and stump harvest and deep soil cultivation (SS-DSC) in comparison to conventional stem-only harvest and a manual patch scarification (S-PS). The SS-DSC management practice represents a "worst case" in terms of potential C and N loss.

We tested the hypotheses that SS-DSC (i) will reduce C and N pools in the soil; (ii) will increase C and N pools in the planted trees; (iii) will not have any effect on the total C and N pools (soil and tree biomass) as compared to S-PS.

Soil C and N pools were lower following SS-DSC in line with hypothesis (i) but only statistically different for C at the northern site. Tree biomass C and N pools were significantly increased by the SS-DSC treatment in line with hypothesis (ii). As a result, the total C and N pools were not significantly affected by SS-DSC in line with hypothesis (iii).

The main conclusion from these results is that judgments on the effects of silvicultural measures on the forest C and N balances or net greenhouse gas emissions cannot be based on measurements of single C or N pool changes (i.e. in the soil or in the trees only) – it has to be based on changes in the total C or N pool. The trade-off between soil and tree biomass C and N pools is discussed in terms of possible causes, current forestry practices, and the climate change mitigation potential of soil *vs.* tree biomass C.

1. Introduction

Following the two oil crises in the 1970s, the UN conference on environment and development in Rio 1992, the Kyoto protocol (United Nations, 1998), and the Renewable Energy Directive in Europe (Directive 2009/28/EC), policies in many countries have shifted in favour of renewable energy sources. This has stimulated the development of market and supply of biomass for energy – a renewable energy source with assumed climate benefits (Berndes and Hansson, 2007). Currently, biomass constitutes a substantial source of energy in many European countries (Ericsson and Nilsson, 2006; Ericsson et al., 2004; Hansson et al., 2009). For instance, in Nordic countries industrial residues from the forest industry (e.g. bark, sawdust, shavings) are already fully used, and increased demand has been met with the use of logging residues: non-merchantable wood, branches, tops and stumps (Mantau et al., 2010).

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The climate benefits of using biomass from long rotation forestry for energy is, however, questioned (Johnson and Curtis, 2001; Zanchi et al., 2012), particularly when it comes to coarse woody biomass like stumps, that decompose more slowly than tops and branches (Pingoud et al., 2012; Repo et al., 2012; Zanchi et al., 2010). Biomass combustion releases carbon dioxide (CO_2) immediately, whereas decomposition of the same biomass left in the forest would release CO_2 at a slower rate. Additionally, the next generation of trees initially accumulates carbon (C) at a relatively slow rate and reaches the maximum C storage only at the end of the rotation period. This creates a time lag before emitted CO_2 from direct combustion of biomass is balanced by CO_2 emitted due to decomposition if the biomass would have been left on site together with CO_2 captured in regrowth in the subsequent stand. This time lag together with the additional CO_2 emissions required to deliver the same energy service as compared to a fossil fuel, is referred to as the C debt (Holtsmark, 2013, 2012; Manomet Center for Conservation Sciences, 2010). Thus, time and rate differences between CO_2 emissions after combustion and C sequestration in forest biomass make combustion of coarse woody biomass less favourable in the short run in comparison to material substitution alternatives (Helin et al., 2012) or decomposition in the forest (Krankina and Harmon, 1995; Melin et al., 2009). But in the long run, stumps provide a source of renewable energy, which leads to overall reduction of CO_2 emissions by substituting fossil fuels and sequestering C in new tree biomass (Agostini et al., 2013; Melin et al., 2010).

Harvest of tops and branches results in a moderate increase in biomass removal at the expense of a substantial increase in nutrient removal from a site because of their higher nutrient concentrations compared to stem wood (Ouro et al., 2000). This is also the case for nitrogen (N), the primary growth limiting nutrient in the boreal and hemi-boreal forest (LeBauer and Treseder, 2008; Tamm, 1991). Harvest of tops and branches for energy purposes and associated nutrient removal, therefore, has the potential to reduce tree growth and consequently C sequestration in the subsequent stand. This has also been shown following whole-tree harvest in final cut (Egnell, 2011) and in thinning (Helmisaari et al., 2011). In contrast, short-term studies (5–10 years) do not reveal any negative growth effects following whole-tree harvest (Fleming et al., 2006; Tamminen and Saarsalmi, 2013).

Since stumps and roots also contain nutrients, stump harvest may cause additional loss of nutrients. Although nutrient concentrations in stumps and coarse roots are relatively low compared to that of the aboveground biomass, the nutrient loss could be significant if a substantial fraction of the more nutrient rich fine roots is harvested (Hellsten et al., 2013; Major et al., 2012). This may cause additional growth losses and consequently a lower C sequestration in the subsequent tree biomass (Weatherall et al., 2006). Stump harvest also has a direct negative impact on the soil C pool simply by the removal of C contained in the stump-biomass (Hope, 2007) – a C pool that otherwise would be slowly released to the atmosphere as the stumps decompose (Repo et al., 2012; Shorohova et al., 2012), while leaving some recalcitrant C fractions in the soil (Berg et al., 2009).

Stump harvest operations typically cause soil disturbance which can stimulate mineralization of the soil organic pool, and thereby further increase the C loss from the site (Kataja-aho et al., 2012; Örlander et al., 1996a). The increased mineralization might also increase the N release (Kataja-aho et al., 2012). This release may lead to further N losses through leaching during the initial years following the clear-cut, unless it is utilized by the trees or other vegetation (Piirainen et al., 2007). On the other hand, increased N mineralization due to soil disturbance and reduced competition for soil N from field and bottom vegetation may lead to increased N availability for the subsequent tree crop (Kataja-aho et al., 2012). This may favour seedling establishment and growth (Örlander et al., 1996b). In other words, the potential forest growth loss caused by the increased N loss following more intensive harvest practices, may be counteracted by stimulated subsequent tree growth due to increased nutrient availability resulting from reduced competition and enhanced mineralization rates following stump harvest operation and/or site preparation. This implies that soil C pool losses could be partly or fully compensated for by tree biomass C pool gains. These gains have potential to substitute fossil fuels and materials with a larger C footprint than wood (Agostini et al., 2013). This points out the importance to take both the soil and tree biomass C pool into account when evaluating the C balance following silvicultural measures like stump harvest and site preparation.

To date, little is known about the soil C and N response to stump harvest. Walmsley and Godbold (2010) concluded in their review of environmental impacts of stump harvest that more empirical studies in this field are needed. For instance, Karlsson and Tamminen (2013) studied effects of stump harvest on soil C and N, however, they accounted only for the humus and the upper 10 cm of the mineral soil. Thus, there is an urgent need to improve our understanding of stump harvest effects on soil C and N in deeper layers. The objective of this study is to provide such knowledge together with corresponding C and N pool data in the subsequent tree crop, making it possible to analyze tradeoffs between the soil and tree pools.

We present C and N pool data in soil (0–70 cm depth of the mineral soil, including litter and field vegetation) and tree biomass in two field experiments 22 and 24 years after stem and stump harvest and intense deep soil cultivation in comparison with conventional stem-only harvest and a moderate site preparation (i.e. manual patch scarification). Our main hypotheses were that, compared to conventional stem-only harvest:

i. Stump harvest and deep soil cultivation reduce C and N in the soil (including litter and field vegetation).
ii. Stump harvest and deep soil cultivation increases the accumulation of C and N in the subsequently planted trees.
iii. The total (soil and tree biomass) C and N pools are less affected by stump harvest and deep soil cultivation (relative to conventional harvest) than when comparing soil C and N pools only.

2. Materials and methods

2.1. Experimental sites

The two experiments at Degerön and Norrkvarn were established to study the long-term effects of intensive mechanical soil preparation on growth, yield and stand structure (Örlander et al., 2002). The less fertile experimental site, hereafter called Degerön, is situated in northern Sweden, Västerbotten County, 60 km from Umeå (Fig. 1). The more fertile site, Norrekvarn, is situated in southern Sweden, Kronoberg County, 40 km from Växjö. Degerön is established on a dry, sandy, fluvial sediment, whereas Norrekvarn is established on a mesic till soil (silt with some sand and clay), with a moderately developed hardpan at 50–60 cm depth. Other site features are given in Table 1.

2.2. Experimental design and treatments

At both study sites, two treatments were replicated on 30×30 m plots surrounded by 5 m buffer zones in a randomized block design with four replicates (Fig. 1). Blocking was based on site and stand characteristics of the previous stand with the aim to keep them similar within each block. The treatments included

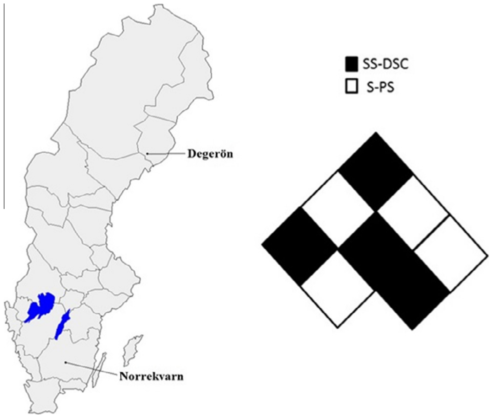

Fig. 1. Location of the experimental sites and the experimental design: stem and stump harvest with deep soil cultivation (SS-DSC) and conventional stem-only harvest with manual patch scarification (S-PS) treatments in a randomized block design with four replicates.

control plots with conventional stem-only harvest and manual patch scarification (S-PS; 40 × 40 cm patches), and stem and stump harvest in combination with deep soil cultivation (SS-DSC) during which the organic layer was displaced 50–60 cm deep into the mineral soil.

The former stand at Degerön was a pure Scots pine (*Pinus sylvestris* L.) stand that was clear-cut in spring 1987. In spring 1988, stumps were removed with an excavator on SS-DSC plots and ploughing was performed by means of a large, single-mouldboard farm plough that flipped down 100% of the top soil 50 cm deep into the mineral soil, leaving a flat layer of pure sand on top. The extracted stumps were then placed back on these plots in a single windrow. Patch scarification on S-PS plots was performed manually in 1988 by removing field vegetation and humus layer and thereby exposing the mineral soil on 40 × 40 cm large planting spots. The plots were manually planted with 2-year old containerized lodgepole pine (*Pinus contorta* L.) seedlings with 2 m spacing a few days after site preparation.

At Norrekvarn clear-cut of a mixed Scots pine and Norway spruce (*Picea abies* (L.) Karst.) stand was completed in spring 1983 with logging residues and stumps left on site. In 1987 disc-trenching was performed and the site was planted. The regeneration was unsuccessful and it was decided to use this site for the field experiment. The few remaining seedlings were removed before the establishment of the experiment in 1990. On SS-DSC plots, stumps were removed and deep soil cultivation was performed with an excavator displacing the topsoil to 50–60 cm depth. On two of the SS-DSC plots, the entire soil surface was cultivated while on the remaining two plots half of the soil surface was cultivated in 1 m wide strips, separated by 1 m wide uncultivated strips. After patch scarification on the S-PS plots manual planting of bare-rooted Norway spruce and Scots pine seedlings was performed in spring 1990. The spruce seedlings were planted at 2 × 2 m spacing and the pine seedlings were planted close (25–30 cm) to every second spruce. Replacement planting was performed in 1991 to replace seedlings killed by frost. To control field vegetation, herbicide (1 l glyphosate ha^{-1}) was applied on S-PS plots once in 1992 (no herbicide was applied on SS-DSC plots). A more complete description of the treatments and sites can be retrieved from Örlander et al. (2002).

Table 1
Site data before establishment of the experiment, description of harvest intensity, soil treatments, and subsequent stand plantation. SS-DSC – stem and stump harvest and deep soil cultivation; S-PS – conventional stem-only harvest and manual patch scarification.

	Degerön	Norrekvarn
Latitude (N)	64°11'	57°11'
Longitude (E)	19°40'	14°47'
Altitude (m a.s.l.)	150	180
Growing season temperature sum[a]	1150	1570
Annual precipitation (mm)[b]	400	600
Annual global radiation (MJ m^{-2})[b]	2270	2750
Inorganic N deposition (kg ha^{-1} $year^{-1}$) [b]	<2	8–10
Soil type[c]	Podzol	Podzol
Soil texture[c]	Sand	Silt
Soil moisture[c]	Dry	Mesic
Field vegetation type	Lichen	Grass
Mineral soil bulk density (g cm^{-3})[d]	1.7	1.2
Soil pH[d]	6.2 (in mineral soil) 5.6 (in humus)	4.4 (in mineral soil) 3.9 (in humus)
N concentration[d] (%)	0.02 (in mineral soil) 0.31 (in humus)	0.08 (in mineral soil) 0.36 (in humus)
Total soil N in 0–0.5 m depth (kg ha^{-1})[d]	1796	4012
Former stand	Scots pine	Scots pine/Norway spruce
Final cut of former stand	1987	1983
Stump and soil treatment	1988	1990
Soil treatments	SS-DSC (0.5 m depth) S-PS (0.4 × 0.4 m area)	SS-DSC (0.6 m depth) S-PS (0.4 × 0.4 m area)
Stump treatment	Returned (in a windrow)	Removed
Plot size	30 × 30 m	30 × 30 m
Planting date	May 1988	May 1990
Replacement planting		May 1991
Spacing	2 × 2 m	2 × 2 m (spruce) with an additional pine planted 0.3 m from every second spruce
Tree species planted	Lodgepole pine	Norway spruce and Scots pine

[a] The sum of daily mean temperature above +5 °C during the growing season (Löfvenius, 2012).
[b] Karlsson et al. (2012).
[c] Hägglund and Lundmark (1977).
[d] Örlander et al. (2002).

2.3. Estimates of C and N in soil, field vegetation and litter

Mineral and organic soil samples including field vegetation were gathered along two diagonal transects between the plot corners. Along these transects, 21 soil samples were collected per plot, 4 m apart from each other, with the first position on each transect randomly selected. Samples from each layer were randomly assigned to one out of three composite samples, thus making up three composite samples per layer and plot. Planned sample position was moved by 0.5 m, when soil sampling was impeded by e.g. a stump. Sampling in or close to the extracted and piled stumps at Degerön was avoided. Field vegetation, litter and humus layer were sampled with a saw-toothed plastic pipe (∅ 0.1 m). Humus was not separated from field vegetation and litter. Mineral soil sampling was done consecutively in the same hole with a soil probe (∅ 1.5875×10^{-2} m) and separated into four soil layers (0–15, 15–30, 30–50, 50–70 cm). Composite samples were put in plastic bags and stored in a freezer (−20 °C) before drying (48 h at 65 °C). It was not possible to distinguish cultivated from uncultivated strips on the two plots at Norrekvarn. Therefore, sampling on these plots was performed as described above, meaning that some of the sample positions may have been taken on uncultivated strips. In the further analysis, the fully cultivated plots and the plots cultivated in strips were taken as one treatment. Mineral soil samples for bulk density estimates were taken from 3 randomly chosen pits per plot. In each pit, composite samples, consisting of four steel cylinder samples (∅ 0.072 m, 0.05 m high), were collected from the pit wall at four opposite directions at 7.5, 22.5, 40, and 60 cm depth. Sample cylinders were carefully inserted to avoid compaction. The samples were weighed immediately after drying (72 h at 65 °C) and soil bulk densities per layer were calculated from the dry weight over sample cylinder volume. The soil bulk density was lower following SS-DSC, particularly at deeper mineral soil layers (Fig. 2).

Differences in soil bulk density between treatments were adjusted for with the equivalent soil mass (ESM) correction method (Lee et al., 2009). Depth specific pre-treatment data were not available, thus, the application of ESM method is restricted (Lee et al., 2009). Soil C and N pools on SS-DSC plots increased by ~5% after ESM corrections to the fixed depth method.

2.4. Estimates of tree biomass, C, and N content

All trees on the 30 × 30 m plots were cross-calipered for the diameter at breast height (*dbh*, 1.3 m) in August (Degerön) and in November (Norrekvarn) 2012. Tree biomass was estimated for stem wood, living branches, dead branches, bark, stumps, cones and needles. For Norrekvarn, allometric functions for Norway spruce and Scots pine developed by Marklund (1988) were used. Since allometric functions for lodgepole pine in Sweden were not available, sample trees from Degerön were used to develop biomass functions for the different tree fractions. A stratified sample (based on diameter) of sixteen undamaged trees (2 per plot; 8 per treatment) were felled, delimbed, and divided into living branches, dead branches, and stems in fall 2012. In addition 4 stumps (2 per treatment) including coarse roots up to a 1 m radius from the center of the stump were excavated. Total fresh weight of all sample tree fractions was taken in the field, with the stump and coarse root fractions carefully cleaned from sand before weighing. A representative sub-sample of each fraction from all sample trees was collected for fresh and dry weight measurements. Fresh discs were debarked and the two fractions were weighed separately on a laboratory scale before and immediately after drying (48 h at 65 °C). Fresh living branches with needles and cones were weighed as a bulk sample assuming the same water content. After drying needles, cones and branches were separated and weighed and the fresh weight of the bulk sample was divided proportionally to the dry weight. These sub-samples from Degerön were also used for C and N analyses.

At Norrekvarn, where biomass in different tree fractions was estimated with available biomass functions, one Norway spruce and one Scots pine close to the average diameter per tree species and plot were sampled in spring 2013 for estimates of C and N concentrations in different tree fractions. Some trees at Norrekvarn had been pre-commercially thinned in summer 2010 and fall 2012 and left on the plots. They were also included in the biomass estimates. For trees pre-commercially thinned in 2010, needles were considered shaded and excluded from the biomass estimates (included in the soil sampling).

The sub-sample collection from sample trees followed the same procedure at both sites with measurement of green crown and tree length. The green crown length was divided in 4 equal parts (strata). One representative living branch sample was collected from each stratum (in total four samples of living branches per tree). One representative dead branch was collected from each tree. In total 6 discs (thickness 0.05 m) were collected from each stem at 0 m, 1.3 m (i.e. at *dbh*) and 30%, 55%, 70% and 85% of the tree heights. Finally a representative sub-sample of about one fifth of stump and root biomass was collected (only at Degerön). Sub-samples were put in plastic bags and stored in a freezer (−20 °C) before further measurements.

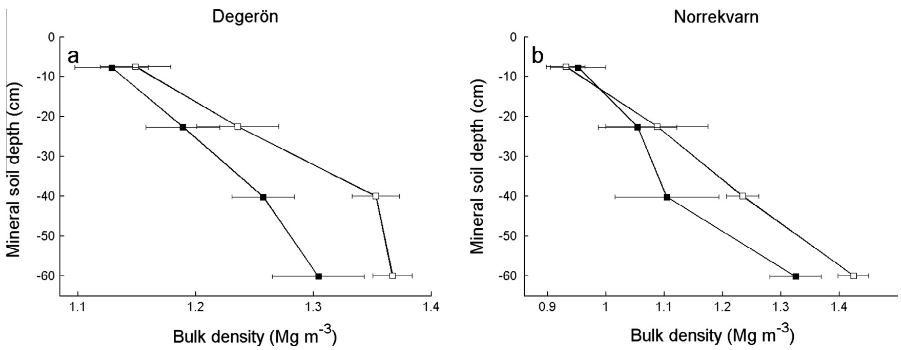

Fig. 2. Mineral soil bulk density (Mg m^{-3}) (a) 24 years at Degerön and (b) 22 years at Norrekvarn after stem and stump harvest and deep soil cultivation (SS-DSC, filled square) compared with conventional stem-only harvest and manual patch scarification (S-PS, open square). Error bars indicate standard error ($n = 12$) of the mineral soil bulk density means.

Table 2
Allometric functions used to estimate biomass in different tree fractions of the lodgepole pine at Degerön; $b = exp(c_1 + c_2 * (ln\ dbh) + SEE^2/2)$, where b is amount of dry biomass in the fraction (kg), dbh is diameter at breast height (cm), c_1 and c_2 are coefficients, SE_1 and SE_2 are standard errors of the coefficients c_1 and c_2 and SEE the standard error of the estimate.

Tree component	Coefficient c_1	SE_1	*P*	Coefficient c_2	SE_2	*P*	Adj.R^2	SEE	N
Dead branches	−4.21	1.34	0.007	1.98	0.57	0.004	0.43	0.24	16
Needles	−3.53	0.86	0.001	2.03	0.36	<.0001	0.67	0.1	16
Living branches	−5.93	0.82	<.0001	3.03	0.35	<.0001	0.84	0.09	16
Cones	−6.2	4.67	0.21	2.29	1.94	0.26	0.03	1.58	15
Stem wood under bark	−3.1	0.37	<.0001	2.52	0.16	<.0001	0.95	0.02	16
Bark	−5.01	0.33	<.0001	2.35	0.14	<.0001	0.95	0.01	16
Stumps + coarse roots	−4.78	1.51	0.09	2.78	0.6	0.04	0.87	0.05	4

2.4.1. Allometric functions for lodgepole pine at Degerön

Dry weights of different fractions of the 16 sample trees from Degerön were used to develop biomass functions based on *dbh* of the trees by means of regression analysis. Using the logarithmic value of *dbh* and biomass in the fraction linearized the relation between a biomass fraction and *dbh*. To correct for logarithmic bias, a correction factor $SEE^2/2$ was added to the functions according to Baskerville (1972). This function (Eq. (1)) was used to estimate the biomass amount in different tree fractions.

$$b = exp(c_1 + c_2 * (ln\ dbh) + SEE^2/2), \quad (1)$$

where b is amount of dry biomass in the fraction (kg); *dbh* is diameter at breast height (cm), c_1 and c_2 are coefficients and SEE – the standard error of the estimate (Table 2).

2.5. Chemical analyses

Dry samples of stem discs, live and dead branches, bark, stumps, cones, needles, mineral soil (including fine roots) and humus (including field vegetation, fine roots and litter) were grinded into a fine powder before the chemical analyses. Needles were grinded in a ball mill (Retsch Ballmill MM400), and soil and humus was grinded in a rolling mill (UNIMEG) for 48 h. All woody fractions were first chipped in a chipper (Retsch Muhle) and then pulverized in a mill (KAMAS, SLAGO-200A, 8-154-053). Samples were mixed and homogenized to get a representative sub-sample of the pulverized material. The sub-samples were taken to the laboratory for chemical analyses. C and N concentrations and isotopic ratios (Table 3) in different tree fractions and soil layers were analyzed with an automated elemental analyzer isotope ratio mass spectrometer (EA-IRMS, Thermo Fisher). Calibration procedures described by Ohlsson and Wallmark (1999) were followed. The isotopic N ratio was expressed using the atmospheric N scale.

Biomass estimates in different tree fractions, dry weight of humus samples (including vegetation and litter), soil bulk densities and C and N concentrations were then used to estimate C and N pools in soil and tree biomass, as well as in different soil layers and tree fractions.

Table 3
Carbon and nitrogen concentrations (%) in different tree compartments (mean ± standard error, $n = 8$ (Degerön) and 4 (Norrekvarn)) and soil layers (mean ± standard error, $n = 12$), including isotope N rations for needles, 24 (Degerön) and 22 years (Norrekvarn) after stem and stump harvest and deep soil cultivation (SS-DSC) compared with conventional stem-only harvest and manual patch scarification (S-PS).

Fraction/layer	Degerön		Norrekvarn			
	SS-DSC	S-PS	SS-DSC		S-PS	
	Lodgepole pine	Lodgepole pine	Scots pine	Norway spruce	Scots pine	Norway spruce
Nitrogen						
Stem wood	0.06 ± 0.005	0.07 ± 0.004	0.08 ± 0.004	0.07 ± 0.01	0.09 ± 0.004	0.09 ± 0.01
Bark	0.30 ± 0.02	0.33 ± 0.02	0.39 ± 0.04	0.49 ± 0.06	0.41 ± 0.03	0.54 ± 0.05
Cones	0.27 ± 0.2	0.18 ± 0.04	–	–	–	–
Stumps + coarse roots	0.1 ± 0.005	0.11 ± 0.03	–	–	–	–
Living branches	0.26 ± 0.04	0.27 ± 0.04	0.44 ± 0.04	0.51 ± 0.02	0.47 ± 0.04	0.56 ± 0.03
Dead branches	0.22 ± 0.08	0.18 ± 0.02	0.27 ± 0.04	0.41 ± 0.07	0.23 ± 0.01	0.45 ± 0.05
Needles	0.92 ± 0.03	0.92 ± 0.08	1.38 ± 0.04	1.00 ± 0.06	1.39 ± 0.07	1.04 ± 0.03
$\delta^{15}N$ in needles	−4.34 ± 0.19	−5.33 ± 0.95	−2.32 ± 0.35	−3.20 ± 0.31	−2.72 ± 0.50	−3.91 ± 0.67
Humus. incl. field vegetation and litter	0.58 ± 0.14	0.68 ± 0.08	0.95 ± 0.07	1.27 ± 0.16		
0–15 cm	0.03 ± 0.006	0.04 ± 0.003	0.11 ± 0.033	0.19 ± 0.05		
15–30 cm	0.02 ± 0.006	0.02 ± 0.003	0.09 ± 0.024	0.09 ± 0.02		
30–50 cm	0.02 ± 0.002	0.01 ± 0.001	0.09 ± 0.037	0.04 ± 0.008		
50–70 cm	0.01 ± 0.002	0.01 ± 0.001	0.05 ± 0.026	0.03 ± 0.006		
Carbon						
Stem wood	51 ± 0.65	51.2 ± 0.43	52.9 ± 0.33	52.5 ± 0.14	53 ± 0.21	52.3 ± 0.08
Bark	54.2 ± 1.1	55.1 ± 1.34	56.2 ± 0.15	53.4 ± 0.33	56.7 ± 0.06	53.8 ± 0.27
Cones	52.5 ± 0.7	52.4 ± 0.36	–	–	–	–
Stumps + coarse roots	51.3 ± 0.01	51.4 ± 0.01	–	–	–	
Living branches	53.1 ± 0.51	53.2 ± 0.31	54.1 ± 0.39	53.5 ± 0.45	54.4 ± 0.4	53.4 ± 0.22
Dead branches	54.4 ± 1.15	54.5 ± 0.6	54.3 ± 0.32	53.3 ± 0.32	54.5 ± 0.28	53.6 ± 0.12
Needles	52.9 ± 0.24	52.8 ± 0.35	53.4 ± 0.16	52.7 ± 0.24	54.1 ± 0.79	52.4 ± 0.12
Humus. incl. field vegetation and litter	26.3 ± 5.6	34.2 ± 4.4	35 ± 3.5	41.5 ± 5		
0–15 cm	0.76 ± 0.212	1.28 ± 0.173	3.32 ± 0.9	5.51 ± 0.8		
15–30 cm	0.45 ± 0.19	0.41 ± 0.08	2.66 ± 0.7	2.45 ± 0.65		
30–50 cm	0.39 ± 0.076	0.19 ± 0.026	2.62 ± 1.075	1.14 ± 0.32		
50–70 cm	0.25 ± 0.078	0.12 ± 0.02	1.3 ± 0.76	0.66 ± 0.154		

Table 4
Results from analysis of variance. Dependent variables in the model are total carbon and nitrogen pools in tree biomass, soil, and the sum of them (Total), 24 (Degerön) and 22 (Norrekvarn) years after two different harvest and soil treatment intensities (SS-DSC = stem and stump harvest and deep soil cultivation; S-PS = conventional stem-only harvest and manual patch scarification). Relations of estimates of the site variances are reported.

Fraction/layer	Treatment			Site	Site ∗ treatment	Relation of the variance estimates
	P-value	DF	F Value	*P*-value	*P*-value	Degerön:Norrekvarn
Carbon						
Tree biomass	0.002	3.64	62.33	<.0001	0.46	1:11
Soil	0.12	3.07	4.64	0.0003	0.70	1:80
Total (tree + soil)	0.58	3.11	0.38	0.0002	0.61	1:57
Nitrogen						
Tree biomass	0.006	3.24	40.61	0.0001	0.54	1:25
Soil	0.17	3.09	3.25	0.0005	0.35	1:67
Total (tree + soil)	0.20	3.09	2.69	0.0004	0.36	1:66

2.6. Statistical analysis

A mixed model analysis of variance (ANOVA) for randomized block designs was used to evaluate treatment effects on C and N pools using the SAS software (SAS Institute Inc., 2011). The full model, including both sites, included fixed effects of treatments, sites, treatment-by-site interactions and blocks. To account for site-specific heterogeneity (cf. Table 4), the model included the assumption that the model was not the same on the two sites. The Satterthwaite method was used for computation of degrees of freedom. With this method the analysis is in line with Welch ANOVA (simple ANOVA with treatment-specific variances). Analyses of variance were also performed at the site level. The site level model included fixed effects of treatments and random effects of blocks. Treatment effects were considered significant, if the *p*-value for the ANOVA test was <0.05.

3. Results

3.1. Soil C and N pools

The soil C pool was lower, but not statistically different, following SS-DSC compared with S-PS (Table 4), with a 25% decrease at Degerön ($p = 0.004$, site-level ANOVA) and a 10% decrease at Norrekvarn ($p = 0.29$, site-level ANOVA), respectively (Fig. 3). The soil N pool was lower, but not statistically different, following SS-DSC

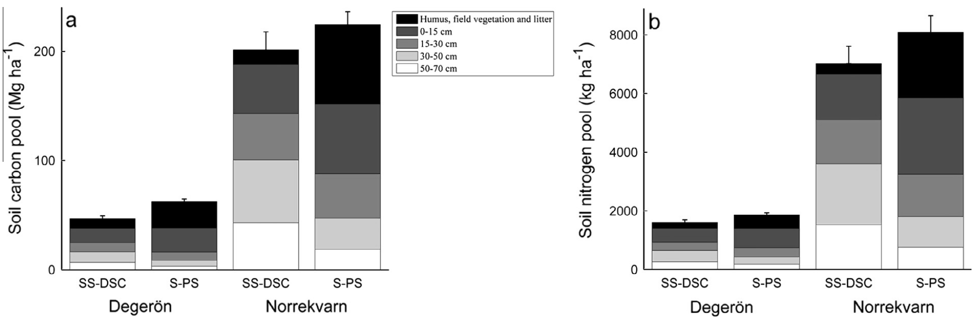

Fig. 3. Soil (a) carbon pools (Mg ha^{-1}) and (b) nitrogen pools (kg ha^{-1}) in different soil layers 24 years at Degerön and 22 years at Norrekvarn after stem and stump harvest and deep soil cultivation (SS-DSC) compared with conventional stem-only harvest and manual patch scarification (S-PS). Error bars indicate standard error ($n = 4$) of the soil pool means.

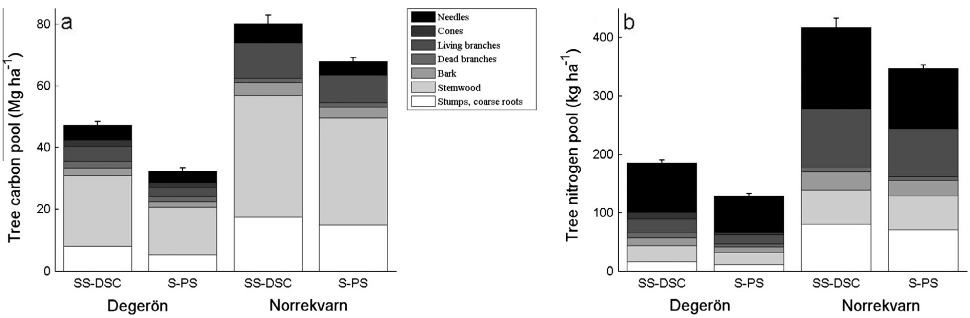

Fig. 4. Tree biomass (a) carbon pools (Mg ha^{-1}) and (b) nitrogen pools (kg ha^{-1}) in different tree fractions 24 years at Degerön and 22 years at Norrekvarn after stem and stump harvest and deep soil cultivation (SS-DSC) compared with conventional stem-only harvest and manual patch scarification (S-PS). Error bars indicate standard error ($n = 4$) of the tree biomass pool means.

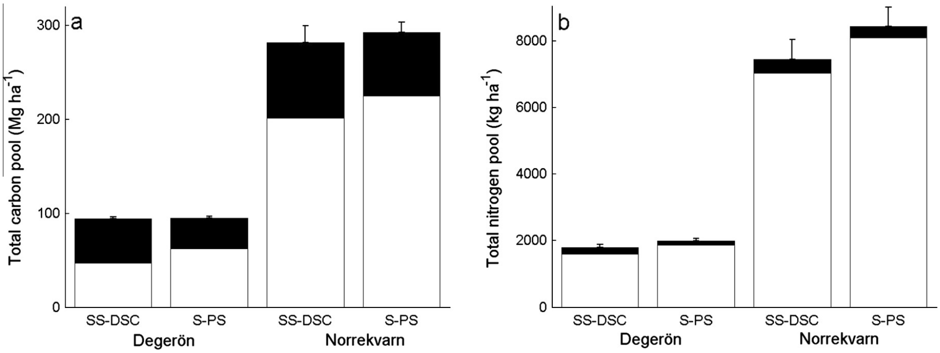

Fig. 5. Total (a) carbon pools (Mg ha^{-1}) and (b) nitrogen pools (kg ha^{-1}) 24 years at Degerön and 22 years at Norrekvarn after stem and stump harvest and deep soil cultivation (SS-DSC) compared with conventional stem-only harvest and manual patch scarification (S-PS). White bars represent soil pools and black bars represent tree biomass pools. Error bars indicate standard error ($n = 4$) of the total pool means.

compared with S-PS (Table 4), with a 14% lower N pool at Degerön ($p = 0.06$, site-level ANOVA) and a 13% lower N pool at Norrekvarn ($p = 0.24$, site-level ANOVA), respectively (Fig. 3).

3.2. Tree biomass C and N pools

The tree biomass C pool was significantly higher following SS-DSC compared with S-SP (Table 4) with a 47% increase at Degerön ($p = 0.0008$, site-level ANOVA) and a 18% increase at Norrekvarn ($p = 0.003$, site-level ANOVA), respectively (Fig. 4). The tree biomass N pool was significantly higher following SS-DSC compared with S-PS (Table 4), with a 44% increase at Degerön ($p = 0.0007$, site-level ANOVA) and a 20% increase at Norrekvarn ($p = 0.01$, site-level ANOVA), respectively (Fig. 4).

3.3. Total C and N pools

The total C pool (soil and tree biomass) was not significantly affected by the SS-DSC treatment (Table 4), with a 0.6% decrease at Degerön ($p = 0.85$, site-level ANOVA) and a 3.8% decrease at Norrekvarn ($p = 0.6$, site-level ANOVA), respectively (Fig. 5). The total N pool was lower, but not statistically different, following SS-DSC compared with S-SP (Table 4), being 10% lower at Degerön ($p = 0.1$, site-level ANOVA) and 12% lower at Norrekvarn ($p = 0.26$, site-level ANOVA), respectively (Fig. 5).

4. Discussion

Soil C and N pools were lower, but not statistically different, following SS-DSC as compared to S-PS. Thus, hypothesis (i) was rejected for the full ANOVA including both sites. However, for the site-level ANOVAs, a statistically significant C loss and almost significant N loss from the soil pools were revealed for the less fertile site Degerön in northern Sweden supporting hypothesis (i). For tree biomass both C and N pools were significantly increased by the SS-DSC treatment in line with hypothesis (ii). As a result, the total C and N pools were not significantly affected by SS-DSC, as suggested in hypothesis (iii). An important conclusion from the results is that judgments on effects of silvicultural measures on the forest C balance or net greenhouse gas emissions cannot be based on single measurements of C pool changes in the soil or in the trees – it has to be based on changes in the total C pool.

4.1. Soil C and N pools

Despite the considerable statistical uncertainty, a comparison of current C data with the 10-year result presented by Nordborg et al. (2006) indicates that total soil C (including litter and field vegetation) has remained stable (SS-DSC at Degerön) or increased since then. Data indicates increases in all soil layers on S-PS plots, but a decrease in the deeper mineral soil layers (15–70 cm) and an increase only in the superficial soil layers on SS-DSC plots. Despite the continuous C losses from the deeper soil layers, data suggest that there is still more C stored in the deeper soil layers following SS-DSC as compared to S-PS (cf. Fig. 3).

The differences in C and N concentrations contributed to the lower soil C and N pools with lower concentrations in the upper soil layers and higher concentrations in the lower soil layers after SS-DSC in comparison to S-PS (Table 3). Similar to the 10-year results presented by Nordborg et al. (2006) the mineral soil bulk density was lower on SS-DSC plots (Fig. 2). This is in contrast to studies on effects of stump harvest suggesting an increase in soil bulk densities (Hope, 2007; Page-Dumroese et al., 1998; Zabowski et al., 2008). It is likely that the deep soil cultivation (DSC) treatments applied in this study counteracted an initial compaction as a result of the stump-removal. Compared to the 10-year results in Nordborg et al. (2006) the soil bulk density differences between the two treatments have decreased with time. This is in line with other long-term stump harvest studies (Hope, 2007; Zabowski et al., 2008).

The DSC treatment used in this study goes far beyond site preparation intensities used in practical forestry, with disc-trenching and mounding being the most common mechanical site preparation methods used in northern Europe (Nilsson et al., 2010). The soil disturbance caused by the additional stump harvest is limited to the area around the harvested stump when practiced on soils with sufficient load bearing capacity, as the soils studied here. Practical experience in Scandinavia shows that soil damages caused by stump harvest partly can replace mechanical site preparation, but a complementary site preparation is usually needed to reach sufficient numbers of planting positions (Laitila et al., 2008). Among studies focusing on effects of stump harvest, Hope (2007) reported that immediate effects of stump harvest on mineral soil densities and humus layer chemistry at three sites in interior BC, Canada, had disappeared after 10 years. Karlsson and Tamminen (2013) found no treatment effect on C and N pools 30 years after stump harvest of a Norway spruce dominated stand in Finland and Strömgren et al. (2013) found no negative effect on the soil C pool 25 years after stump harvest of four sites in Sweden, although there was a significant reduction in the top organic soil layer. In contrast, Zabowski et al. (2008) reported lower C and N concentrations in the mineral soil 22–29 years after stump harvest by means of a bulldozer equipped with brush blade at five sites in the Pacific Northwest, USA. This harvest technology differs from the one used in Scandinavia, where the stumps are lifted up by means of an excavator equipped with a special stump rake extraction-splitting device (Laitila et al., 2008). Thus, the bulldozer technique might be more intense in terms of soil disturbance and potentially also the loss of organic layer when the stumps are raked into piles.

The four stump harvest studies cited above sampled the mineral soil down to a depth of 10–20 cm only, whereas this study sampled and estimated C and N concentrations and bulk density to a depth of 70 cm. This was required since the DSC treatments transferred the organic soil layer including litter and vegetation to a depth of 50–60 cm. One effect of this is that easily decomposed high quality organic material is transferred to a soil position where temperature conditions for decomposition may be less favourable than closer to the soil surface, as would be the case following practical site preparation (Johansson, 1994). From a climate impact perspective the fate of the C lost from the sampled soil pool is largely unknown even though a large proportion of it most likely have been emitted to the atmosphere as greenhouse gases – primarily as CO_2 (cf. Kataja-aho et al., 2012). However, some of the more labile C, buried deep down in the mineral soil as a result of the DSC, may have been removed from the sampled layer via leaching as dissolved organic compound down below the sampled soil profile, with some amount reaching surrounding water bodies where a fraction could be oxidized and another buried in aquatic sediments (Cole et al., 2007; Fahey et al., 2005).

4.2. Tree biomass C and N pools

Tree biomass C and N pools were significantly higher following SS-DSC in comparison with S-PS as a result of both improved seedling survival and tree growth. The tree C pool at Degerön increased more than at Norrekvarn both in absolute and relative terms. There are a number of possible explanations for this difference in growth response linked to the experimental design and location with potential impacts on N availability and thereby tree-growth: (i) unaccounted initial N losses, (ii) herbicide effects, (iii) stump N accumulation, (iv) inconsistent DSC treatment and (v) initial N availability. (i) The site history at Norrekvarn differed from that at Degerön by being clear-cut in 1983, disc-trenched and planted in 1987, before the experiment was established and replanted in 1990. It is likely that a large proportion of the more easily available N originating from N-rich logging residues (fine branches and foliage) and fine roots following the harvest was released (Hyvönen et al., 2000) and potentially leached or immobilized already by the time the experiment was established. Initial N losses could have been further reinforced by the disc trenching in 1987, where the organic layers including vegetation are buried by or mixed with mineral soil and thereby stimulated N mineralization (Salonius, 1983). Since N is the major growth-limiting nutrient in northern temperate and boreal forest (Tamm, 1991), this may have to some extent affected our results. (ii) The S-PS plots at Norrekvarn was treated with a herbicide (no herbicide on the SS-DSC plots) – a treatment that can have a positive impact on net N mineralization (Vitousek et al., 1992) and tree growth (Ponder et al., 2012; Wagner et al., 2006) and therefore could have hidden the potential effect of DSC as compared to PS. This is further supported by a study by Fu et al. (2007) showing that for all four coniferous species studied, the 15-year growth performance increased significantly with site preparation intensity on sites without herbicide treatment, but did not change on sites with herbicide treatment. (iii) The stumps on DSC-plots at Norrekvarn were harvested 7 years after clear-cut. During this period decomposers exploiting the C source in the stumps might have increased the N concentration and content in the stumps (Fahey et al., 1991; Palviainen et al., 2010). This may have caused an additional N loss on SS-DSC plots, where the stumps were removed, counteracting the positive effect of DSC on N mineralization and availability. In a practical operation the stumps would have been harvested in conjunction with the clear-cut and consequently with a lower N content. (iv) Two out of four SS-DSC plots at Norrekvarn were DSC-treated in strips and only 50% of the area was treated. The differences between the 100% and 50% DSC-treatments were, however, not detectable. The effect on our results is therefore assumed to be negligible. (v) The higher N deposition (cf. Table 1), initial N pool and site fertility at Norrekvarn may also explain the moderate growth response following DSC at Norrekvarn.

A possible explanation for a larger treatment effect at the less fertile site Degerön could be linked to a finding by Näsholm et al. (2013), suggesting that the ratio between C allocated from the trees to the ectomycorrhizal community in the soil and N transferred from the ectomycorrhizal community to the trees increases with increasing N limitation. Thus, trees on a less fertile N-limited site like Degerön may have gained more from the net release of N caused by DSC, as this could have reduced the C cost for N within the ectomycorrhiza-tree trading system. This hypothesis is supported by Menkis et al. (2010) who found that the ectomycorrhizal colonization rate of seedling roots was lower on stump harvested plots compared with mounded plots and this coincided with higher growth rates for seedlings planted on stump harvested plots.

Another crucial question is whether the same tree performance could have been gained with a less intensive site preparation method than DSC? Several studies show that mechanical site preparation is beneficial for forest establishment and growth (Boateng et al., 2009; Hawkins et al., 2006; Örlander et al., 1998). Örlander et al. (1998) compared survival and growth, ten growing seasons after planting, following four different mechanical site preparation methods compared with an untreated control. Aboveground mean tree dry weights following site preparation were 4–11 times larger in lodgepole pine and 4–8 times larger in Norway spruce. Survival rates were also significantly higher on site prepared plots. The best result was achieved for an intermittent method restricted to the planting spot (inverting), providing a planting spot containing a humus turf flipped upside down and covered in loose mineral soil without making a mound or a ridge. This suggests that a similar increase in tree growth and thereby C sequestration in tree biomass could be gained with a more moderate mechanical soil treatment and thus, potentially at a lower soil C loss than in this experiment. An integrated stump harvest and site preparation technology could be a route towards higher operational efficiency in practical forestry.

Will the trees continue to grow better on SS-DSC plots? Growth trends recorded at the sites indicate that the initial positive effect of SS-DSC is over. Even though nutrients in organic compounds are likely to be released more slowly than nutrients from a mineral fertilizer, this is in line with fertilization experiments suggesting that the growth stimulation effect lasts only for seven to ten years (Saarsalmi and Mälkönen, 2001). Reduced seedling growth following whole-tree harvest in Norway spruce in northern Sweden was also shown to be temporal (Egnell, 2011). Thus, the positive effect of leaving nutrient rich logging residues on-site did not have any long-term effect on subsequent tree growth. Although it was decided to use the same allometric functions for both treatments at Degerön, sample tree data indicated that the green crown base occurred at greater height for trees on SS-DSC plots and more dead branches were present below the green crown base as compared to trees of similar size on S-PS plots. At the same time, the N concentrations in the needles were similar for the two treatments at both locations (cf. Table 3). It should be noted, however, that the observed N concentrations are below the optimum N concentrations of 2%, suggested as the target values for maximum growth of Norway spruce by Linder (1995), based on a nutrient optimization experiment. Although the N isotopic ratios in the needles were slightly higher on SS-DSC plots indicating a higher N availability (Högberg et al., 2011), they were not statistically different, and for both treatments depleted in ^{15}N (cf. Table 3) indicating that N is limiting growth and that ectomycorrhizal fungus plays an important role in the N cycling (Hobbie and Högberg, 2012). Overall, this suggests that the initial period with superior growth conditions following SS-DSC were already over by the time of this study. The full outcome of the treatments on the C balance over an entire rotation period is yet to be seen.

4.3. Total C and N pools

The experiments presented here clearly showed that the soil and tree C pools are linked in managed forests. This creates a challenge for forest managers from a climate change mitigation perspective in finding adequate management strategies that optimize a large and valuable harvest with minimum C losses. The trade-off between the soil and tree C pools raises the question on which of the two C pools provides the most benefits for mitigating climate change. From a C storage perspective, soil C is more secure since C stored in trees is always at risk of being lost due to i.e. forest fires, storms and forest pests (Schelhaas et al., 2003) and climate change may further increase that risk (Allen et al., 2010).

Studies focusing only on biomass for energy from long-rotation forestry often conclude that using forest biomass for energy purposes is not a good strategy to mitigate climate change – at least not with a short term perspective (e.g. Cherubini et al., 2011; Holtsmark, 2013). Biomass for energy is, however, together with pulpwood, a low-priced commodity unlikely to by itself support forest management initiatives to maintain or increase forest growth in northern temperate and boreal forests. Forest management in these areas is primarily driven by other, more valuable assortments, i.e. the sawmill industry. Studies on climate impacts of different forest management and end use strategies in long-rotation forestry including the full suite of forest products show that the largest climate change mitigation potential comes from material substitution where wood substitutes other materials with a larger carbon footprint (e.g. Lundmark et al., 2014; Sathre and Gustavsson, 2012).

Despite the low price for biomass for energy and pulpwood, large markets for these commodities are good news for foresters since production and processing of timber produces large quantities of wood unsuitable as timber like small diameter trees, damaged stems, unsuitable tree species, logging residues, stumps, and process residues in the industry. Thus, low-priced wood is part of the overall economy in long-rotation forestry and in the forest industry. By this, markets for low-priced wood can have an impact on the timber production per acreage with a larger potential to mitigate climate change. From a climate impact perspective, this implies that the major conclusion from this study, that the total C pool has to be considered when effects of a silvicultural measure on net greenhouse gas emission is evaluated, has to be expanded further and include the full suite of forest products delivered from that forestry practice and their climate change mitigation potential. A complete climate impact assessment also includes other factors such as net uptake and emissions of greenhouse gases other than carbon dioxide and emissions from input energy and materials in primary production, transports, and wood processing, preferably with a landscape and long-term perspective rather than a single stand and short-term perspective.

4.4. Other issues

In this study we focus on effects of stump harvest and mechanical soil disturbance on forest production, C pools, and climate change. There are, however, other environmental issues to consider when planning for large scale stump harvest or more intense site preparation methods. Important issues are i.e. (i) impacts on biodiversity where stumps represents coarse dead wood that often are scarce and limiting for biodiversity in managed forest landscapes (Hjältén et al., 2010); (ii) impacts on surrounding water ecosystems and ground water (Laudon et al., 2011) – not least impacts on methyl mercury leaching (Eklöf et al., 2012); (iii) aesthetics and public perception.

5. Conclusions

Based on our finding we conclude that stem and stump harvest and deep soil cultivation have the potential to reduce soil C and N pools more than conventional stem-only harvest and manual patch scarification, although the reductions were only statistically significant for one of the experiments presented here. These reductions in the C and N soil pools can be partly compensated for by increases in the tree pools as a result of improved growing conditions following the deep soil cultivation. The intense site preparation method studied here cannot be recommended for practical forestry since the literature on mechanical site preparation suggests that it is likely that the same favourable growing conditions could be achieved with a less intense site preparation method – potentially with reduced losses in the soil C and N pools. An integrated stump harvest and site preparation technology could be a route towards higher operational efficiency in practical forestry. Judgments on effects of silvicultural measures on the forest C balance or net greenhouse gas emissions cannot be based on single measurements of C pool changes in the soil or in the trees – it has to be based on changes in the total C pool. Estimates of the total climate impact potential of long-rotation forestry practices have to go beyond changes in the forest C pools and among other things include the full suit of forest products, their C pools and substitution potential, input energy and materials in primary production and processing of the wood produced. Preferably such analyses should include the landscape level rather than the stand level and have a long-term perspective.

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Slash and stump harvest have no general impact on soil and tree biomass C pools after 32–39 years ☆

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ABSTRACT

The energy from forest biomass is central in achieving climate mitigation goals in the European Union (EU). The carbon (C) balance and climate mitigation benefits of this strategy are, however, questioned; particularly, when stumps and slash are also removed during harvest. Stump and slash harvest result in nutrient loss, which might cause reduced growth and thereby decrease C sequestration of the next generation of trees. In addition, the removal of the slowly decomposing biomass may lead to a depletion of the soil C pool. In the case of stump harvest, these negative effects may be partly compensated for by increased nutrient availability due to a stimulated mineralization and reduced competition from understory vegetation as a result of the soil disturbance caused by the stump harvest.

Here we analyze the effect of different harvest intensities on total, soil (humus and mineral down to 10 cm), and tree biomass C pools based on data from eight field experimental sites across Sweden regenerated with Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* (L.) Karst.) 32–39 years after clear-cut with (i) stem-only harvest; (ii) stem and stump harvest; (iii) stem and slash harvest; and (iv) stem, stump and slash harvest. Due to a lack of replicates at the site level we focused our analyses on general treatment effects across all sites and on species level effects ($n = 4$). The main hypotheses were that across all sites (i) the total C pool is generally unaffected by stump harvest, (ii) whereas the total C pool generally decreases after slash harvest. We also hypothesized that (iii) the total C pool of spruce stands is more negatively affected by slash harvest in comparison to pine stands.

Despite considerable variation, there was no significant general effect of harvest treatments on the total, soil or tree biomass C pools across all sites, thus hypothesis (i) was confirmed, whereas hypothesis (ii) was rejected. As compared to the total C pool following stem-only harvest the average total C pool was reduced following the two treatments which included slash harvest in spruce stands, whereas the C pool was unaffected or increased in pine stands, indicating a species-specific effect. However, these differences were not statistically different and hypothesis (iii) was therefore also rejected. Based on the results presented here we conclude that stump and/or slash harvest have no general medium-term effects on the total forest C pool. However, given the limitations of the experimental design in this study and the general lack of studies investigating stump and slash harvest effects on the C balance, we call for more studies with focus on long-term field experiments that are replicated at the site level to be able to reveal potential site- and species-specific responses to slash and stump harvest.

1. Introduction

Currently, more than half of the renewable energy in the EU comes from biomass due to a well-established infrastructure and market (Mantau et al., 2010; Pelkonen et al., 2014). For example, forest industry residues are fully utilized in Sweden and Finland (Saal, 2010). Furthermore, the EU member states have accepted binding targets to reduce greenhouse gas emissions and increased share of renewable energy (EC, 2009). Demand and use of forest biomass will likely continue to increase (UNECE/FAO, 2011). To satisfy an increasing demand, one option is to increase the harvest intensity by including stumps and slash (i.e. tree tops and branches).

The climate benefits of using forest biomass instead of fossil energy have been questioned, particularly when coarse logging

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residues like non-merchantable stemwood and stumps are harvested and combusted (Hannam, 2012; Zanchi et al., 2012). Stump harvest has been disputed, firstly, because of the direct removal of C stored in the stump biomass and its combustion which results in an instant emission of carbon dioxide (CO_2) (Hope, 2007). Left in the forest, stump biomass would slowly decompose and release CO_2 into the atmosphere at a much slower rate (Repo et al., 2012; Shorohova et al., 2012) and possibly add some recalcitrant fractions to the soil C pool (Berg et al., 2009). Secondly, there is a concern that stump harvest causes soil disturbance that may increase C mineralization and release CO_2 from the soil organic matter (Grelle et al., 2012; Walmsley and Godbold, 2010), although this effect has been disputed (Strömgren and Mjöfors, 2012; Strömgren et al., 2012).

There are other effects of stump harvest that potentially will increase nutrient availability and thus forest production, at least in the short run. If soil disturbance causes increased mineralization of soil organic matter it will likely increase nutrient availability (Kataja-aho et al., 2012a). Furthermore, exposed mineral soil following stump harvest reduces competition from vegetation and thereby creates better conditions for seedling establishment (Nilsson and Örlander, 1999) and seed germination (Winsa, 1995). Stump harvest might therefore promote planted and naturally regenerated seedling establishment (Karlsson and Tamminen, 2013; Tarvainen et al., 2015) and subsequent tree growth (Kataja-aho et al., 2012b; Örlander et al., 1996). Subsequently, increased tree growth will result in a higher C pool and provide more above- and belowground litter that will add to the soil C pool, eventually compensating for soil C losses (Egnell et al., 2015).

Compared to stump harvest, slash harvest has potentially less negative short-term effects on the soil C pool as a result of lower soil disturbance and faster decomposition rate (Hyvönen et al., 2000). On the other hand, slash biomass contains more nutrients than stump biomass (Hellsten et al., 2013; Ouro et al., 2000) and therefore more nutrients are directly lost from the site during slash harvest. Additionally, slash left on-site may have a short-term mulching effect resulting in an increased nutrient availability for the subsequent stand (Bai et al., 2014; Emmett et al., 1991). Consequently, nutrient losses during slash harvest may potentially reduce tree growth (Egnell, 2011) and thereby decrease C sequestration in the subsequent stand. Overall, this suggests that slash harvest might reduce subsequent tree growth and thereby C sequestration, whereas stump harvest might increase tree growth at the expense of a decreased soil C pool. Thus, the combined effects from stump and slash harvest on the total C pool (soil + tree biomass) might counterbalance and therefore have no or a smaller net effect relative to the individual impacts of stump and slash harvest.

Recent reviews have highlighted that the knowledge on the long-term effects of stump and slash harvest on the total forest C pool is still limited (Clarke et al., 2015; Walmsley and Godbold, 2010). Egnell et al. (2015) recently reported a significantly reduced soil C pool and a significantly increased C pool in tree biomass with no significant net effect on the total C pool 24 years after stump harvest in combination with deep soil cultivation. However, slash was not harvested in that study and the extreme harvest intensity (100% of stumps harvested) and soil disturbance (up to 100% soil disturbance down to a depth of 50 cm) was beyond what could be expected following a practical stump harvest operation (Kataja-aho et al., 2011; Tarvainen et al., 2015). Consequently, there remains a need to explore different effects from slash harvest and stump harvest as well as more realistic soil treatments. Furthermore, Strömgren et al. (2013) investigated effects on C pools in soil and biomass for harvest of (i) stem-only, (ii) stem and stump, and (iii) stem, stump and slash in four stands. They found a lower total C pool 25 years after stem, stump and slash harvest in comparison to the two lower harvest intensities. However, to our knowledge, no empirical study to date has compared the separate and combined effects of stump and slash harvest on the total C balance in the forest.

In addition, the impact of stump and slash harvest on soils may be further modified by the response of the new stand which may differ between species (Walmsley and Godbold, 2010). These differences might result from contrasting adaptation potentials of pine and spruce to disturbance caused by stump harvest operations (Saksa, 2013). For example, Hope (2007) reported increased growth of lodgepole pine (*Pinus contorta* L.), but not for hybrid spruce (*Picea glauca* (Monech) Voss × *Picea engelmannii* Parry) after stump harvest. Likewise, Karlsson and Tamminen (2013) found significantly increased stem biomass production in Scots pine (*Pinus sylvestris* L.) whereas no effect was detected in Norway spruce (*Picea abies* (L.) Karst.) planted at the same site following stump and slash harvest.

In this study, we compared C pool data for soil (humus and 10 cm down into the mineral soil) and tree biomass from eight field experiments in Sweden 32–39 years after conventional clear-cut with (i) stem-only harvest; (ii) stem and stump harvest; (iii) stem and slash harvest; and (iv) stem, stump and slash harvest. The main objective was to study the effect of the different harvest treatments on the total C pools including C in soil and tree biomass across all sites. Our main hypotheses were that across all sites (i) the total C pool will be generally unaffected after stump harvest, whereas (ii) the total C pool will generally decrease after slash harvest. Consequently, the total C pools will differ in the order: stem-only harvest = stump harvest > slash harvest = stump + slash harvest. We also hypothesized that (iii) the total C pool of spruce stands is more negatively affected by slash harvest in comparison to pine stands.

2. Materials and methods

2.1. Study sites

Eight field experiments were established between 1978 and 1980 after clear-cutting of mature Scots pine, Norway spruce or mixed conifer stands with the aim to study long-term effects of stump and/or slash harvest (Table 1, Kardell and Wärne, 1981). They were geographically distributed over the whole of Sweden, covering most climate regions (Fig. 1) with climatic, site productivity and nitrogen (N) deposition gradients. The altitude of the study sites ranged from 30 to 530 m a.s.l. The soils were mesic sandy–silty till with developed haplic podzols, although with a poorly developed E-horizon at Tagel, Remningstorp and Ekenäs.

2.2. Experimental design and treatments

At all study sites, four treatments were applied on 30 × 30 m plots with a 10 m buffer (Fig. 1 and Table 1). The original design included two blocks per site, however, as the soil sampling was limited to one of the blocks, only one block per site was used in the analyses. The treatments were: conventional clear-cut with (i) stem-only harvest (stem-only); (ii) stem and stump harvest (stump); (iii) stem and slash harvest (slash); and (iv) stem, stump and slash harvest (stump + slash). Treatments were randomly allocated within the used block. The study sites were clear-cut in 1978–1980, primarily during winter time with sufficient snow cover; however, at Tagel, Grävsvinsberget and Rackasberget harvest was done without snow cover. At Kvisslevägen and Grävsvinsberget, a feller-buncher was used for clear-cutting. At Garpenberg and Rackasberget the trees were felled manually and delimbed

Table 1
Former stand and treatment data of the study sites.

Study site	Tagel	Remningstorp	Grävsvinsberget	Rackasberget	Ekenäs	Garpenberg	Svartberget	Kvisslevägen
Former stand species composition (%)[a]	0, 90, 10	50, 50, 0	70, 30, 0	0, 100, 0	80, 20, 0	50, 50, 0	10, 90, 0	40, 60, 0
Former stand age	90	70	95	125	95	100	115	120
Growing stock (m^3 ha^{-1})	400	280	240	280	220	230	180	210
Latitude (N)	57°02′	58°25′	60°25′	60°35′	58°55′	60°20′	64°15′	62°45′
Longitude (E)	14°24′	16°35′	17°35′	12°35′	13°40′	16°15′	19°50′	15°45′
Altitude (m a.s.l.)	185	140	30	530	50	225	250	410
Temperature sum[b]	1324	1278	1250	821	1324	1092	834	791
Site index (H_{100})	32	30	26	20	26	24	22	20
Nitrogen deposition (kg N ha^{-1} $year^{-1}$)[c]	10–12	8–10	2–4	6–8	4–6	4–6	<2	2–4
Soil texture	Sandy–loamy till	Sandy–loamy till	Loamy till	Sandy–loamy till	Sandy–loamy till	Sandy–loamy till	Sandy–loamy till	Sandy–loamy till
Stone content range (% of soil volume)	34–38	50–60	63–72	27–45	4–38	41–70	10–79	38–60
Soil moisture	Mesic-moist	Mesic-moist	Mesic	Mesic	Mesic	Mesic	Mesic	Mesic
Clear-cut	1978	1980	1978	1979	1979	1978	1979	1979
Stump and slash harvest	1979	1980	1979	1980	1980	1979	1980	1980
Year planted	1981	1981	1981	1982	1981	1982	1982	1983
Age of planted seedlings, years	5	5	1	1	3	2	1	2
Planted species	Norway spruce	Norway spruce	Norway spruce	Norway spruce	Scots pine	Scots pine	Scots pine	Scots pine
Supplementary planting	1985						1983/85	
Pre-commercial thinning				2004		1990	2004	
Thinning	2008/14	2014			2005/14	2013		
Latest revision of inventory	2014	2012	2013	2013	2012	2012	2013	2013
Stand age at latest revision	39	36	33	32	35	33	32	32
Harvested biomass (Mg C ha^{-1})								
Stumps (including roots > 5 cm)[d]	29	18	15	20	13	14	12	13
Slash[e]	23	23	19	26	16	20	11	19

[a] Species composition based on stem volume in the order of Scots pine, Norway spruce and birch (*Betula* sp.).
[b] The sum of daily mean temperature in degree-days with threshold +5 °C based on Morén and Perttu (1994).
[c] Karlsson et al. (2012).
[d] Based on standing volume and equation by Lehtonen et al. (2004).
[e] At Tagel and Svartberget, only part of the needles were harvested, therefore foliage is not included in the slash C pool. The top of the stem and bark biomass was set to 1% the of tree biomass and added to the slash biomass.

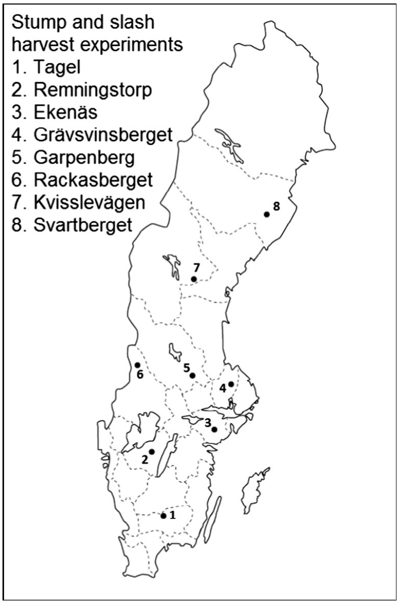

Fig. 1. Location of study sites.

with a Logma delimber. At the remaining sites, trees were harvested manually. Within one year after stem harvest, slash was carefully removed manually – i.e. more complete than in commercial slash harvest operations possibly with the exception of Tagel and Svartberget, where the slash dried up before it was removed from the plots, resulting in some shedding of needles (Table 1). In the same year, stumps were harvested by means of an excavator equipped with stump extraction heads, commercially available in the early 1980s (Pallari or Lokomo). At all plots, harrowing was performed as a site preparation method before planting Norway spruce or Scots pine monocultures at four study sites each. Planting was done manually with bare-rooted seedlings with 1.8 m spacing (3100 plants per ha). Due to seedling mortality, supplementary planting was performed where needed.

2.3. Soil C pool

2.3.1. Soil sampling

Soil sampling was performed in the autumn of 2012 at Garpenberg and Ekenäs and of 2013 at the other sites. In each experimental plot, 25 sampling spots were located in a regular grid pattern, where the position of the starting spot near the corner of the plot was located randomly. Cores were taken from the humus layer with a sharp-edged cylinder (∅100 mm). In the same spots, the mineral soil was sampled at 5 cm sections down to 10 cm with a 28 mm ∅ steel auger. Soil samples included in this study were restricted to the upper 10 cm of the mineral soil, due to practical difficulties associated with penetrating deep into stony soils in a replicable manner at all sites. Sampling spots located near (⩽50 cm) stems of living tree were replaced with a new random spot, but sample spots located to boulders, coarse live roots or other hard woody objects on the soil surface were not replaced, in order to correctly estimate the actual organic matter content in the humus layer. The soil samples from each soil layer and plot were pooled and kept cool (4 °C) until preparation and chemical analyses. Fresh soil samples were sifted through a 6 mm steel mesh for humus and 2 mm steel mesh for mineral soil to mix and homogenize the samples and to remove gravel and the fraction of live fine roots >2 mm. Thus, the sifted material included only organic matter in advanced stages of decomposition. Since remaining stumps were not included in the soil samples, the stump C pool was estimated using allometric decay equations with standing stem volume as input variable (see Section 2.5).

2.3.2. Chemical analyses and estimates of soil C pool

One sub-sample of the sifted soil was dried at 105 °C for 24 h for determining the fresh/dry mass ratios. Another sub-sample was dried at 60 °C for 24 h and then analyzed for C content by dry-oxidation with an elemental analyzer (LECO, St Joseph, MI, USA). The dry mass of the humus layer per unit area was calculated as the plot sample dry mass divided by the plot sample area. The bulk density (BD) of the mineral soil for fractions <2 mm was calculated in two steps. In the first step, the volume of the mineral soil <2 mm in the 0–10 cm horizon in each plot was estimated by subtracting the volume of stones and boulders which was calculated by the surface penetration method of Stendahl et al. (2009). In a second step, the BD of the mineral soil fraction <2 mm in each 5 cm layer was calculated using the plot average volume of mineral soil and the pedotransfer equation by Nilsson and Lundin (2006) to account for the influence of C content on the BD of mineral soil (<2 mm):

$$\mathrm{BD}_{(<2\ \mathrm{mm})} = 1546.3 * EXP(-0.313 * \mathrm{C}^{0.5}) + 0.00207 * d$$

where (C) is % C content and (d) is the soil depth in cm below the mineral soil surface. The content of the gravel (2–20 mm) fraction was not included in the method by Stendahl et al. (2009), and since the gravel content was not directly quantified and accounted for in the present study, BD of the mineral soil was probably slightly overestimated. However, this systematic error is probably inferior to the uncertainty associated with estimating the volume and boulder contents by the penetration method. Most sites in this study had markedly high stone and boulder contents (Table 1). The root mean square error in estimating stoniness with the penetration method is 9.2–9.5% for a particular site according to Stendahl et al. (2009), and about 90% of this uncertainty is caused by limitations and errors in the method (Eriksson and Holmgren, 1996).

2.4. C pool in tree biomass

All trees were cross-calipered at breast height (dbh, 1.3 m). Based on these diameters, tree biomass was estimated for stem wood, living branches, dead branches, bark, needles and stumps including roots. Stump and root biomass (diameter > 2 mm) was estimated with an allometric equation developed by Petersson and Ståhl (2006). All other fractions were calculated according to allometric equations for Norway spruce, Scots pine and birch developed by Marklund (1988). Carbon content was assumed to be 50% of the dry mass for all biomass fractions. All fractions were summed up to the tree biomass C pool.

Thinning was carried out at Tagel, Remningstorp, Ekenäs and Garpenberg with only stem-wood harvested for all treatments. Removed C in stemwood and bark during these thinnings was estimated based on tree diameter with the equations of Marklund (1988) and added to the tree C pool. Biomass in the top fraction of the stem, left on the site following thinning, was assumed to represent 1% of the stem biomass and was excluded from the harvested biomass and thereby also from the tree C pool.

2.5. Carbon pool in residual stumps

As the soil sampling procedure excluded stumps and coarse roots, residual C in stumps still remaining after the harvest on stem-only and slash plots was estimated with a decomposition equation by Melin et al. (2009), suggesting an annual stump biomass decomposition rate of 4.6%. Since data on previous stand characteristics lacked individual tree data and stem number, C pools in residual stumps (including roots > 5 cm) were estimated with biomass expansion factors based on standing volume (Lehtonen et al., 2004). The carbon pool in residual stumps was added to the soil C pool in the statistical analyses.

2.6. Statistical analyses

With the assumption of a normal distribution and equal variances met, mixed model analyses of variance (ANOVA) were used to evaluate treatment effects on C pools (total, soil and tree C pools) using the Minitab software (Minitab Inc., 2010). The first model consisted of the fixed effects of the stump harvest treatment, slash harvest treatment and an interaction between these treatments and site as a random effect. The model was run for all tree species, but also separately for Scots pine and Norway spruce stands. In addition, a second model was used to test the effects of planted tree species, which in addition to the fixed effects in the former model, included also tree species and the interactions between tree species and the stump harvest treatment, tree species and slash harvest treatment and interaction of all variables.

3. Results

Total C pool for the different harvest treatments at the eight sites showed an irregular pattern (Fig. 2). The statistical analyses for the ANOVA models did not reveal any significant general treatment effects of stump harvest on total C, tree C or soil C pools (Table 2), which was in line with hypothesis (i) In addition, the model did not reveal any significant effect of slash harvest on total C pool, nor did it for tree C and soil C pools (Table 2). Thus, hypothesis (ii) was rejected.

The effect of tree species on C pools was tested with the second ANOVA model, which did not reveal any significant effect (Table 2). Separate tests with the first model for Norway spruce and Scots pine also did not reveal any significant treatment effect. Consequently also hypothesis (iii) was rejected. It is however noteworthy that the average C pools were lowest following treatments including slash harvest in Norway spruce stands in line with hypothesis (ii) and (iii) (Fig. 3). For Scots pine stands, rather an opposite pattern could be distinguished, with in general higher total C pool for slash harvest, for stump harvest and for slash and stump harvest, mainly as a consequence of a higher tree C pool after stump and/or slash harvest and higher soil C pool after slash harvest.

4. Discussion

This study is limited to the C balance of the subsequent forest stand and soil following more intense harvest operations including slash and stumps. Since the scientific and societal interest in this C balance is driven by finding ways to mitigate climate change, it is important to keep in mind that there is a difference in soil C and tree C pools. Carbon sequestered in tree biomass may have a higher climate mitigation potential than soil C since the tree biomass can

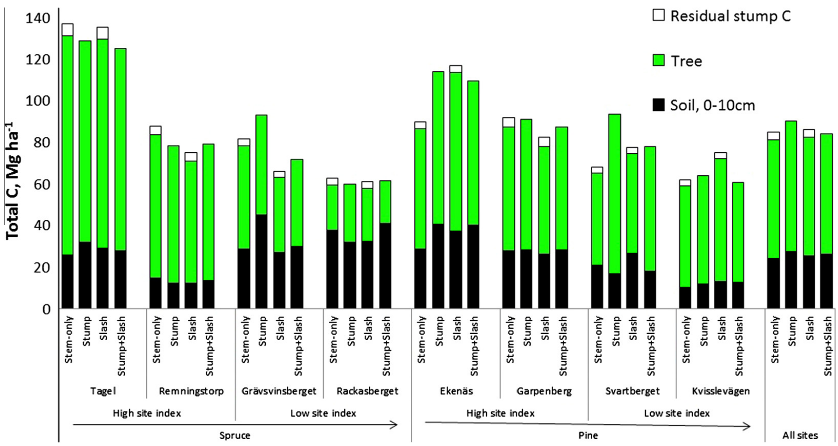

Fig. 2. Carbon pools (Mg ha^{-1}) in the total, soil (0–10 cm depth), residual stumps and tree biomass 32–39 years after stem-only harvest in combinations with stump and slash harvest. The experimental sites are split into Norway spruce and Scots pine sites and within species sorted in fertility order (site index based on top height).

Table 2
P-values of the fixed effects from the two tested ANOVA models with the overall effect of the stump, slash, species, interaction stump × slash, species × stump and species. Dependent variables in the model are carbon (C) pools in the tree biomass (Tree), the soil (Soil), and the sum of them (Total) 32–39 years after stem and stump harvest and/or slash harvest compared with conventional stem-only harvest. Model 1 was run for all sites (all, $n = 8$) as well as for the different planted tree species separately (pine and spruce, $n = 4$).

Model	Tree species	C pool	Stump	Slash	Stump × Slash	Species	Species × Stump	Species × Slash	Species × Stump × Slash
1	All	Total	0.83	0.77	0.67				
		Soil	0.68	0.97	0.78				
		Tree	0.67	0.74	0.75				
	Pine	Total	0.65	0.87	0.39				
		Soil	0.65	0.71	0.76				
		Tree	0.19	0.91	0.21				
	Spruce	Total	0.95	0.67	0.94				
		Soil	0.88	0.73	0.95				
		Tree	0.99	0.77	0.93				
2	All	Total	0.85	0.78	0.69	0.77	0.77	0.65	0.6
		Soil	0.65	0.97	0.79	0.35	0.82	0.6	0.86
		Tree	0.69	0.75	0.76	0.91	0.67	0.8	0.63

be used to substitute products with a large C footprint (Lundmark et al., 2014; Sathre and O'Connor, 2010).

4.1. Total C pool

The results from our study imply that there were no significant general treatment effects of neither stump nor slash harvest on the total C pool, and there were no significant interactions with species that would imply strong species-specific responses. Similar conclusions have been made in two recent reviews for the soil C pool (Clarke et al., 2015) and for the tree C pool (Thiffault et al., 2011). Assuming, with the limitation of the sample size, that our study sites were considered representative for the forests in Sweden, our results imply that an increase in harvest intensity would not change the C balance of Swedish forests – at least not in the medium-term (32–39 years). On the other hand, if there is a variation between sites in response to slash and stump harvest, sites with a high risk to suffer C losses could be separated from those with a possibility to gain C, which could help guiding management toward increased C sequestration. In contrast to our results, Strömgren et al. (2013) found a lower total C pool based on an analysis of two Norway spruce stands and two Scots pine stands 25 years after stump and slash harvest in comparison to stem-only harvest and stump harvest. The treatment response varied among the individual sites and was only significantly different for the low fertility spruce site. Overall, it cannot be excluded that there are site-specific conditions causing additional effects on the C pool which, however, could not be identified here due to the experimental design and, thus, it is a subject to further studies.

4.2. Soil C pool

The results with respect to stump harvest are in line with other medium-term studies of stump harvest effects on the soil C pool (Hope, 2007; Karlsson and Tamminen, 2013; Strömgren et al., 2013). Our findings are, however, in contrast with Zabowski et al. (2008) who found a decrease in the mineral soil C pool (down to 15 cm). One possible reason for the discrepancy between the studies can be that the latter study also may have caused a removal of the organic horizon, since it used a bulldozer equipped with a brush blade and a rear splitting wedge for the stump harvest. Our results are in contrast to some studies on slash harvest, in which a reduction of the soil C pool has been observed (Johnson and Curtis, 2001; Kaarakka et al., 2014; Strömgren et al., 2013), but agree with results from a 15–27 years study on effect of slash harvest effects in Sweden (Brandtberg and Olsson, 2012).

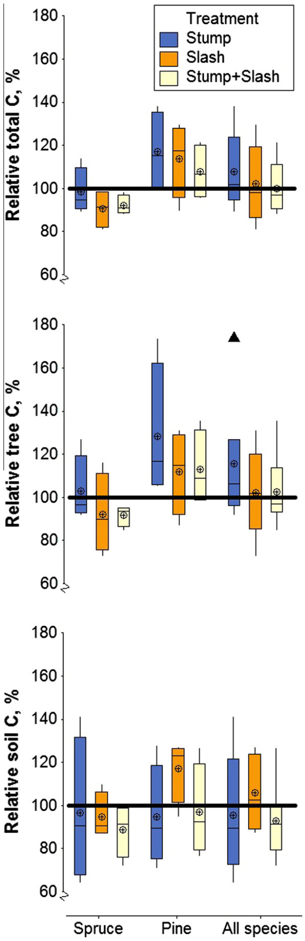

Fig. 3. Box plot showing the total carbon (C) including soil C (down to 10 cm depth in the mineral soil and humus) and tree C, 32–39 years after stem and stump harvest and/or slash harvest in relation to stem-only harvest (100%) based on data from eight sites (four planted with Norway spruce and four with Scots pine). Box width extends to the 25th and 75th percentile, circles indicate averages and horizontal lines – medians. The triangle represents outlier data outside the ±1.5 interquartile whisker range.

The effect of stump and slash harvest on soil C pool can be explained by three central factors; (*i*) the direct loss of C with harvested stump and slash biomass, (*ii*) the possible change in soil organic matter decomposition due to more disturbed soils and (*iii*) an influence on the litter production of the new stand. Among these factors, the first two have their strongest impact in the first few years following harvest, whereas the third factor will be increasingly important with increasing stand age. This temporal change was demonstrated in a Q-model prediction of slash and stump harvest effects based on field data from Swedish field studies (Hyvönen et al., 2012).

Regarding the first factor, Johnson and Curtis (2001) showed in a meta-analysis that whole-tree harvest (i.e., stem and slash) on average decreased the C pool in the A horizon by 6%, while stem-only harvest increased this pool by 18% in comparison to the situation before harvest or a control. However, the category for whole-tree harvest also included studies with forest floor removal, thus effects of slash harvest for energy purposes should be expected to be smaller. Nevertheless, Kaarakka et al. (2014) observed a 11% decrease in the soil C pool (organic layer + 0–10 cm of mineral soil) in a slash harvest study ten years after the final harvest in Southern Finland. In their study, slash harvest was performed at two thinnings and was repeated at the following final felling. The repeated treatments probably explains the marked effects in contrast to the study by Brandtberg and Olsson (2012) who found no significant effect 28 years after single slash harvest.

The effect of stump and/or slash harvest on the soil C pool, however, will change over time, as rotation time until the final harvest may reach hundred years. The harvest of forest residues entails a subsequent removal, while stumps or slash left at site will decompose slowly year by year, hence the difference in soil C pool between sites with different levels of biomass harvest is expected to diminish over time. After 34 years, which was the average time since harvest in our study, only 20% of the C pool in stumps is assumed to be remaining according to decay equations established by Melin et al. (2009). This proportion is small in comparison to the soil C pool in our study sites (Fig. 2). Since slash has higher decomposition rates, even less can be assumed to be remaining of the slash C pool (ca 10% after 35 years assuming decomposition rates established by Hyvönen et al., 2000). Thus, soil C-pool differences caused solely by additional C harvested in slash and stumps will be difficult to discern after 30+ years as in this study.

The second factor affecting the soil C pool refers to the effect of the increased soil disturbance caused by the stump harvest. The concern that soil disturbance might cause a soil C loss has been raised in several reviews regarding forest management and carbon sequestration (eg. Hyvönen et al., 2007; Jandl et al., 2007). Johnson (1992) produced a fundamental review, which included only few studies of site preparation (nine), whereof the majority (seven) also involved burning and/or litter raking or harvest of slash. Johnson (1992) also states that "*it is frequently not possible to separate soil C lost by displacement and that which is lost due to decomposition*". In another review about soil C following afforestation, Paul et al. (2002) did not find any differences between sites subjected to no or low soil disturbance in comparison to medium or high disturbance after site preparation. They stated that the "*observation by many that soil C decreases following forest establishment may be predominantly attributable to the lack of plant growth and thus C input into the soil rather than to soil disturbance during site preparation*". More recent studies showed that soil disturbance can cause an initial increase in soil CO_2 emissions or soil C loss the first few weeks after disturbance (Strömgren et al., 2012) or the first few months (Mallik and Hu, 1997), but conclude that this increase in CO_2 emission is transient. Other studies have shown that the disturbance caused by site preparation or stump harvest has no effect or even can decrease CO_2 emissions during the first two years after the disturbance (Mjöfors et al., 2015; Pumpanen et al., 2004). Thus, there is poor empirical evidence that soil disturbance *per se* increases decomposition and thereby decreases the soil C pool in the medium-term.

The third factor, regarding the change in soil C pool due to litter input, caused by changes in biomass production, can be assumed to be of minor importance in our study since no significant effect on tree C pool was observed. Thus, if we consider all the three discussed factors above we can assume that they all have a quite low impact on soil C pool after 30–40 years, which could be a reason why we were not able to observe any effects on soil C pool after stump harvest in our study.

Soil C data in our study are associated with several common uncertainties related to soil sampling: spatial variability, sampling errors, random method-related errors from measurement replication, as well as uncertainties in variables, equations and factors.

However, the spatial variability between sites and between plots has likely contributed the most to the total uncertainty rather than uncertainties associated with limitations and errors in methods (Simonsson et al., 2015). The total soil C pools were also underestimated since soil C stored below 10 cm was not included in this study due to sampling constraints. However, in other studies (e.g. Strömgren et al., 2013), the effects of stump and or slash harvest have mainly been observed in the organic soil layer, which was also covered in our study.

4.3. Tree C pool

Our results, showing no significant general effects of stump and/or slash harvest on the tree C pool, are in line with Kaarakka et al. (2014) who also found no effect on the Norway spruce stand growth ten years after final felling with slash harvest and mounding. In contrast, tree growth reduction was reported in a slash harvest field experiment with four replicates in Norway spruce stand in northern Sweden 31 year after clear-cutting (Egnell, 2011), where recovery rate was almost 100% and no soil preparation was performed. A reason for these contrasting results may be differences in site-conditions caused by different recovery rates and site preparation intensities.

Similar to effects on soil C pools, there are four potential main factors influencing the stump and/or slash harvest effects on the tree C pool. All of the factors are related to effects on nutrient availability; (*i*) the direct loss of nutrients with stump and slash biomass at harvest, (*ii*) the potential effect of increased soil disturbance by stump harvest on nutrient availability, (*iii*) microclimatic impacts, reduced competition from vegetation and improved planting spots and seed beds for natural regeneration due to increased soil disturbance and (*iv*) changes in the physical properties of the soil, potentially affecting root development and thereby also the growth of trees and C pool. Thus, stump and/or slash harvest may have both negative and positive effects on subsequent tree growth.

The impact of nutrient removal is expected to be stronger for slash than for stump harvest due to the higher nutrient concentrations and total nutrient pools in slash. The major part of N and phosphorus (P) in the slash is expected to be mineralized upon decomposition within the first 10–15 years after clear-cutting (Hyvönen et al., 2000), and corresponding effects on tree growth at the same study sites have been revealed by Egnell and Leijon (1999) and Egnell (2011). Moreover, growth reductions following slash harvest seems to be more pronounced for Norway spruce than Scots pine (Egnell and Leijon, 1999; Helmisaari et al., 2011). Other studies have recently provided experimental support to reduced N availability after slash harvest. Ring et al. (2015) found reduced NO_3^-–N and NH_4^+–N in soil water sampled 50 cm down into the mineral soil after slash harvest at two recently harvested spruce sites in Sweden. Also, Smaill et al. (2008) found lower soil N pools after slash harvest in four 8–16 year old *Pinus radiata* stands in New Zealand. Still, no effect of slash harvest on the tree C pool was revealed in our study, where harrowing was performed on all treatment plots. Thus, site preparation might counteract slash harvest effects.

Stump harvest also means removals of nutrients in the harvested stump biomass, but due to the relatively low N content in stumps (Uri et al., 2015), the N loss is small compared to losses in slash harvest. A consequence of leaving the stumps is that N is immobilized in the stumps for a long time and consequently not available to the following tree generation (Palviainen et al., 2010). This effect has also been proposed from modelling (Hyvönen et al., 2012) and from N mass balance studies of a clear-felling (Bergholm et al., 2015). Thus, any negative effect due to the moderate export of N with the harvested stumps may be counteracted by reduced N immobilization in stumps – at least in the short to medium term. This could explain the higher soil N concentrations and lower C:N ration following slash and stump harvest as compared to slash harvested and mounded plots 1–5 years after harvest in Finland reported by Kataja-aho et al. (2012a). In contrast, Butnor et al. (2012) reported a lower total soil N pool 50 years after stump harvest and soil cultivation of southern pine sites in south-eastern USA suggesting that stumps are important for the long term N retention. However, these studies deal with soil N concentrations or total soil N pools, whereas the impact on forest production is determined by N availability together with stand demand over time.

The second potential factor affecting the tree growth and tree C pool is related to soil disturbance. There are some evidence that soil disturbance increase decomposition of organic material and amplify soil C and N mineralization (Piirainen et al., 2007), but other studies indicate no effect or even reduced mineralization from disturbance (see section above on soil C). One reason for the variation in the results is that disturbance might also reduce vegetation establishment, a factor that may be more important than mineralization and not often clearly separated from the effect on mineralization *per se*.

The third factor is related to the seedling establishment since stump harvest may result in improved microsites for regeneration as a consequence of soil disturbance (Saksa, 2013). Improved planting spots and seed beds might increase seedling survival and support natural regeneration (Kardell, 1992) due to an increase in nutrient availability and reduced competition from vegetation (Buitrago et al., 2015). A study in Finland showed that an increased area of disturbed soil from stump harvest also increased establishment of birch seedlings (Tarvainen et al., 2015). Natural regeneration of primarily birch was favoured by stump harvest also in our study. However, pre-commercial thinning was carried out on all plots, reducing the difference between treatment plots. In addition, harrowing was performed on all treatment plots before planting, resulting in soil perturbation also on plots with no stump harvest. Thus, pre-commercial thinning and harrowing might have reduced potential differences in stand growth and thereby the tree C pool between treatments. Our study is still relevant since mechanical site preparation and pre-commercial thinnings are performed on most regeneration sites in practical forestry in Sweden and Finland.

Site-specific factors like soil fertility were suggested to explain different treatment responses for 4-year woody biomass production following stump and slash harvest in northern, central and southern Finland (Tarvainen et al., 2015). In forest management guidelines poor sites are often suggested to be more susceptible to increased harvest intensities. However, the results presented here, limited by the site index range included in the study, did not support that poor sites should be more susceptible (Fig. 2).

4.4. Tree species effects

Our study did not reveal a statistically significant species-specific response. However, mean total C pools in the slash and slash + stump harvest treatments were considerably lower than in the stem-only and stump harvest treatments for Norway spruce stands. In comparison, the mean total C pool was higher for all stump and slash harvest treatments compared to stem-only harvest among the Scots pine stands. These trends in species effects observed in our study are in line with Karlsson and Tamminen (2013) who found positive effects of stump harvest on the tree growth in plots planted with Scots pine, but not in plots planted with Norway spruce when planted at the same experimental site. Burgess et al. (2010) also reported species-specific responses of jack pine (*Pinus banksiana* [Lamb.]), black (*Picea mariana* [Mill.] BSP), white (*P. glauca* [Moench] Voss) and Norway spruce in a site preparation experiment in New Brunswick, Canada. Tree species response differences were also reported by Hope (2007) who found increased height and diameter growth for lodgepole pine, but not for hybrid spruce (*Picea glauca* × *engelmannii*) after stump harvest with different site preparation methods. Lodgepole pine performed better on the most intensive site preparation plots, whereas hybrid spruce tended to decrease height growth at year 10. More support comes from Egnell (2016) who reports increased growth in Scots pine and decreased growth in Norway spruce following stump and slash harvest based on data from another Swedish experimental series. Thus, the main reason for these species-specific responses might be that pine as a pioneer species is favored by disturbance whereas spruce, as a secondary species, is more adapted and competitive on undisturbed sites. Together these results suggest that species specificity in response should be added to site specificity in order to identify sites where increased harvest intensity will affect tree growth and thereby carbon sequestration. However, given the limited evidence in our data, further studies are required to confirm the observed trends in species-specific responses to stump and slash harvest.

5. Conclusions

We compared C pool data in the humus layer and mineral soil to 10 cm depth, and the tree biomass after conventional clear-cut and stem-only harvest, with an additional stump and/or slash harvest in eight 32–39 year old Norway spruce and Scots pine stands across Sweden. Based on our results, we conclude that:

- Slash and stump harvest, alone or in combination, had no significant general effect on the total, tree or soil C pool. This result suggests that neither stump nor slash harvest may cause a large-scale C depletion over all site types.
- There was no significant species-specific effect of slash and/or stump harvest on C pools. However, the total C pool of slash and slash + stump harvest treatments tended to be reduced in Norway spruce stands and increased in Scots pine stands in relation to stem and stump harvest, indicating a potential for species-specific responses to harvest treatments.
- The lack of general treatment effects might be due to contrasting site-specific responses. However, limitations in the experimental study design did not allow for separating potential site-specific effects of slash and/or stump harvest. Improved knowledge on site-specific responses with respect to harvest effects on the forest C pool could help guiding management toward increased C sequestration.

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III

forests

Article

Stand Volume Production in the Subsequent Stand during Three Decades Remains Unaffected by Slash and Stump Harvest in Nordic Forests

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Abstract: The renewable energy policies of the European Union rely on forest biomass in achieving climate mitigation targets. In Sweden, where secondary residues from the forest industries are fully utilized, primary residues following harvest such as stumps and slash offer a potential as an additional biomass source. Stump and slash harvest may, however, have adverse effects on site productivity due to increased nutrient loss from the site which could negatively impact the stand volume production of the subsequent stand. Stand volume production is also affected by seedling survival, seedling input from natural regeneration and management of the regenerated stand. In this study, we evaluate the effects of stump and slash harvest on stand volume production of the subsequent stand based on data from eight experimental sites across Sweden planted with Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* (L.) Karst.) over period of 31–34 years after clearcut with (1) traditional stem-only harvest; (2) stem and stump harvest; (3) stem and slash harvest; and (4) stem, stump and slash harvest. With the goal to explain treatment differences in stand volume production, treatment effects on site productivity estimated through initial height growth (10–19 years after planting), seedling survival, and input of seedlings through natural regeneration were also analyzed. We found that stand volume production was higher following stump harvest as compared to slash harvest, but stand volume production for the more intense harvest treatments (2)–(4) did not differ from stem-only harvest (1). Initial height growth (i.e., site productivity) did not differ between treatments, but followed the trend in stand volume production with (2) > (4) > (3) > (1). Survival of planted seedlings was not affected by the treatments, whereas natural regeneration after 5 years was significantly increased after both treatments including slash harvest (3) and (4) in comparison to stem-only harvest. However, since most of that natural regeneration was removed in subsequent pre-commercial thinnings, this initial increase did not affect stand volume production. The absence of a significant interaction between treatment and species planted for all independent variables tested suggests that there were no species related response differences. Since the experimental design did not allow for site-level analyses, we cannot exclude the possibility that site-specific harvest treatment effects might have masked general effects across all sites. Thus, slash and stump harvest effects at the site level need to be further studied. These results suggest, at least over a 3-decade perspective, that logging residues like stumps and slash can provide an additional renewable energy source to help achieving climate change mitigation goals in the Nordic countries without depleting the future forest biomass resource.

Keywords: forest biomass utilization; whole-tree harvest; stump and slash biomass; stand volume; soil disturbance; natural regeneration; forest management; boreal forest; seedling survival; bioenergy

1. Introduction

Driven by climate change concerns, a major outcome of the United Nations Conference of the Parties (UNCOP) 21 held in Paris in 2015, was that the participating states agreed to reduce greenhouse gas emissions with the goal of limiting global warming to less than 2 °C. One of the available strategies to reach this goal is to reduce consumption of coal, gas and oil by increasing the use of bioenergy. Consequently, the share of biofuel in energy production is projected to increase with a need to provide 100–150 EJ by 2050 [1]. In Sweden, most of the industrial residues are already utilized [2], and increased bioenergy demand requires additional biomass resources [3]. For instance, extending forest harvest to include previously unutilized biomass components such as stumps and slash may have the potential to meet some of the increased biomass demand in the future. However, the sustainability of stump and slash harvest practices have been questioned. Sustainability issues raised include its (1) potentially negative effects on site and stand productivity [4]; (2) carbon balance and thereby climate mitigation potential [5–7]; (3) contribution to soil acidification [8]; (4) impacts on biodiversity [9], and (5) impacts on water quality [10]. Although, all of these effects are important, this study focuses on impacts of slash and stump harvest in clearcut on stand volume production, site productivity, survival of planted seedlings and recruitment of seedlings through natural regeneration.

Local site productivity is driven by availability of nutrients, water, and light [11–13]. Site productivity on upland sites in the temperate and boreal zones are typically nutrient limited, with nitrogen being the most important limiting nutrient [14]. Since, the amount of nutrients extracted increases substantially after slash and stump harvest [15–19], subsequent site productivity might be negatively affected. Given that more nutrients are stored in slash than in stumps and coarse roots [20,21], effects on site productivity may be more severe following slash harvest. Slash left on site can also have a mulching effect thus potentially reducing competing vegetation and affecting decomposition conditions resulting in more available nutrients [22,23]. This could further amplify the effect of slash harvest on site productivity. In the case of stump harvest, associated soil disturbance might stimulate soil mineralization at the same time as potentially competing vegetation is buried under soil and killed. This might result in increased nutrient availability following stump harvest which could counteract the impact of additional nutrients removed with the stumps [24]. Conversely, slash harvest has been reported to reduce site productivity estimated through height growth of planted seedlings [25,26], whereas stump harvest appears to have limited impacts [27].

Besides site productivity, impact on regeneration success (i.e., planted seedling survival) is another factor that may be affected by stump and slash harvest. Previous studies have shown that disturbing and exposing mineral soil improves seedling survival [28,29]. Stump harvest is suggested to have effects similar to site preparation by disturbing and exposing mineral soil. Hence, stump harvest might improve seedling survival [30,31]. Tamminen and Saarsalmi reported increased seedling survival after slash harvest in four out of six sites [32]. That, however, was in disagreement with Smolander et al. [33], who found decreased number of seedlings after slash harvest, suggesting a site-specific response. Thus, evidence is contradictory about seedling survival after slash harvest and needs more study to understand its impact on stand volume production individually and in combination with stump harvest.

Another factor that may impact stand volume production is recruitment of seedlings through natural regeneration. Stump harvest disturbs the soil surface resulting in more exposed mineral soil [24]. Previous studies suggested that exposed mineral soil provides favorable conditions for seed germination [34,35]. It is also possible that slash left at a harvested site inhibits natural regeneration through its mulching effect [4]. Increased natural regeneration following slash harvest has been reported by McInnis and Roberts [36]. In addition, higher stem density has been reported after slash harvest in comparison to control [37] and somewhat higher after stump harvest [38,39]. Increased natural regeneration increases the total seedling recruitment and could therefore enhance stand volume production which may counteract a decrease in site productivity caused by additional nutrient removal with harvested slash and stumps.

Pine as a pioneer species is suggested to be more adapted to disturbance and can grow on most sites, including poor and dry sites. In comparison, spruce as a late-successional species is less adapted to disturbance and is more nutrient demanding [40,41]. Consequently, tree species might further modify slash and stump harvest treatment effects. For instance, Egnell and Leijon [42] found that seedling survival increased following slash harvest in Scots pine plantations, but had no effect in Norway spruce plantation. In contrast, Tamminen and Saarsalmi [32] reported increased seedling survival after slash harvest for Norway spruce, and no effect for Scots pine. Differences between spruce and pine have also been reported for height growth [43], seedling survival [39] and standing volume [30]. Thus, slash and stump harvest treatment effects need to be further investigated for different species.

To date, no empirical study has analyzed the individual and combined effects of slash and stump harvest on the site productivity, seedling survival, natural regeneration, and stand volume production of the subsequent stand. Here we use an extensive dataset based on an experimental series established on eight forest sites across Sweden in 1978–1980. Four different harvest intensities were applied at conventional clearcuts including (1) traditional stem-only harvest; (2) stem and stump harvest; (3) stem and slash harvest; and (4) stem, slash and stump harvest. Our main objective was to study the individual and combined effects of slash and stump harvest on production of the subsequent stand. This analysis was broken down into analyses of treatment effects on (1) stand volume production after 31–34 years, (2) site productivity (estimated through early tree height growth (i.e., height measured 10–19 years after planting)), (3) survival of planted seedlings, and (4) recruitment of natural regeneration. Since the experimental series included both Scots pine and Norway spruce plantations, analyses also included a species effect. Our hypotheses were that:

- Stand volume production and site productivity increases after stump harvest due to increased nutrient availability as a result of soil disturbance but decreases after slash harvest as the nutrient rich needles and branches are removed;
- Survival of planted seedlings increases after stump harvest due to increased nutrient availability and reduced vegetation competition;
- Recruitment of trees through natural regeneration increases after both stump and slash harvest, resulting in an even higher increase after combined stump and slash harvest. This increase is due to greater mineral soil exposure and reduced vegetation competition after stump and slash harvest.

2. Materials and Methods

2.1. Study Sites

This study explored data from eight experimental sites across Sweden, representing different climate and site productivity (Table 1). The original stands at these sites included Scots pine and Norway spruce dominated stands and mixed conifer stands. After clearcutting of the stands, slash and/or stump harvest experiments were established between 1978 and 1980. Prevailing soil types were mesic sandy-silty tills with an established haplic podzol (spodosol) at the study sites, although the E-horizons were poorly developed at the Tagel, Remningstorp and Ekenäs sites.

Table 1. Location and characteristics of the experimental sites and information about the former stand and the new stand including silvicultural measures applied over the study period according to [44].

Study Site	Tagel	Remningstorp	Norduppland	Rackasberget	Ekenäs	Garpenberg	Svartberget	Kvisslevägen
Former Stand								
Species composition (%) [a]	0, 90, 10	50, 50, 0	70, 30, 0	0, 100, 0	80, 20, 0	50, 50, 0	10, 90, 0	40, 60, 0
Age	90	70	95	125	95	100	115	120
Growing stock (m^3 ha^{-1})	400	280	240	280	220	230	180	210
Site Characteristics								
Latitude (N)	57°02′	58°25′	60°25′	60°35′	58°55′	60°20′	64°15′	62°45′
Longitude (E)	14°24′	16°35′	17°35′	12°35′	13°40′	16°15′	19°50′	15°45′
Altitude (m a.s.l.)	185	140	30	530	50	225	250	410
Temperature sum [b]	1324	1278	1250	821	1324	1092	834	791
Site index (H_{100}) [c]	32	30	26	20	26	24	22	20
Nitrogen deposition (kg N ha^{-1} yr^{-1}) [d]	10–12	8–10	2–4	6–8	4–6	4–6	<2	2–4
Soil texture	Sandy-loamy till	Sandy-loamy till	Loamy till	Sandy-loamy till	Sandy-loamy till	Sandy-loamy till	Sandy-loamy till	Sandy-loamy till
Stone content (% of soil volume)	34–38	50–60	63–72	27–45	4–38	41–70	10–79	38–60
Soil moisture	Mesic-moist	Mesic-moist	Mesic	Mesic	Mesic	Mesic	Mesic	Mesic
Treatments and Management								
Clearcutting of former stand	1978	1980	1978	1979	1979	1978	1979	1979
Stump and slash harvest	1979	1980	1979	1980	1980	1979	1980	1980
Site preparation and planting year	1981	1981	1983	1983	1981	1982	1982	1983
Age of planted seedlings, years	5	5	2	1	3	2	1	2
Planted species	Norway spruce	Norway spruce	Norway spruce	Norway spruce	Scots pine	Scots pine	Scots pine	Scots pine
Supplementary planting	1982–1985	1983–1986	1984–1986	1986–1988	1982	1983–1985	1983–1985	1985–1986
Pre-commercial thinning	1986	1988, 1991, 1993, 1996	1987, 1991	2004	1986, 1992	1987, 1990, 1993	1987, 1991, 2004	1994
Thinning	2008, 14				2005			
Latest revision of inventory	2014	2012	2013	2013	2012	2012	2013	2013
Harvested Biomass (Mg ha^{-1}) [e]								
Stumps (including roots >5 cm)	58	36	30	40	26	28	24	26
Slash [f]	46	46	38	52	32	40	22	38

[a] Species composition based on stand volume in the order of Scots pine, Norway spruce and birch (*Betula* sp.); [b] The sum of daily mean temperature in degree-days with threshold +5 °C based on Morén and Perttu [45]; [c] Estimated dominant tree height at age 100 years; [d] Based on Karlsson et al. [46]; [e] Based on standing volume and equation by Lehtonen et al. [47]; [f] At Tagel and Svartberget, only part of the needles were harvested, therefore needles are not included in the estimates for these sites. The top of the stem and bark biomass was set to 1% of the stem including bark biomass and added to the slash biomass.

2.2. Experimental Design

Based on previous site and stand characteristics, two blocks were established at each site in a randomized block design with the goal of reducing distance between plots and variation in site and stand characteristics within a block. Within blocks, four treatments were randomly assigned to 30 × 30 m plots surrounded by a 10 m buffer zone at all sites but one (Tagel), where the plot size was 30 × 40 m. The harvest treatments were: (1) stem-only (stem-only); (2) stem and stump (stump); (3) stem and slash (slash); and (4) stem, slash and stump (slash + stump).

Most of the study sites were clearcut in winter 1978–1980, when there was sufficient snow cover; however, there was no snow cover at Grävsvinsberget, Rackasberget and Tagel at the time of harvest. There was no indication that harvest without snow cover resulted in higher soil damage in comparison to other sites. In spring and summer, slash and stumps were harvested manually and mechanically, respectively, and removed from the experimental plots. At Tagel and Svartberget, the slash was allowed to dry out before harvest and transport from the plots, allowing some shedding of needles. Slash left on site in treatments was evenly distributed. Stump harvest was performed with a special stump extraction head (Pallari or Lokomo) mounted on an excavator. Between one and four years following stump harvest, all sites were mechanically prepared by harrowing or in one case by manual patch site preparation (Svartberget). Bare-root seedlings were planted at 1.8 m spacing (3100 plants per ha), with Norway spruce on half of the sites and Scots pine on the remaining sites. Norduppland, Svartberget and Kvisslevägen were replanted with a different tree species than the dominant tree species of the former stand (Table 1).

Supplementary planting was conducted multiple times to ensure that enough planted seedlings would survive for this long-term study. Natural regeneration at the study sites was relatively dense, ranging from 5511 to 80,225 trees per ha, and there was a need for pre-commercial thinning (PCT). Therefore, all study sites received a PCT after five years, and it was repeated one or several times for some of the sites. Trees removed during the PCT represented 10%–20% of the stem number with focus on removing natural regeneration. Thereafter, commercial thinning targeting smaller trees has been carried out twice at the most fertile site Tagel and once at Remningstorp, Ekenäs and Garpenberg, with focus on removing all natural regeneration and 20%–25% of the volume of the planted tree species, leading to a total mean thinning intensity 25%–28% of volume. Only stemwood was harvested during the thinnings, i.e., slash and stumps were left on the plots for all treatments (cf. Table 1).

2.3. Measurements of Stand Characteristics

2.3.1. Seedling Establishment and Growth

Seedling damage and mortality were measured annually during the first five years. We only used data on the seedling survival of the originally planted seedlings (excluding supplementary planted seedlings) after 5 years and before PCT. Natural regeneration was measured by counting all the naturally regenerated seedlings by species on the study plots five years after initial planting, but before PCT.

Seedling/tree height was measured every year during first five years and thereafter in a more irregular manner every 5–10 years during the establishment of the new stand. As a proxy for site productivity, tree height data from the last measurement when height was measured on all trees was used (depending on site at 1.2–8.9 m mean height measured 10–19 years after planting). Mean heights used in the analyses were measured before any of the thinnings. No height data was available for Rackasberget. Thereafter tree measurements were restricted to cross-calipering of the diameter at breast height (1.3 m) on all trees and height measurements of sample trees selected according to a standardized practice described by Karlsson et al. [48].

2.3.2. Stand Volume Production

All standing trees were cross-calipered at breast height (dbh, 1.3 m) 31–34 year after planting, and tree heights were measured on sample trees. Thinned trees that were included in the estimates of stand volume production were measured at the time of thinning. Stand volume estimates for Scots pine and Norway spruce were based on Brandel's volume equations [49] with diameter and height as independent variables. For trees without a height measurement, height was estimated by means of secondary tree height equations with dbh as the independent variable and based on heights from sample trees. It was decided to exclude one block from the statistical analysis of total stand volume production at Tagel, Remningstorp and Norduppland due to severe frost and browsing damages that would obscure any treatment differences.

2.4. Statistical Analyses

Dependent variables tested were stand volume production after 31–34 years, early mean height 10–19 years after planting (used as a proxy for site productivity), seedling survival rate, and natural regeneration (no of stems). The analysis of the treatment effects where done separately for each variable using a general linear models approach. Minitab 17 was used for all analyses (Minitab Inc., State College, PA, USA). The final model consisted of block (nested within species and site) set as a random effect, the fixed effects of treatment, species, site (nested within species), and the interaction between species and treatment. Site index and stem number were tested as covariates in the model, but since no significant effect of them was detected, they were omitted from the final model:

$$Y = T + Sp + Si(Sp) + B(Sp; Si) + T \times Sp + E \quad (1)$$

where Y is the dependent variable, T is treatment, Sp is species, Si is Site, B is Block and E is the error term. Given the lack of a significant species effects no statistical analyses were performed at the species level. However mean values for Scots pine and Norway spruce are presented in the result section.

To separate significant differences between treatment means, Tukey's pairwise comparisons test was used as a post hoc test ($p \leq 0.05$). In this study, we defined any result with p between 0.05 and 0.10 as a 'trend'. Results were presented relative to the stem-only harvest treatment which was considered as the control treatment.

3. Results

3.1. Stand Volume Production

The statistical analysis revealed a treatment effect on stand volume production (p = 0.01). The post hoc test showed that stand volume production was higher after stump harvest as compared to slash harvest. Although not statistically different compared to stem-only harvest, total stand volume tended to be higher after stump (12%, p = 0.06) and stump + slash harvest (10%, p = 0.06) (Table 2).

Table 2. Stand volume production (m^3 ha^{-1}) during 31–34 years for stands planted after additional harvest of stumps, slash, both stumps and slash relative to the control treatment where only the stem wood was harvested leaving stumps and slash behind.

Treatment	Spruce		Pine		All Sites		*p*-Value
	Mean	SE	Mean	SE	Mean	SE	
Stem-only (control)	158	56	180	19	172	23	
Stump	161	44	211	16	192	20	
Slash	134	53	184	16	165	23	
Stump + Slash	159	48	208	15	189	21	
Post-hoc test							
Stem-only vs. Stump							0.06
Stem-only vs. Slash							0.68
Stem-only vs. Stump + Slash							0.06
Stump vs. Slash							0.02
Stump vs. Stump + Slash							0.99
Slash vs. Stump + Slash							0.36

SE is standard error for spruce (n = 5), pine (n = 8) and all sites (n = 13) and p-values for an analysis of variance for all sites and for the post-hoc test comparing treatment means. The statistical analysis did not reveal any tree species effects. Therefore no statistical analyses were performed for the species level data presented in the table.

3.2. Height Growth

Our results indicated a significant treatment effect on early mean tree height, here used as a proxy for site productivity, 10–19 years after planting (p = 0.03). Despite this, and due to the more conservative post hoc comparisons test, no significant differences between treatment means were revealed. Although not statistically different, compared to stem-only harvest, the mean tree height 10–19 years after planting over all sites tended to be 5% (p = 0.052) higher after stump harvest (Table 3).

Table 3. Mean height (m) 10–19 years after planting for seedlings planted after additional harvest of stumps, slash, both stumps and slash, relative to the control treatment where only the stem wood was harvested leaving stumps and slash behind.

Treatment	Spruce		Pine		All Sites		*p*-Value
	Mean	SE	Mean	SE	Mean	SE	
Stem-only (control)	3.24	0,90	2.95	0.49	3.06	0.36	
Stump	3.35	0.65	3.12	0.49	3.22	0.28	
Slash	3.26	0.88	2.90	0.43	3.07	0.43	
Stump + Slash	3.77	1.06	2.90	0.48	3.17	0.52	
Post-hoc test							
Stem-only vs. Stump							0.052
Stem-only vs. Slash							1.00
Stem-only vs. Stump + Slash							0.89
Stump vs. Slash							0.98
Stump vs. Stump + Slash							0.99
Slash vs. Stump + Slash							0.88

SE is standard error for spruce (n = 6), pine (n = 8) and all sites (n = 14) and p-values for an analysis of variance for all sites and for the post-hoc test comparing treatment means. The statistical analysis did not reveal any tree species effects. Therefore no statistical analyses were performed for the species level data presented in the table.

3.3. Seedling Survival

Seedling survival after 5 years for the initially planted seedlings was not significantly different (p = 0.37) among the harvest treatments. Mean values for seedling survival rates were highest after stump + slash harvest, followed by stump harvest and slash harvest, and all three were higher compared to stem-only harvest by 6% (p = 0.38), 4% (p = 0.39) and 8% (p = 0.06), respectively (Table 4).

Table 4. Survival rates (%) after 5 years for seedlings planted after additional harvest of stumps, slash, both stumps and slash, relative to the control treatment where only the stem wood was harvested leaving stumps and slash behind.

Treatment	Spruce		Pine		All Sites		*p*-Value
	Mean	SE	Mean	SE	Mean	SE	
Stem-only (control)	49	11	79	3	64	7	
Stump	54	10	81	4	67	6	
Slash	53	9	85	3	69	6	
Stump + Slash	56	8	78	6	68	6	
Post-hoc test							
Stem-only vs. Stump							0.39
Stem-only vs. Slash							0.06
Stem-only vs. Stump + Slash							0.38
Stump vs. Slash							0.95
Stump vs. Stump + Slash							1.00
Slash vs. Stump + Slash							0.97

Survival data only includes initially planted seedlings, leaving supplementary planted seedlings out. SE is standard error for spruce (n = 6), pine (n = 8) and all sites (n = 14) and p-values for an analysis of variance for all sites and for the post-hoc test comparing treatment means. The statistical analysis did not reveal any tree species effects. Therefore no statistical analyses were performed for the species level data presented in the table.

3.4. Natural Regeneration

The statistical analysis revealed a significant treatment effect on the number of naturally regenerated seedlings (p = 0.002). Compared to stem-only harvest, the number of naturally regenerated seedlings tended to be greater after slash and stump + slash harvest by 43% (p = 0.051) and 37% (p = 0.10), respectively (Table 5). The number for naturally regenerated seedlings was not significant different between stump harvest treatments and stem-only harvest treatment.

Table 5. Sum of naturally regenerated seedlings (ha^{-1}) five years after additional harvest of stumps, slash, both stumps and slash, relative to the control treatment where only the stem wood was harvested leaving stumps and slash behind.

Treatment	Spruce		Pine		All sites		*p*-Value
	Mean	SE	Mean	SE	Mean	SE	
Stem-only (control)	27,135	8533	17,444	3496	22,290	4627	
Stump	21,608	5074	22,838	4166	22,223	3175	
Slash	32,664	5715	31,024	6680	31,844	4252	
Stump + Slash	26,653	4740	34,372	6056	30,513	3846	
Post-hoc test							
Stem-only vs. Stump							0.99
Stem-only vs. Slash							0.051
Stem-only vs. Stump + Slash							0.10
Stump vs. Slash							0.09
Stump vs. Stump + Slash							0.19
Slash vs. Stump + Slash							0.98

All data retrieved before any of the pre-commercial thinnings in the experiment. SE is standard error for spruce (n = 8), pine (n = 8) and all sites (n = 16) and p-values for an analysis of variance for all sites and for the post-hoc test comparing treatment means. The statistical analysis did not reveal any tree species effects. Therefore no statistical analyses were performed for the species level data presented in the table.

3.5. Species

The statistical analyses did not show any significant interactions between species and treatment. This suggests that differences in species response did not further modify the impact of stump, slash and stump + slash harvest on the stand volume production, tree height 10–19 years after planting, seedling survival and natural regeneration.

4. Discussion

4.1. Stand Volume Production

Although not significant, stand volume production lined up according to our hypothesis with, on average over all sites, a 12% higher stand volume production following stump harvest, a 4% lower production following slash harvest, and an intermediate response for stump + slash harvest (10% increase), as compared to stem-only harvest. Although our results suggested a treatment effect on stand volume production, none of the more intense harvest treatments resulted in statistically different total stand volume production as compared to stem-only harvest. The only statistically significant difference between treatment means was between stump harvest and slash harvest, with a higher stand volume production following stump harvest. Thus, from a forest production perspective these results suggest that stumps should be harvested before slash. In practice, however, slash is harvested before stumps since it is a cheaper harvest operation [50].

Some studies have suggested negative effects of slash harvest on stand volume production [33,42,51] and positive effects following stump harvest [27,30]. Worth noting is that the statistically significant negative treatment effects of slash harvest on growth in these studies were found in spruce plantations, whereas the positive effects following stump harvest were found in Scots pine plantations. An even more common result reported from various studies is that growth of the subsequent stand is unaffected by slash and/or stump harvest [52,53]—i.e., in line with this study. This is also the case for results reported from the "Long-Term Soil Productivity study" (LTSP), with a large number of experiments scattered over North America [54]. No significant effects of slash harvest on subsequent tree growth were detected in one LTSP-study based on 15-year growth data from 9 jack pine (*Pinus banksiana* Lamb.) experimental sites [55], and similar results were reported after 15 years for 9 black spruce (*Picea mariana* (Mill.) B.S.P.) experimental sites [56]. A meta-analysis approach, including a large number of studies from all over the world, supports a growth reduction response (3%–7%) following more intensive harvest treatments [57]. Despite the strength of the large number of studies included in that meta-analysis, there are some limitations related to the data used in the analysis. Firstly, most of the included data originated from short-term (<10 years) studies. Studies in northern temperate and boreal forests suggested that it takes years up to decades before important nutrients in logging residues are available for the subsequent crop—particularly for coarse residues like branches and stumps [58,59]. Therefore a delayed treatment response should be expected [25,55]. Secondly, the data behind the analysis also included highly intense harvest treatments where slash and stumps where removed together with the forest floor (blading). Other studies support the contention that blading is negative for growth of the subsequently planted pine and spruce seedlings on most soils [55,56]. However, blading is not relevant for practical forestry practices in many areas including the Nordic countries. This makes it difficult to generalize Fleming et al. [55] and Morris et al. [56] results to slash and/or stump harvest. Achat et al. [57] also points out an exception in their data (with reference to figure S2 in their supplementary information) where growth tends to be stimulated by stump harvest, i.e., in line with other studies and the data presented here. It should also be noted that the recovery rates of stumps and slash in the experiments reported here were almost 100%, whereas recovery rates in practical operations are substantially lower. From Finland, Nurmi [60] reports slash recovery rates between 60% and 80% and Peltola et al. [61] concludes that at least one third of the slash biomass is left on site in practical operations where the slash is seasoned in small heaps on the clearcut over the summer. In a review focusing on results from boreal and temperate forests Thiffault et al. [62] report an average recovery rate of 50%. It is likely that nutrient rich fine fractions (e.g., needles) are overrepresented in retained biomass suggesting that the nutrient recovery is even lower.

In the absence of a treatment-tree species interaction ($p = 0.583$), no species-level analyses were performed. However, the species-related trends in our data are in line with other studies where stand volume production in spruce plantations tends to be negatively affected by slash harvest, whereas stand volume production in pine plantations is unaffected by slash harvest and to a larger extent positively affected by stump harvest [52]. One suggested reason for species differences in response to slash harvest is that spruce forests, due to their larger foliage biomass, hold more nutrients than pine forests. In the data presented here spruce were planted following harvest of a pine-dominated stand at the site Norduppland and pines were planted following harvest of a spruce-dominated stand at the site Svartberget. There is, however, no indications of an altered growth response pattern on these sites due to different preceding dominant tree species (cf. Figure 1). Treatment response differences between pine and spruce could also be due to species autecology with pine as a pioneer species being better suited for disturbance caused by stump and/or slash harvest in comparison to spruce that is more of a late-successional species [63].

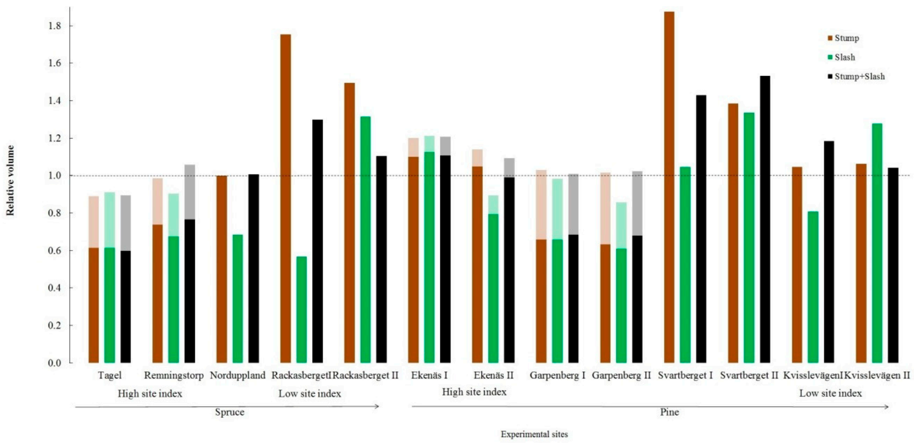

Figure 1. Block level data from eight experimental sites showing relative stand volume production during 31–34 years for stands planted after additional harvest of stumps, slash, both stumps and slash, relative to the control treatment where only the stem wood was harvested leaving stumps and slash behind (horizontal dashed line) that is set to 1. Standing volume at the last revision is colored darker and stem volume removed in thinnings lighter.

4.2. Height Growth as a Proxy for Site Productivity

The height of the dominant trees in a stand (top height) is commonly used as a proxy for site productivity [64]. Here we used early mean height development 10–19 years after planting for the planted trees as an estimate of the production potential of the site [25]. The statistical analysis showed a significant treatment effect on mean height 10–19 years after planting, but according to the post hoc test there were no statistical differences between treatment means due to the more conservative post hoc comparisons test. The mean heights 10–19 years after planting (relative to stem-only harvest) lined up in the same order as stand volume production, with the highest value following stump harvest and the lowest for slash harvest with an intermediate value for stump + slash harvest. Two experimental sites tended to have substantially larger mean heights 10–19 years after planting following stump harvest as compared to stem-only harvest. Those were the spruce site Remningstorp (+27% following stump harvest and +29% following stump + slash harvest) and the pine site Svartberget (+31% following stump harvest and +29% following stump + slash harvest). These are also the sites showing the largest, although nonsignificant, increase in volume production following stump harvest (Figure 1). Thus, the trends in stand volume production are in line with the trends in height growth/site productivity 10–19 years after planting. This supports the idea that volume production could be affected by changes in site productivity and gives some support to hypothesis, although it had to be rejected since no statistically significant differences between treatment means were detected as a result of the large variation in responses. A study based on detailed analysis of height growth from one slash harvest experimental site in northern Sweden suggests that the reduced height growth following slash harvest in Norway spruce is transient [25]. If that is a general pattern, future differences in stand volume production should not be driven by treatment-related changes in site productivity in this experimental series.

In Sweden, mechanical site preparation is common practice before planting. Site preparation causes soil disturbance that is similar to those triggered by stump harvest. Thus, positive stump harvest effects on site productivity may have been counteracted by effects associated with the soil preparation performed on all study plots in this study. Manual patch site preparation was selected as site preparation method at one site (Svartberget), while mechanical site preparation (harrowing) was used on the other sites. Therefore, it is likely that the difference in soil disturbance was larger between stump-harvested plots and other plots at Svartberget. This could be one explanation for the relatively large mean height 10–19 years after planting following stump harvest at the pine site Svartberget. However, no such explanation is valid for the spruce site Rackasberget where a similar positive response to stump harvest was observed.

4.3. Seedling Survival

Stand volume production of the subsequent stand could be affected by impacts of slash and/or stump harvest on nutrient availability, however, impacts on the regeneration success could be equally important [52]. This could explain the lack of consistency in the results from different studies [65]. Although not significantly different, seedling survival for the initially planted seedlings tended to be higher after stump harvest (Table 4), in line with our hypothesis. The trend for the slash harvest treatment also points towards a positive response as compared to stem-only harvest, in line with many other studies, not showing a statistically significant difference [52,55,56]. There was no significant interaction between treatment and planted species although the data suggest a stronger effect on seedling survival at the spruce sites. However, this is largely a result of one single spruce site (Remningstorp), with low survival rates for all treatments (12%–56%), and with particularly low survival rates on stem-only harvested plots (12% and 14% for the two blocks, respectively). Notes from the experiment point out frost as the major cause of seedling mortality. With Remningstorp excluded from the data, only moderate differences in seedling survival remained in both Scots pine and Norway spruce. Nevertheless, a small positive effect on seedling survival could counteract stand volume production losses induced by changes in nutrient availability/site productivity [56]. In a practical operation, this can be important for a sustained yield. Furthermore, productivity and quality of regeneration operations can be improved following slash and stump harvest [66]. However, in this experimental series, supplementary planting was performed multiple times to secure fully stocked stands of spruce or pine (cf. Table 1). As supplementary planting is rare in practical forestry this may have masked treatment effects relevant for practical implications of the results presented here.

4.4. Natural Regeneration

Natural regeneration increased following slash and slash + stump harvest as compared to stem-only harvest, i.e., in line with hypothesis. This could partly counteract the potentially negative effect of slash harvest on site productivity and consequently on future stand volume production (Tables 3 and 5). It is possible that the removal of slash and stumps has been positive for the recruitment of natural regeneration as it has exposed suitable micro sites for seed germination on exposed mineral soil. Although stump harvest resulted in a higher number of naturally regenerated seedlings, this increase was not significantly different compared to the stem-only harvested plots. Considering that stump harvest results in soil disturbances with the potential to favor natural regeneration this result was somewhat unexpected. It is possible that the relatively intense mechanical site preparation (harrowing) applied over all treatments overshadowed a positive effect by the stump harvest. This is supported by the fact that there were substantially more (64%) naturally regenerated stems on stump harvested plots at the only site where a more moderate manual site preparation was applied

(Svartberget). Further support comes from a study by Karlsson et al. [37] in which slash removal increased the number of naturally regenerated seedlings somewhat on control plots not receiving site preparation, whereas the increase was substantial following mechanical site preparation (mounding), and with the highest number of naturally regenerated seedlings found on slash harvested mounded plots. From a forest management point of view this observation is not so important since slash is, for practical reasons, harvested as well on sites where stumps are harvested. Increased input from natural regeneration on clearcuts is also reported from survey studies in Finland [38,39], where stump harvest had been practiced on a commercial scale.

Although natural regeneration increased significantly after slash and stump + slash harvest treatments in this study, it contributed to only about 3% of the stand volume production, when estimated after a growth period of 31–34 years. Thus, the natural regeneration modified the harvest treatment effects on stand volume production only marginally in this experimental series. The management strategy of the input from natural regeneration is critical for its contribution to total stand volume production. In this experimental series most of the natural regeneration was removed in multiple pre-commercial thinnings and first commercial thinning to promote the development of the planted seedlings (cf. Table 1). Together with the multiple supplementary plantings, this helped assure well-stocked and almost pure stands of the planted tree species on the plots. This opens up the question on how relevant these results are for practical forestry, where supplementary planting rarely is practiced and pre-commercial thinning usually is not carried out multiple times. Data from the Swedish National Forest Inventory gives a hint: out of 400 permanent plots regenerated with Scots pine and 311 plots regenerated with Norway spruce in 1983–1989, 35% of the pine plots and 40% of the spruce plots had developed into different species mixtures or forests dominated by another tree species 25 years later [67]. Saksa [39] also showed that only 30% of the subsequent stands were pure conifer stands following stump harvest and one pre-commercial thinning, whereas it was 50% for stem-only harvested sites in practical operations in Finland. This suggests that in practical forestry changes in input from natural regeneration may play a more important role for stand volume production than in experiments like the experimental series presented here. A study based on four Norway spruce sites in Finland by Tamminen and Saarsalmi [32] gives some support to this by showing no treatment effect of slash harvest on 10-year biomass production of the planted spruce seedlings. But if also the naturally regenerated seedlings were accounted for, biomass production was significantly larger following slash harvest as compared to stem-only harvest. These are, however, short term results. The potential future impact of that natural regeneration will depend on how the stand will be managed. Note that natural regeneration in Nordic forests and in the results presented here is dominated by birch species (e.g., [37,39]), and forest owners species preferences have to be taken into account. If a majority of the forest owners will promote planted conifer species rather than naturally regenerated birches, the birches will be cut in the pre-commercial thinning or early thinnings, as in the experiments presented here, and thereby contribute less to stand volume production.

Management of natural regeneration in stand can also have an impact on the results by altering the planted seedlings exposure to competition for nutrients, water and light. Particularly if pre-commercial thinning comes in later during stand establishment and the production in the removed trees is not accounted for in the analyses. This could result in both reduced growth and mortality for the planted seedlings and hence, in a negative effect on future forest production following slash harvest. This hold true also for practical operations. The ambitious planting and pre-commercial thinning regimes in the experimental series analyzed here most likely eliminated such an effect. This could explain the lack of negative effects of slash harvest on stand volume production in this study. Reported negative effects on stand volume production in other studies could then partly be due to less ambitious and late pre-commercial thinnings.

5. Conclusions and Practical Implications

Based on our results we conclude that slash and stumps can be harvested in clearcut without significant negative impacts on future stand volume production. This is further strengthened by the fact that almost 100% of slash and stump biomass was removed in the experiments behind the study, whereas in practical forestry recovery rates are lower. From a forest production perspective, our results further suggest that stumps should be targeted before slash. However, in practice, slash is targeted before stumps because it is cheaper to harvest slash than stumps with current procurement technology. Furthermore, since slash constitutes a physical impediment for the stump harvest operation common practice is to harvest the slash on sites where stumps are harvested. New harvest technologies, however, may change these practices in the future.

The possibility to evaluate the impacts off seedling survival on future stand volume production was compromised in this study by multiple supplementary plantings in an attempt to secure fully stocked stands on the experimental plots. The ambition to maximize regeneration is likely to be higher in most experimental studies than in practical forestry. Therefore, positive or negative impacts on seedling survival could have a stronger impact on forest production in practical forestry than indicated from the experimental data presented here.

We further conclude that slash harvest, solely and in combination with stump harvest, may positively affect natural regeneration whereas no impacts from stump-only harvest were observed. It is however possible that site preparation measures applied over all treatments in this study overshadowed the stump harvest effect. In practical stump harvest operations, slash is normally harvested as well and the stump-harvest induced "site preparation" (i.e., soil disturbance) is often supplemented with additional mechanical site preparation to achieve enough suitable planting spots. Thus, in a practical context, the combined stump + slash treatment would be the most relevant treatment for comparison with stem-only harvest. Furthermore, since it is not common practice to conduct multiple pre-commercial thinnings in practical forestry, natural regeneration will likely add more to stand volume production and competition with the planted seedlings than in our study where natural regeneration was systematically removed.

It remains a major challenge to obtain statistically conclusive results from long-term field experiments studying slash and stump harvest effects on stand volume production of the subsequent stand. This is likely due to the large number of possible direct and indirect effects from (1) the different treatments themselves, (2) specific measures taken to maintain the experiments over time (i.e., supplementary planting and pre-commercial thinning removing natural regeneration) and (3) concurrent management activities on forest growth. We therefore emphasize the importance of accounting for these separate effects to be able to compare results from different studies and to develop best management practices for forestry. Future studies are encouraged to also investigate the impact of biomass removal practices on temporal dynamics of carbon and nutrient cycles for ensuring a sustainable use of forest biomass.

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The thesis examines the impact of harvesting slash and stumps on carbon (C) and nitrogen (N) pools in soil and forest stands in Sweden. Results show no negative effects on site C and N pools or stand production, even with intense soil disturbance. The study highlights the importance of comprehensive C pool analysis and practical experimental designs, suggesting that logging residues can be a renewable energy source without depleting forest resources or hindering climate goals.

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