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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].

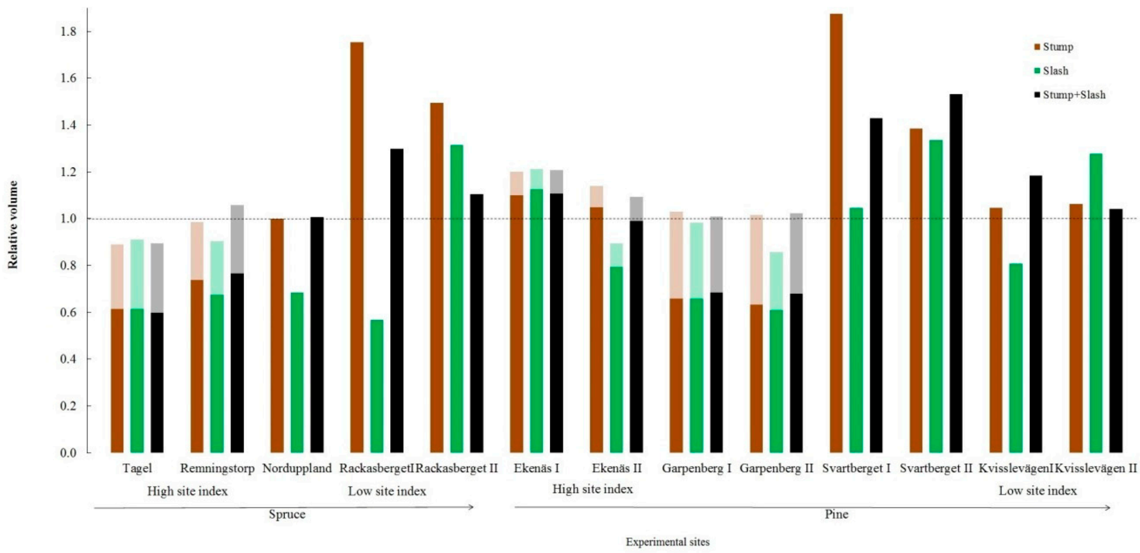

Figure 1. Block level data from eight experimental sites showing relative stand volume production during 31–34 years for stands planted after additional harvest of stumps, slash, both stumps and slash, relative to the control treatment where only the stem wood was harvested leaving stumps and slash behind (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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