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Effects of delayed regeneration and slash removal 30 years after establishment of Norway spruce

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ABSTRACT

Treatments done in the regeneration phase significantly affect seedling growth and survival. Postponing regeneration up to four years after clearfelling can reduce seedling damage and mortality caused by pine weevils (Hylobius abietis). However, under delayed establishment, competing vegetation can colonize the site, possibly reducing seedling growth. Slash removal after clearfelling can facilitate later regeneration treatments such as site preparation and planting, increasing planted seedlings' survival. But slash removal can also reduce long-term stand growth, due to nutrient removal from the site. In this study, the long-term effects of clearcut age and slash removal on volume production was evaluated 30-years after planting Norway spruce. Data was collected from a long-term experiment established between 1989 and 1993. The experiment included four sites in southern Sweden. At each site, a clearcut was made every year from 1989 to 1993. To study the slash-removal effect, slash was retained on half of the clearcut area and removed from the other half. To study the effect of clearcut age, clearcuts were planted each subsequent year until the end of the experiment, creating five different clearcut ages. Clearcut ages were compared when they had reached the same age. For the 1500 largest trees per hectare, the total volume significantly differed among clearcut ages. The youngest clearcut age had higher total volume than the oldest. There was also a significant difference between slash treatments, where slash removal lowered total volume compared to slash retention. However, delaying regeneration treatments caused a larger total volume loss than slash removal.

1. Introduction

Actions during the regeneration phase of a stand can be more or less advantageous for seedling establishment and growth. Most treatments aim to improve site conditions to facilitate establishment, increase survival and continued growth of seedlings. However, some treatments, such as postponing regeneration after clearfelling and slash removal, have two sides. On one hand, they can improve seedling survival and growth while on the other hand they can inhibit seedling establishment and growth. Delaying regeneration treatments can be used to reduce pine weevil (*Hylobius abietis*) damage and mortality of seedlings since the abundance of pine weevils declines over time following the clearcut (Nordenhem, 1989). Therefore, longer gaps between clearfelling and regeneration hereafter referred to as “clearcut age” will decrease pine weevil mortality and damage (von Sydow, 1997; Örlander and Nilsson, 1999; Nordlander et al., 2011). To minimize pine weevil damage, regeneration treatments need to be delayed up to four years (Örlander and Nilsson, 1999). Due to competing vegetation, this delay can increase competition for available water, nutrients, and light for later-planted seedlings (Sands and Nambiar, 1984; Nilsson and Örlander, 1995; Nilsson and Örlander, 1999), compared with regenerating a fresh clearcut. In Sweden, clearcuts are commonly regenerated one to two years after clearfelling (Berglund et al., 2024). This is still within the window for pine weevil damage. Therefore, treatments such as site preparation and mechanical protection against pine weevil are commonly done to minimize damage. Combined, these treatments can successfully reduce levels of damage and increase seedling survival (Petersson and Örlander, 2003; Sikström et al., 2020).

Removing slash after clearfelling can facilitate later regeneration treatments such as site preparation and planting (Saarinen, 2006). This can increase planted seedling survival (Egnell and Leijon, 1999; Thiffault et al., 2011) by creating more suitable planting spots. But slash

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removal could also negatively affect long-term stand growth. When slash is removed, nutrients are removed with it. This might reduce nutrient availability, and potentially reduce growth in the young- or mature stand. In several studies comparing whole tree and conventional harvest, slash removal reduced volume growth of the new or existing stands (Helmisaari et al., 2011; Egnell, 2016; Jacobson et al., 2017). Helmisaari et al. (2011) found reduced growth 10 and 20 years after slash removal during thinnings in Norway spruce and Scots pine stands compared to retaining slash during the thinnings, indicating that slash removal impacts could be long lasting. The decrease in volume production depended on the amount of removed slash. As more slash was removed, growth reduced further. However, the effect of slash removal on tree growth seems to vary, possibly due to site characteristics and tree species (Thiffault et al., 2011). For example, Hjelm et al. (2019) did not

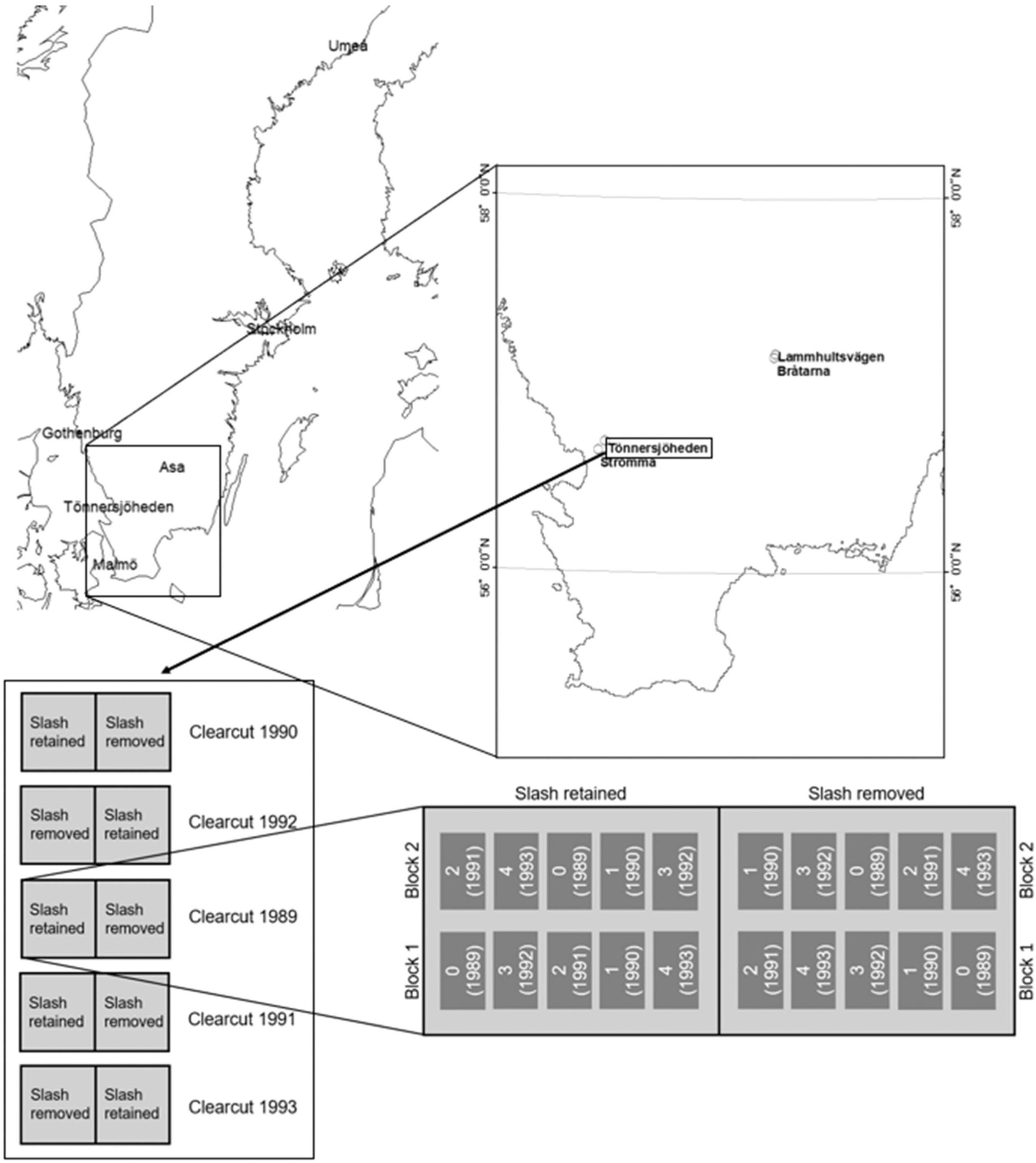

Fig. 1. The geographical location of the four sites (Strömma, Tönnersjöheden, Bråtarna and Lammhultsvägen) included in the study, as well as the design of the experiment. Five clearcuts were made in each year from 1989 to 1993 and regenerated under following years resulting in five clearcut ages (0–4). The year in the parentheses is the planting year.

find any negative long-term effects of slash removal after clearfelling on volume production in lodgepole pine, Scots pine or Norway spruce stands 18 years after establishment.

This study evaluates the long-term effects of clearcut age and slash removal 30 years after planting. In the short term, longer gap between clearfelling and planting reduced seedling growth and survival (Nilsson and Örlander, 1995; Nilsson and Örlander, 1999), mainly due to higher competition found on older clearcuts. But no significant difference was seen in seedling survival and growth between the two slash treatments. This study aims to answer the question of what the long-term effects of clearcut age and slash removal on volume production are.

The hypotheses are that older clearcut ages will have a long-term negative effect on volume production. This due to the reduced growth and survival in the early stages of stand development on the older clearcuts (Nilsson and Örlander, 1995; Nilsson and Örlander, 1999). Second, slash removal will not reduce long-term volume production. Slash removal can facilitate regeneration treatments, such as site preparation and planting, thereby increasing seedling survival, which in turn improve growth and volume production. To mimic practical forest management, 20 % of the slash was left in the slash removal treatment. This has been suggested to mitigate the negative effects of slash removal on growth and volume production since less nutrients are removed from the stand (Egnell and Leijon, 1999). Third, weather conditions during the year of planting will influence new-stand establishment which in turn might influence long-term volume production. During the period (1989–1993) when the experiment was established, a severe drought occurred from May to July in one of the years (1992), killing many seedlings planted that year and also reducing growth for seedlings planted the years before. This drought event is therefore hypothesized to cause a long-term reduction in volume production especially for the regenerations made during the drought year. To summarize, the hypotheses are as follows:

I. Regeneration on fresh clearcuts will show greater long-term volume production than on older clearcuts.
II. Slash removal will not negatively affect long-term volume production.
III. Drought during regeneration will negatively affect long-term volume production.

2. Material and methods

2.1. Experimental design

Data for this study was collected from a long-term regeneration experiment established between 1989 and 1993. The experiment includes four relatively fertile sites in southern Sweden, with site indices 30 m and 34 m (H100; Fig. 1; Table 1). At each site, a 1–4 ha clearcut was made every year between 1989 and 1993 with the aim to study the effects of clearcut age, slash removal, seedling type and vegetation management on the survival and growth of seedlings (Nilsson and Örlander, 1995). To study the slash removal effect, slash was retained on half of each clearcut area while about 80 % of the total slash mass was removed from the other half, and about 20 % was left, mainly needles and small twigs.

To study the effect of clearcut age at planting, clearcut sites were prepared with an excavator and planted the following years until the end of the experiment. For example, on the first clearcuts made in 1989 five equally large year-plots were demarcated and one year-plot was regenerated every year until the end of the experiment in 1993. The year-plots were site prepared the same year as the planting was done. For example, the plantings made in 1993 on the clearucuts made in 1989 were site prepared in 1993. The regeneration years were randomly assigned to year-plots. New clearcuts were also made each subsequent year. In 1990 a new clearcut was made on each site and these clearcuts were divided into four equally large year-plots to be planted in the coming years. This was repeated until the last year of the experiment in 1993, resulting in following planting schedule: In the first year (1989), only fresh clearcuts were planted; in the second year (1990) both fresh clearcuts and one-year-old clearcuts were planted and in the third year (1991) fresh clearcuts, one-year-old and two-year-old clearcuts were planted and so forth until 1993 when regenerations were made on clearcuts with ages ranging from fresh to four-years-old. This yielded an unbalanced experimental design, with more replications of younger clearcut ages than older (Table 2). Planting on a fresh clearcut occurred four times on each site while planting on four-year-old clearcut occurred only once at each site.

The halves of the clearcut with and without slash removal were regenerated in the same way, and separate blocks were established on the two halves to repeat the regeneration treatments in the two slash treatments (Fig. 1).

In the original experiment, effects of seedling type, insecticide treatment, herbicide, mechanical site preparation and time of planting were included as treatments within the year-plots. Year-plots were between 0.008 and 0.027 ha depending on site and included eight treatment plots with 16 planted Norway spruce seedlings, half of which were 3-year-old bare-rooted and half 2-year-old containerized. All seedlings were of the same origin, Maglehem seed orchard, and from the same seed lot. There was a total of 128 seedlings (16 seedlings x 8 treatment plots) in each year-plot. More information about the experimental design and the sites can be found in Nilsson and Örlander (1995). In this study, effects of seedling and site preparation treatments were not included. Effects of clear-cut age and slash removal after planting were evaluated on a year-plot level.

2.2. Data collection

The clearcuts in this experiment were regenerated in different years (1989–1993). For this study, data for each year-plot was collected at 20 and 30 years after regeneration and only planted seedlings were measured. The comparisons in growth and volume production in this study were thereby made at the same amount of time since planting for the different year-plots.

In each year-plot, all trees were cross calipered at 1.3 m above

Table 1
The four sites included in the study and their growth conditions. No field vegetation was found in the understory for any of the sites.

	Bråtarna	Lammhultsvägen	Tönnersjöheden	Strömma
Latitude (° N)	57.08	57.08	56.20	56.20
Longitude (° E)	14.47	14.47	13.10	13.10
Altitude (m)	245	175	85	60
Soil moisture	Mesic	Wet	Dry	Dry
Soil texture	Silty sandy till	Sandy silt	Silty sand	Silty sand
Site index (H100, m)	32	30	33	34

Table 2
Planting schedule for the study. The values in each cell of the table indicate clearcut ages. A separate clearcut was made in each year at each site and regenerated in the following years resulting in five clearcut ages (0–4). Clearcut age 0 means that the clearcut was regenerated the same year as clearfelling.

Clearcut ages (years)					
Clearcut year →	1989	1990	1991	1992	1993
Planting year ↓					
1989	0				
1990	1	0			
1991	2	1	0		
1992	3	2	1	0	
1993	4	3	2	1	0

ground to the nearest mm (DBH). In addition, height and height to first living branch were recorded for 20 sample trees in each year-plot. The five trees with the largest DBH and 15 additional trees covering the diameter range were selected as sample trees within each year-plot.

Height and DBH of the sample trees in a year-plot were used to estimate height and volume for all trees within the same plot. "Näslund's height-curve" (Näslund, 1936) was used to estimate all trees' height:

$$H = \frac{DBH^x}{(a + b \times DBH)^x} + 1.3$$

where H is tree height (in m), DBH is diameter at breast height (in cm), a and b are coefficients estimated from the sample tree data and x 3 for spruce (Pettersson, 1955).

Sample tree volumes were calculated using Brandel's (1990) volume function for Norway spruce. The DBH^2-weighted volume of sample trees was used to estimate the volume for all trees within each year-plot (Nilsson et al., 2010).

2.3. Calculations and statistical analysis

When evaluating the treatment effects on volume production all trees within a year-plot were used for the comparisons. But to understand the treatment effect on future crop trees a selection of the 1500 largest trees per hectare for each year-plot was made and additional comparisons were made for the volume produced by the 1500 largest trees per hectare.

Due to the nature of the data, hierarchical structure and imbalance in the experimental design, a linear mixed model was used to analyze the effects of planting year, clearcut age and slash treatment on the response variables using the *lme4* package in R version 4.2.2 (R Core Team, 2019). The model used were:

$$Y_{ijklm} = \mu + \alpha_i + \beta_j + \gamma_k + d_l + (d\alpha)_{li} + (d\alpha c)_{lik} + (d\alpha cf)_{likm} + e_{ijklm}$$

The response variables (Y_{ijklm}) were total volume, total volume for the 1500 largest trees per hectare, basal area and height. The fixed effects ($\alpha_i, \beta_j, \gamma_k$) in the model were planting year, clearcut age and slash treatment. The random effects ($d_l, (d\alpha)_{li}, (d\alpha c)_{lik}, (d\alpha cf)_{likm}$) in the model were (due to the hierarchical structure) site, planting year, slash treatment and block. Interactions among the fixed effects were not significant and were therefore not included in the model. Differences between slash treatments and among clearcut ages were analyzed using ANOVAs with the Kenward-Roger degrees of freedom calculation. The significance level was set to $\alpha = 0.05$ for all analyses.

Extreme values in the measured height data were identified after diagnostic plot and Shapiro-Wilk normality test indicated on non-normally-distributed residuals. Removing the extreme values resulted in the same patterns of significance for the explanatory variables as when including them. All data was therefore included in the statistical analyses despite the non-normal distribution of the residuals.

In the results the estimated mean is presented as the average value for the response variables, total volume, total volume for the 1500 largest trees per hectare and height.

3. Results

3.1. Clearcut age

There were no significant differences in volume production when including all trees among clearcut ages after 20 years ($p = 0.1898$; Table 3) nor after 30 years ($p = 0.0825$; Table 3; Fig. 2).

When selecting the 1500 largest trees per hectare for each planting year, the total volume differed significantly among clearcut ages after both 20 years ($p = 0.0098$; Table 3) and 30 years ($p = 0.0064$; Table 3; Fig. 2) of growth. After 20 years of growth clearcut age 0 had a significantly higher total volume than clearcut age 4. After 30 years of growth significant differences were found between clearcut ages 0 and 4, and 1 and 4. The clearcut ages 0 and 1 had higher total volume than 4 regardless of slash treatment.

3.2. Slash removal

The total volume produced for all trees differed significantly between the two slash treatments after both 20 years ($p = 0.0093$; Table 3) and 30 years ($p = 0.026$; Table 3; Fig. 3). Retaining slash generated the highest total volume for all clearcut ages. After 30 years, the volume produced varied from 254 m^3 ha^{-1} to 317 m^3 ha^{-1} for the five clearcut ages when slash was removed and between 279 m^3 ha^{-1} and 342 m^3 ha^{-1} when slash was retained.

There was also a significant difference between slash treatments for the 1500 largest trees per hectare after both 20 years ($p = 0.0012$; Table 3) and 30 years ($p = 0.009$; Table 3; Fig. 3). Slash removal resulted in lower total volume compared to slash retained; the difference was 22 m^3 ha^{-1} between the two treatments after 30 years.

3.3. Planting year

There was a significant difference among planting years in total volume for all trees after 20 years ($p = 0.0208$; Table 3; Fig. 4). The difference found was between planting year 1991 (159 m^3 ha^{-1}) and 1992 (131 m^3 ha^{-1}). No significant difference persisted after 30 years ($p = 0.4648$; Table 3; Fig. 4).

There was a significant difference in total volume for the 1500 largest trees after 20 years in one case; between planting year 1989 (77.2 m^3 ha^{-1}) and 1990 (101.6 m^3 ha^{-1}; $p = 0.0493$; Table 3; Fig. 4). No significant difference was found after 30 years ($p = 0.4687$; Table 3; Fig. 4).

3.4. Height growth

There were significant differences in height among clearcut ages both at 20 years ($p = 0.0215$; Table 3) and at 30 years ($p = 0.0107$; Table 3; Fig. 5). After 30 years, heights between clearcut ages 0 (16.1 m) and 4 (14.3 m) and ages 1 (16.0 m) and 4 differed significantly.

A significant difference was also found between slash treatments both after 20 years ($p = 0.0112$; Table 3) and 30 years ($p = 0.01$; Table 3; Fig. 5) of growth. With retained slash tress grew 0.7 m taller across all clearcut ages compared with slash removal. There were no

Table 3
P-values for the differences between slash treatments and among clearcut ages and planting years when conducting ANOVAs for the different variables: volume, basal area and height.

		P-value					
	df	Volume (m^3 ha^{-1}) 20 yrs	Volume (m^3 ha^{-1}) 30 yrs	Volume (m^3 ha^{-1}) 1500 st ha^{-1} 20 yrs	Volume (m^3 ha^{-1}) 1500 st ha^{-1} 30 yrs	Height (m) 20 yrs	Height (m) 30 yrs
Planting year	4	**0.0208**	0.4648	**0.0493**	0.4687	0.249	0.4657
Clearcut age	4	0.1898	0.0825	**0.0098**	**0.0064**	**0.0215**	**0.0107**
Slash treatment	1	**0.0093**	**0.026**	**0.0012**	**0.009**	**0.0112**	**0.01**

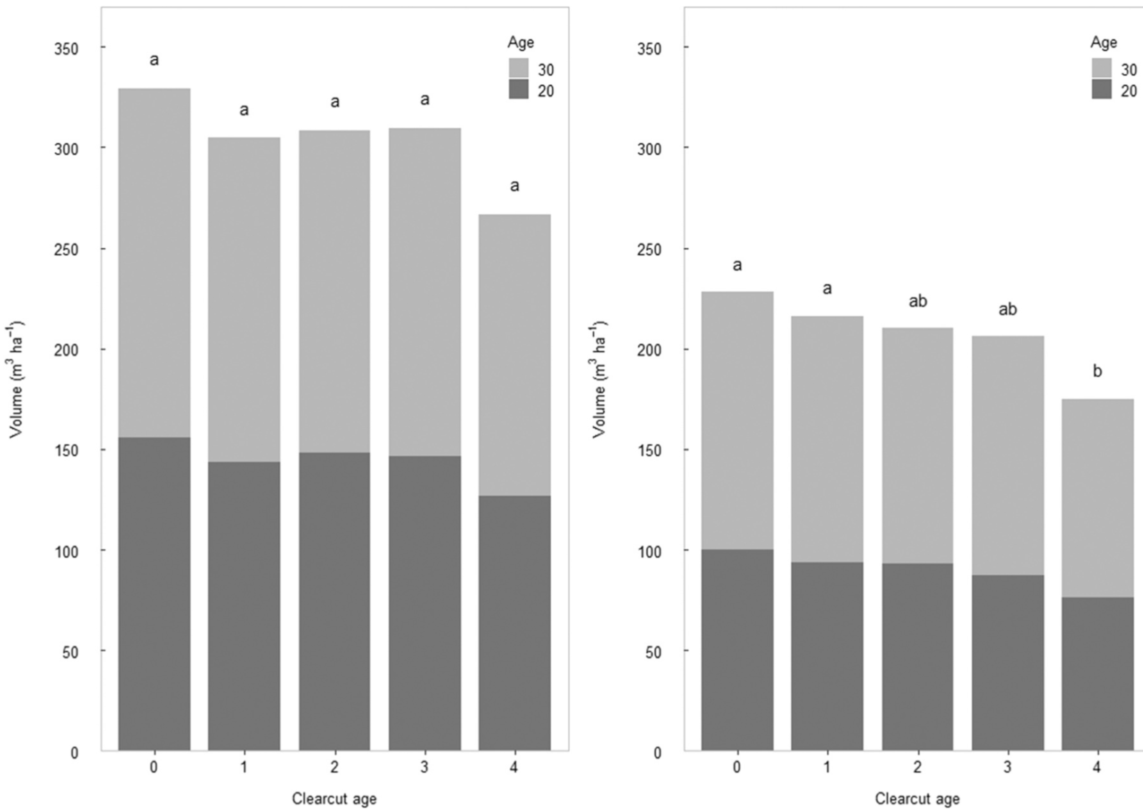

Fig. 2. Total volume 20 and 30 years after establishment for each clearcut age for all trees (left) and for the 1500 largest trees per hectare (right). Significant differences ($p < 0.05$) among clearcut ages after 30 years are indicated with different letters.

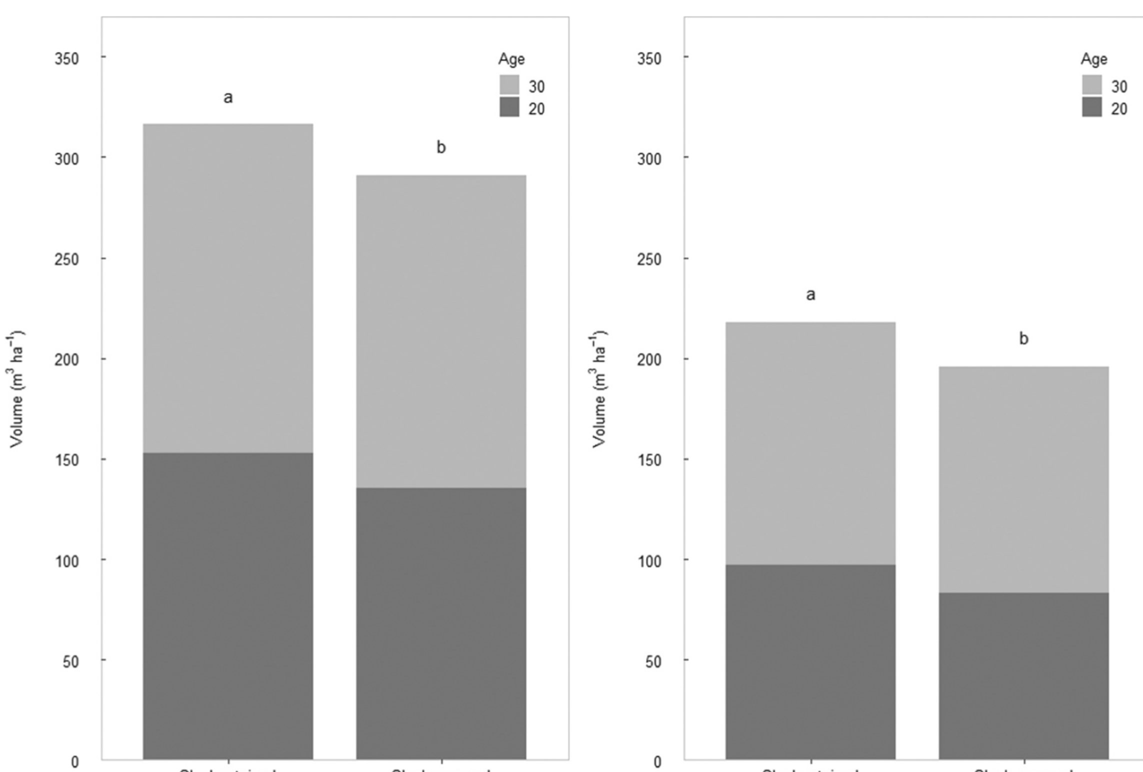

Fig. 3. Total volume after 20 and 30 years for the two slash treatments for all trees (left) and for the largest 1500 trees per hectare. Significant differences ($p < 0.05$) between slash treatments after 30 years are indicated with different letters.

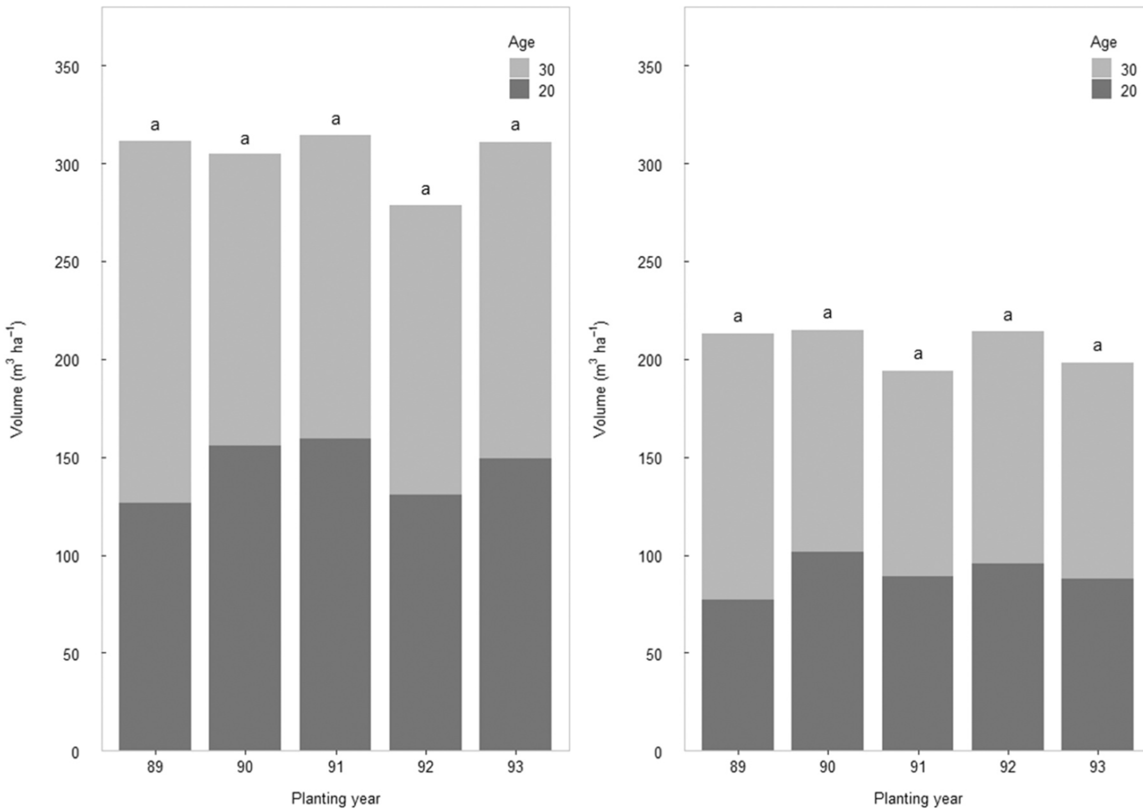

Fig. 4. Total volume after 20 and 30 years for each planting year for all trees (left) and for the largest 1500 trees per hectare. Significant differences ($p < 0.05$) among planting years after 30 years are indicated with different letters.

significant differences in height among planting years after 20 years ($p = 0.249$; Table 3) nor after 30 years ($p = 0.4657$; Table 3).

4. Discussion

Earlier results from this experiment indicated that clearcut age was an important factor for growth and survival (Nilsson and Örlander, 1995; Nilsson and Örlander, 1999). Younger clearcuts had higher survival and growth compared to older clearcuts due to less competition. But when the first results were analyzed, no differences were found between the two slash treatments. This study aimed to evaluate the longer-term effects of clearcut age and slash removal, on volume production and growth.

After 30 years there was still an effect of the clearcut age, with higher volume production found in the younger clearcut ages compared to the oldest clearcut age, when comparing the 1500 largest trees per hectare. The selection of the largest 1500 trees per hectare was made to understand the treatment effect on future crop trees. The treatment effect is likely to only be seen on the largest trees in a stand since these trees can develop without any major competition, thereby benefitting from any eventual treatment effect. Smaller trees in a stand can never reach full growth potential since they are in constant competition with other trees.

For the 1500 largest trees per hectare the volume production of the oldest clearcut age (4 years) was lower compared with the two youngest clearcut ages (0 and 1 years). Studies evaluating the long-term effect of forest regeneration treatments have identified similar patterns of volume production and growth (Nilsson and Allen, 2003; Boateng et al., 2009; Johansson et al., 2013; Thiffault et al., 2017). The early gain in growth due to reduced competition and suitable growth conditions created by site preparation or vegetation control was found to persist 18–25 years after establishment. In two of the studies (Nilsson and Allen, 2003; Johansson et al., 2013), the difference in volume production (between site preparation and no site preparation or more intense site preparation compared to less intense site preparation) was mainly explained by less competition between seedlings and other vegetation in the establishment phase. This was also the main reason for the early differences in survival and growth in the experiment this study is based on (Nilsson and Örlander, 1995; Nilsson and Örlander, 1999). It could therefore be suggested that the difference in volume production 30 years after establishment is partly explained by the early growth conditions. Seedlings planted on the four-year-old clearcut encountered more competition from other vegetation than seedlings planted on fresh or one-year-old clearcuts (Nilsson and Örlander, 1995; Nilsson and Örlander, 1999).

The loss in volume production between the youngest clearcut ages (0 and 1 year) and the oldest cleracut age (4 years) equals a few years of growth. However, the differences in volume production between the youngest and the oldest clearcut ages could potentially be larger if including the direct loss which the years of waiting result in. If the comparisons were made with the same year instead of at the same age, as done in this study, the oldest clearcut age would have a direct loss of four growing seasons compared to the youngest. This because the youngest clearcut age (0 years) reaches 30 years of growth 30 years after clearfelling, while the oldest clearcut age (4 years) only reaches 30 years of growth 34 years after clearfelling.

The design of this experiment was unbalanced, resulting in more observations for, and thus more certainty about, the younger clearcut ages than the older ones. However, the statistical analysis used a mixed model that accounted for the imbalance in the number of replications among clearcut ages.

The two slash treatments did not differ in early-stage survival and growth. But 30 years after establishment, the picture was different. Slash removal reduced volume production by 22 m^3 ha^{-1} for the 1500 largest trees compared to slash retention. The delayed effect of slash removal might be explained by seedlings' and trees' nutrient requirements. At age 30, the growth rate is much higher than in the initial phase of

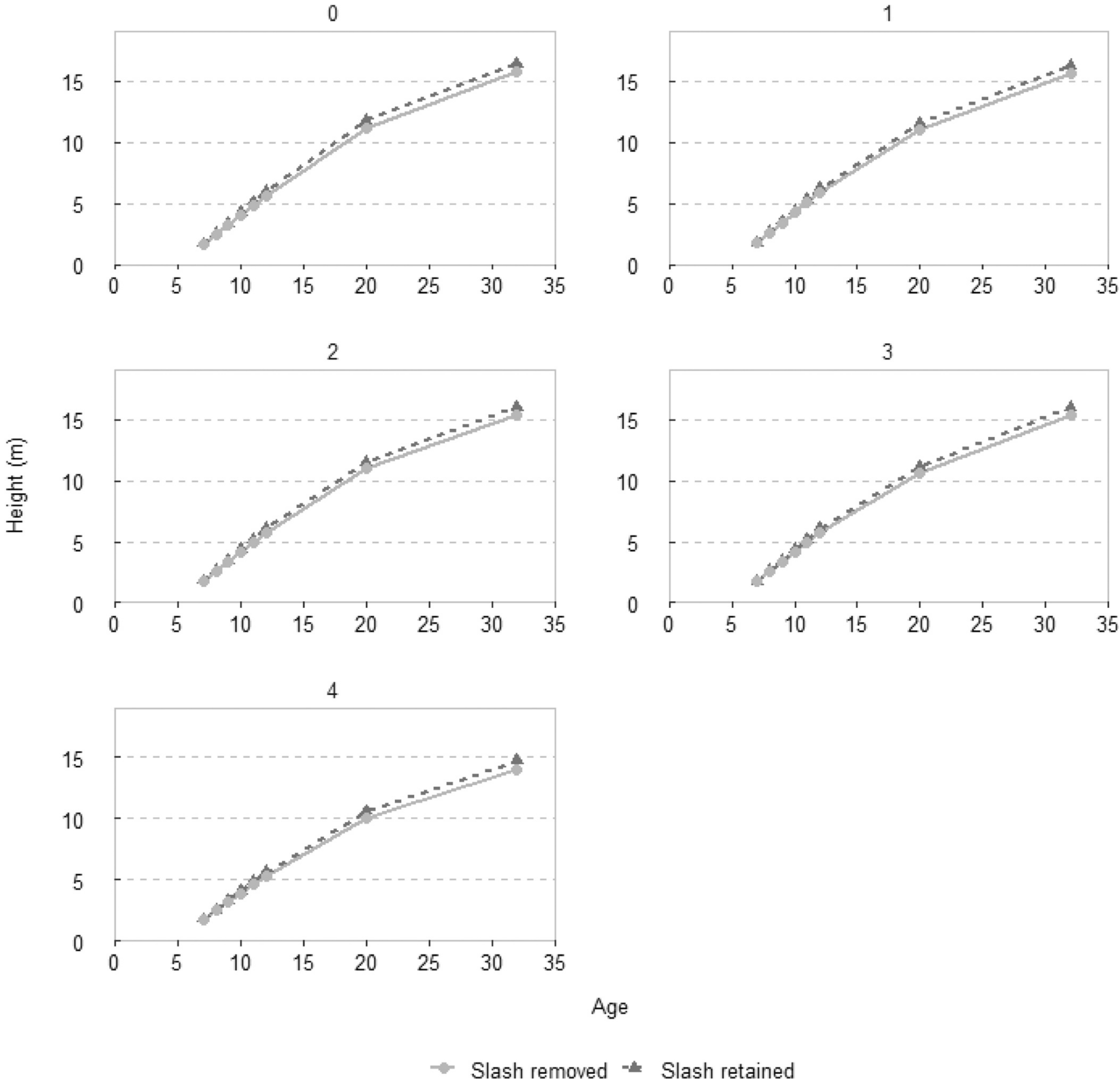

Fig. 5. Height growth for each clearcut age (0–4 years) and slash treatment.

seedling establishment, which requires more nutrients. This could explain why no effect was seen in the first evaluation but became clearly apparent after 20 and 30 years.

The lower growth and volume production when slash has been removed agrees with results from other studies investigating the long-term (10–30 years after establishment) effect of slash removal (Egnell and Leijon, 1999; Egnell, 2011; Helmisaari et al., 2011; Jacobson et al., 2017). All these studies found reduced growth after slash removal due to removed nutrients. When slash removal was compensated with added NPK fertilizer (Helmisaari et al., 2011), growth was the same as when slash was retained. This indicates that slash removal and nutrient loss could be related.

Other studies investigating the effect of slash removal have indicated that slash removal effects might be both site and tree species dependent (Thiffault et al., 2011). Norway spruce seems to be more sensitive to slash removal than Scots pine (Egnell and Leijon, 1999). The tree species used in this experiment helps explain the results. It should be highlighted that this study was only conducted on relatively fertile sites and the results might differ on sites with lower fertility. Egnell (2017) concluded that the growth-reducing effect of slash removal on Norway spruce might be stronger on less fertile sites than on more fertile.

The difference in volume growth over 30 years between the two slash treatments equals two years of growth at these sites. However, if slash is not removed regeneration treatments usually need to wait until the slash is dry to improve site preparation conditions and ensure suitable planting spots are created (Saksa et al., 2018).

It should be mentioned that in this study the sites were prepared using an excavator. This increases the chances of creating suitable planting spots, even in stands where slash has been retained. Continuous site preparation method is more common in practical forestry, where retained slash can interfere with creating suitable planting spots (Saksa et al., 2018). If this experiment had used a continuous site preparation method its result could have been different.

There were significant growth and survival differences among planting years when the first studies were conducted, mainly due to the drought in 1992 (Nilsson and Örlander, 1999). After 20 years of growth, significant differences in volume production among planting years were found, but disappeared by 30 years. No long-term negative effects on volume production can therefore be associated with the drought in 1992. However, in this study either ca. 4000 or 10000 seedlings ha^{-1} were planted depending on plot size. In practical forestry only about 2000 seedlings ha^{-1} are planted, which might make the effect of a drought year on long-term growth more evident.

5. Conclusions

Clearcut age had a long-term effect on volume production. As hypothesized, higher total volume was found in younger clearcut ages compared to the oldest clearcut age. The long-term effect of slash removal was opposite to the hypothesis. Slash removal reduced long-term volume production and resulted in lower total volume than when slash was retained after clearfelling. The loss equaled approximately two years of growth. However, if slash is retained, regeneration treatments commonly need to be postponed until the slash has dried to improve site preparation conditions. This study shows that regeneration treatments should be done soon after clearfelling to increase long-term volume growth. It might therefore be important to consider the loss in total volume when slash is removed in relation to the regeneration success of regeneration treatments and seedling establishment. However, the long-term effects of slash removal needs to be further investigated. To our knowledge studies made have only so far been able to evaluate the long-term effect of slash removal after at most 30 years after establishment. There is therefore a need to further evaluate the effects after a full rotation as well as the effects of repeated slash removal from a site.

CRediT authorship contribution statement

Axelina Jonsson: Writing – original draft, Visualization, Project administration, Formal analysis, Conceptualization. **Karin Hjelm**: Writing – review & editing, Supervision, Conceptualization. **Tomas Lämås**: Writing – review & editing, Supervision, Conceptualization. **Göran Örlander**: Writing – review & editing, Methodology. **Urban Nilsson**: Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

No potential conflict of interest was reported by the authors.

Data availability

Data will be made available on request.

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