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Tree growth and ground vegetation 17 years after disc trenching and pre-harvest nitrogen fertilization

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ABSTRACT

Silvicultural practices such as site preparation and nitrogen (N) fertilization are commonly used to increase growth of a stand. These practices may affect the forest ecosystem for several decades, impacting not only the trees, but also the stand structure and ground vegetation. Long-term field experiments are thus necessary to study these effects. In our study, two field experiments, Hagfors and Nissafors, established around 1980, were used to study residual effects of previous N-fertilization and disc trenching (DT) on tree growth and ground vegetation 17 years after final felling. At both sites, DT reduced tree mortality and increased individual tree growth, resulting in higher stem numbers and tree volume per hectare after 17 years. Previous N-fertilization had no significant effect on tree growth. The ground vegetation was affected by DT at both sites. At Hagfors, the most pronounced effects were a reduction in the cover of *Cladonia rangiferina*, and an increase in *Calluna vulgaris* after DT. *Cladonia rangiferina* was also negatively affected by previous N-fertilization. At Nissafors, DT caused a shift in cover of *Vaccinium vitis-idaea* to *Vaccinium myrtillus*. The impact of DT on the field layer composition appears to have been caused by the soil disturbance but also the increased shading resulting from the increased tree growth and survival. This study indicates that previous N-fertilization and DT affect the ground vegetation in the longer term. This should be considered when developing guidelines and forestry practices.

1. Introduction

To make forestry more profitable, silvicultural practices that increase tree growth are used throughout the rotation of a stand. In the regeneration phase, mechanical site preparation (MSP) is often used to increase establishment success of both artificially and naturally regenerated seedlings (Sikström et al., 2020). Depending on the management goals, the stand will eventually undergo several interventions to increase growth of the crop trees, such as pre-commercial thinning, commercial thinning, and fertilization. These silvicultural practices, however, will not only affect growth and development of the trees but also change the dynamics of the whole forest ecosystem. Since the practices applied may have effects in the long term, it is important to increase the knowledge about these effects to allow sustainable forestry to be carried out.

Plant available nitrogen (N) limits tree growth on mineral soils in boreal and nemo-boreal forests (Tamm, 1991; Bergh et al., 1999). Forest fertilization with N can, therefore, be used to increase both stem biomass and timber value growth and is often applied in the later parts of a forest rotation (Nohrstedt, 2001; Pukkala, 2017). A greater part of the added N tends to be stored in the soil (Melin and Nômmik, 1988). A build-up of soil N caused by N-fertilization may have negative side effects such as elevated N leaching following final felling and subsequent site preparation, but studies suggest varying effects (Rappe George et al., 2017; Ring et al., 2018). Furthermore, changes in vegetation composition (e.g. Strengbom et al., 2001; Olsson and Kellner, 2006; Strengbom and Nordin, 2008; Hedwall et al., 2011), and changes in soil chemistry have been found after fertilization (Nohrstedt, 2001; Högbom et al., 2001). Larsson et al. (2024) reported that, even though the effects of N-fertilization diminish over time, care should be taken to mitigate unwanted, long-term effects of N addition in boreal forests. There are reports indicating vegetation changes occurring after harvesting of previous fertilized stands (Olsson and Kellner, 2006; Strengbom and Nordin, 2008; Hedwall et al., 2013). Forest N-fertilization increases crown canopy cover, causing a reduction in the light availability at the forest floor, which usually leads to changes in the ground vegetation composition towards more shade tolerant species (Jacobson et al., 2020). After clearcutting, the number of fast-growing species, such as graminoids and

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herbs, increase at the expense of slow-growing species such as dwarf shrubs (Olsson and Kellner, 2006). The numbers of common mosses and lichens usually decrease (Kellner, 1993; Olsson and Kellner, 2006; Strengbom and Nordin, 2008), but some of these induced changes could be reversed if plant available N decreases over time (Hedwall et al., 2013).

After final felling, MSP is generally undertaken with the aim of improving site conditions for regeneration (Sikström et al., 2020). According to the Swedish Forest Agency, in 2023, MSP was carried out on 167,800 ha across Sweden, close to 90 % of the regenerated area (Skogsstyrelsen, 2024). Disc trenching (used in our study) is widely used and involves tractors or forwarders equipped with rotating discs. This method simultaneously creates different types of soil disturbance involving continuous furrows with exposed mineral soil, with a tilt on the side consisting of a mixture of mineral soil and humus (Sikström et al., 2020). Such disturbance affects water and temperature conditions, and nutrient availability, and reduces undesired competition from vegetation or other tree species, thereby improving seedling establishment (Thiffault et al., 2005; Löf et al., 2012; Johansson et al., 2013). Moreover, MSP provides significant protection against *Hylobius abietis* L. damage (Petersson et al., 2005; Wallertz et al., 2018). Seedlings planted in exposed mineral soil have significantly lower mortality compared to seedlings planted in non-prepared planting spots (Nordlander et al., 2011). In conclusion, the overall response to MSP is high initial survival and growth, but the beneficial effects of MSP seem to continue even after the initial establishment phase. Several studies have shown that the growth effects continue at least over the first 20–30 years approximately (Johansson et al., 2013; Hjelm et al., 2019; Wotherspoon et al., 2020). However, the duration and the overall impact of MSP on long-term production remain uncertain.

Although it has a positive effect on seedling establishment, concerns about the negative effects of MSP have been raised. MSP, as currently carried out, causes significant soil disturbance, with generally more than 30–40 % of the soil surface area affected (Sikström et al., 2020). Increased nutrient leaching and greenhouse gas emissions (GHG) have also been seen as potential risks after MSP. In a review of the environmental impacts of MSP by Ring and Sikström (2024), they stated that MSP affects N and carbon (C) cycling during the first few years, but has only a minor impact on GHG emissions. The authors concluded that more research is needed on the environmental effects of MSP, particularly regarding its long-term effects.

Although there is evidence that silvicultural practices, such as N-fertilization and MSP, impact both the composition of the ground vegetation and tree growth, the long-term impact and the interaction between field layer composition and tree growth have rarely been investigated concurrently. In a study by Fetouab et al. (2024), an interaction between MSP and planting density was found on the understory diversity and composition, and there is reason to believe that these changes remain over time. In our study the aim was to describe how previous N-fertilization and DT affected both the ground vegetation and the tree layer. The study was carried out at two N-fertilization experiment sites established around 1980. In 2006, the experiments were clear-felled, disc trenched and planted with Scots pine (*Pinus sylvestris* L.). The current investigation was carried out 17 years after regeneration. The experimental set-up was unique and provided an opportunity to study the long-term residual effect these silvicultural treatments have on tree growth and ground layer composition, for the individual practices as well as in combination. Based on results from the first five years (Johansson et al., 2013), the following hypotheses were tested regarding tree growth and ground vegetation composition 17 years after harvest and disc trenching:

H1. No effect of previous N-fertilization is detectable, either for tree growth or ground vegetation composition.

H2. Disc trenching increases tree growth, both for individual trees and per hectare.

H3. The relative cover of ground vegetation species differs depending on the type of soil disturbance i.e. between furrows and tilts created by disc trenching, and in the area without site preparation.

H4. No interaction between N-fertilization and disc trenching is detectable, either for tree growth or ground vegetation composition.

2. Material and methods

2.1. Site description

Two long-term field experiments originally established to study stem-volume growth of Scots pine after N-fertilization were used in this study: 165 Hagfors and 132 Nissafors (Table 1, Fig. 1). Both experiments were located in Sweden and had a similar randomized block design (n = 3).

2.2. Fertilization

The 165 Hagfors experiment was established in 1981. Besides an untreated control plot of 0 kg N ha^{-1}, N-fertilizer was applied at 150 kg ha^{-1} of N at 8, 4 or 2 year intervals, resulting in total N application rates of 450 kg N ha^{-1}, 900 kg N ha^{-1}, and 1800 N ha^{-1} (Table 1). In the following, the abbreviations 0 N, 450 N, 900 N, and 1800 N will be used. Each treatment was replicated in three study plots distributed in three blocks. Nitrogen was applied as ammonium nitrate (AN) with 1 kg ha^{-1} of boron (B) and, from 1991 onwards, as AN with the addition of lime (N-fertilizer containing 20 % dolomite).

Table 1
Description of the two field experiments 165 Hagfors and 132 Nissafors.

	165 Hagfors	132 Nissafors
Location	60°00 N, 13°42 E	57°24 N, 13°37 E
Year of establishment	1981	1977
Soil	Sandy-silty till	Sandy sediment
Soil type	Podzol	Podzol
Annual mean precipitation[a] (mm yr^{-1})	750	865
Annual mean temperature[a] (°C)	5.3	6.5
Open-field N-deposition[b] (kg N ha^{-1} yr^{-1})	3–4	5–6
Dominant tree species	*Pinus sylvestris* L.	*Pinus sylvestris* L.
Tree age	65	40–46
Site quality class (m^3 ha^{-1} year^{-1})	5.9	5.5
Number of blocks	3	3
Study plot size	30 m × 30 m	Block 1: 25 m × 25 m Blocks 2, 3: 30 m × 30 m
N-fertilization (kg N ha^{-1}) with years of application within brackets	3x150N (1981, 1989, 1997) 6x150N (1981, 1985, 1989, …2001) 12x150N (1981, 1983, 1985, … 2003)	3x150N (1977–78[c], 1984, 1989)
Other nutrients added	(see Ring et al., 2011)	(see Ring et al., 2011)
Clear-felling and slash removal	March 2006	May 2006
Disc trenching	May 2006	June 2006
Fencing	No fence around the plots	Plots fenced between 2006 and 2020–2021
Pre-commercial thinning	Broadleaves and spruces removed, date not documented	Broadleaves and spruces removed summer 2013

[a] Annual mean for the 1991–2020 reference period (Swedish Meteorological and Hydrological institute, https://www.smhi.se/data, accessed 26/4/24).
[b] N deposition measured in open field (Swedish Throughfall Monitoring Network, http://www.krondroppsnatet.ivl.se, accessed 26/4/24).
[c] Split applications of, in total, 150 N were made during 1977–1978 (Ring et al., 2011).

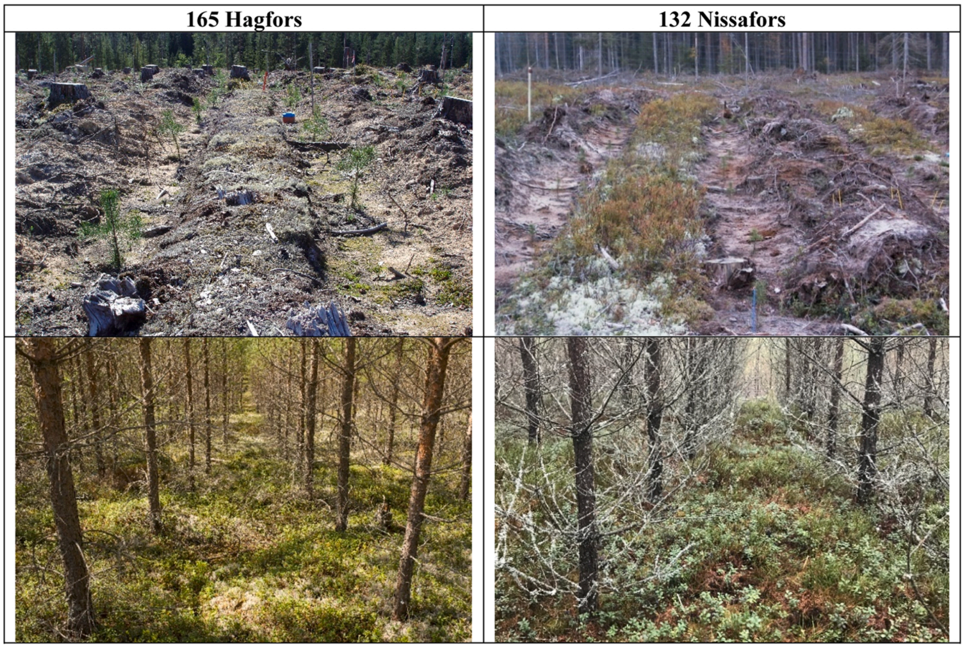

Fig. 1. Photos from 165 Hagfors (left) and 132 Nissafors (right). The upper panel illustrates the sites close to clear-felling and planting (two growing seasons after planting at Hagfors and one growing season after planting at Nissafors). The lower panel was taken after 16 growing seasons at Hagfors and 15 growing seasons at Nissafors. Photos by E Ring, K Hjelm and H Lundström.

The 132 Nissafors experiment was established in 1977. In our study, three unfertilized control plots and three plots that had received a total of 450 N were used. Ammonium nitrate was applied on four occasions (1977–78, 1984, and 1989), resulting in a total dose of 450 kg N ha^{-1} (450 N).

In our study, a sub-set of the total number of treatments in the original study was used. For a detailed description of the nutrients added to both Hagfors and Nissafors, see Ring et al. (2011).

2.3. Clear-felling, site preparation and planting

Clear-felling was carried out in early spring 2006. Before clear-felling, the study plots were divided into two MSP subplots of which one subplot was prepared with DT and the other subplot left untreated (no DT). Thus, MSP is hereafter used when referring to the main effect of MSP, and DT or no DT when referring to the respective treatment effect or treatments. During clear-felling, the harvester was not allowed to enter the study plots. No logging residues were left on the plots. Disc trenching was carried out in spring 2006 (in May at Hagfors, and in June at Nissafors) and consisted of eight rows where three types of soil disturbances were created by the rotating discs mounted at the rear of the machinery: between furrows, furrow, and tilt. On average, the furrows were 17 cm deep and 70 cm wide at Hagfors, and 6 cm deep and 63 cm wide at Nissafors (Ring et al., 2013).

Soon after disc trenching, both sites were planted with 1.5-year-old containerized Scots pine seedlings of suitable provenances. The seedlings were planted in rows with 2 × 2 m spacing in both DT and no DT subplots, with 15 seedlings in each row. In the no DT subplots the seedlings were planted directly in the undisturbed soil. In the DT subplots, the seedlings were planted in the middle of the furrows (in bare mineral soil). All seedlings were treated with insecticides (Cyper Plus 2 % at Nissafors and Merit Forest WG at Hagfors) prior to planting and again during the following spring, to prevent damage by pine weevil. In contrast to Hagfors, the experimental plots at Nissafors were fenced to protect against damage caused by larger browsing animals.

Additional information about the experimental sites and design, and previous results, can be found in: Nohrstedt (1998), Jacobsson and Pettersson (2010), Ring et al. (2011, 2013), Johansson et al. (2013), Svensson et al. (2013), Rappe George et al. (2017), and Hansson et al. (2018).

2.4. Tree measurements

In fall 2022, all the sample trees were measured. As in the previous revisions, the outermost rows in the subplots were considered buffer rows and thus not sample trees, resulting in five rows with originally 11 trees (total of 55 trees) to measure in each subplot. A total of 1320 trees were measured at Hagfors and 660 trees at Nissafors. Diameter at breast height (DBH) of each sample tree was cross calipered to the nearest mm, and height was measured to the nearest dm with a height measuring pole. Naturally regenerated trees in the subplots with a height greater than 1.3 m were registered and both DBH and height were measured on these trees. Individual tree stem volume was then estimated using Eq. (1) (Brandel, 1990):

$$V = 10^{\alpha} \times D^{\beta} \times (D + 20)^{\gamma} \times H^{\delta} \times (H - 1.3)^{\varepsilon} \tag{1}$$

where V = stem volume (dm^3), D = diameter at breast height (cm) and H = tree height (m). The coefficients were α = -1.38903, β = 1.84493, γ = 0.06563, δ = 2.02122 and ε = -1.01095.

Tree mortality was assessed using data from earlier measurements (Johansson et al., 2013). Trees that had disappeared during the period from the inventory five years after planting (in 2010) until the last inventory in 2022 were assumed dead. To convert individual tree stem volume and number of trees to values per hectare, the subplot size of 10 × 22 m was used (i.e. the subplot without buffer zones), thus the plot mean value was multiplied by 45. As a reference, this corresponded to 2 m spacing and 2500 seedlings per hectare at the time of planting.

2.5. Ground vegetation measurements

The coverage of field and bottom layer species was estimated as a percentage by visual inspection within a 50 cm × 50 cm metal frame. The measurements were made in August 2022. For the no DT subplots, six estimates were made for each plot in a pre-determined pattern (in two rows 7, 14 and 21 m from the short side of the subplot). For the DT subplots, six individual estimates were made from each of the three soil disturbance types created by disc trenching i.e. between furrows, furrow, and tilt (Fig. 2). The four different soil disturbance types were seen as individual treatments, resulting in a total of 24 estimates per study plot.

2.6. Light measurements

As a proxy for crown density, the reduction in photosynthetic active radiation (PAR) at the forest floor was measured. Light close to the ground i.e. a few decimeters above the forest floor, was simultaneously measured in the subplots and in open field using an Accupar LpP80 (Decagon Devices, Inc.). Measurements were made between 10 am and 2 pm to avoid a low solar angle and care was taken to avoid measurements when clouds blocked the sun. Canopy light reduction was measured as the relative light reduction (in percent) at the forest floor compared to the open field according to Eq. (2):

Light reduction (%) = [(open field – closed canopy)/open field] × 100 (2)

2.7. Statistical analyses

The data from each site were individually analyzed due to differences in the studied fertilization regimes. In the statistical analyses, a split-plot design was applied with N-fertilization as main plot treatment and MSP as subplot treatment using the following mixed effect model (Eq. (3)):

$$Y_{ijk} = \mu + b_i + \alpha_j + (b_i\alpha_j) + \delta_k + (\alpha_j\delta_k) + \varepsilon_{ijk} \quad (3)$$

where Y_{ijk} is the response variable, μ the general mean, b_i the random effect of block (i = 3), α_j is the fixed main plot effect of fertilization treatment j (j = 4 for Hagfors and 2 for Nissafors), δ_k is the fixed subplot effect of MSP (involving no DT and DT) (k = 2) and ε_{ijk} is the residual error term. When evaluating effects on individual trees, the number of trees in each individual subplot was considered by adding subplot id as a covariate to the model (c_l), where l = 12 in Nissafors and 24 in Hagfors. The ground vegetation data were analyzed using the same mixed model (Eq. (3)), but with the four soil disturbance types i.e. no DT, between furrows, furrow, and tilt treated as individual treatments (with six estimates per treatment, Fig. 2), resulting in k = 4 for the fixed effect of soil disturbance type (i.e. MSP) (δ_k). For multiple comparisons, the emmeans in R or lsmeans in SAS were used and separated by Tukeys test. Both SAS (vegetation data, Proc Mixed and Proc Glimmix in SAS, SAS 9.4, SAS Institute, Cary, N.C., USA) and R (tree data, lme4 package and lmer function for mixed effect models in RStudio version 2024.12.1-563) were used when analyzing the data. Residual panels were used to verify the assumption of normally distributed residuals. A significance level of 0.05 was used for all statistical analyses.

3. Results

3.1. Individual tree growth

At both Hagfors and Nissafors, previous N-fertilization had no significant effect on the individual trees, except for height at Nissafors (Table 2). In contrast, MSP affected several individual tree growth parameters, including mortality. Most of the mortality occurred during the first five years after planting, 30 % for no DT and 4 % for DT at Hagfors, and 37 % for no DT and 9 % for DT at Nissafors (Figs. 3a and 3b, respectively). Between years five and 17, mortality only increased by another 5 % on average. At Hagfors, a significant interaction between N-fertilization and MSP was found on mortality 17 years after planting (Table 2, Fig. 3a). One of the subplots of the 1800 N treatment (block 1, no DT) had no surviving planted trees, thus the overall mortality (59 %) was affected in this treatment.

At Hagfors, there was a significant main effect of MSP, showing that DT increased the overall height (Table 2, Fig. 4A). The positive effect of DT was already visible five years after planting with a difference of 25 cm; this had increased to about 100 cm after 17 years (Fig. 4A). No interaction between the treatments was found, but the highest mean height was reached in subplots with DT fertilized with 900 N (790 cm),

Table 2
p-values according to the mixed linear model (Eq. (3)) for each model factor on individual tree growth parameters (mortality, height and volume) at Hagfors and Nissafors. N = N-fertilization treatment (0 N, 450 N, 900 N and 1800 N at Hagfors, and 0 N and 450 N at Nissafors), MSP = MSP treatment (no DT and DT), and N × MSP = interaction between N-fertilization and MSP.

	p-value					
	Hagfors			Nissafors		
Factor	Mortality	Height	Volume	Mortality	Height	Volume
N	0.3307	0.5693	0.2295	0.2820	**0.0166**	0.0674
MSP	**< .0001**	**< .0001**	**0.0109**	**0.0017**	**0.0025**	0.6330
N × MSP	**0.0067**	0.1519	0.3400	0.9435	0.0591	0.1665

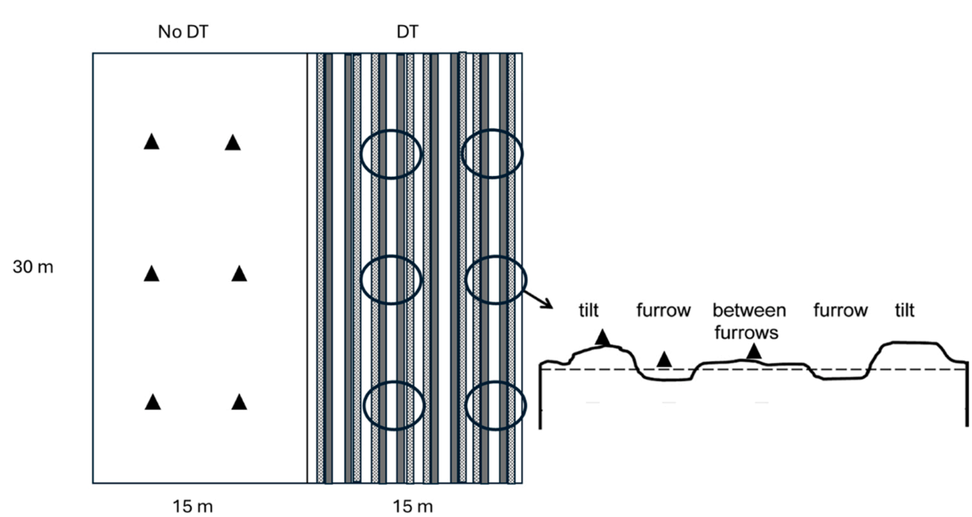

Fig. 2. Layout of vegetation sample plots (▲) in the undisturbed subplots (no DT) and in the three different soil disturbance types in the disc trenched subplots (DT, including tilt, between furrows, and furrow). DT = disc trenching.

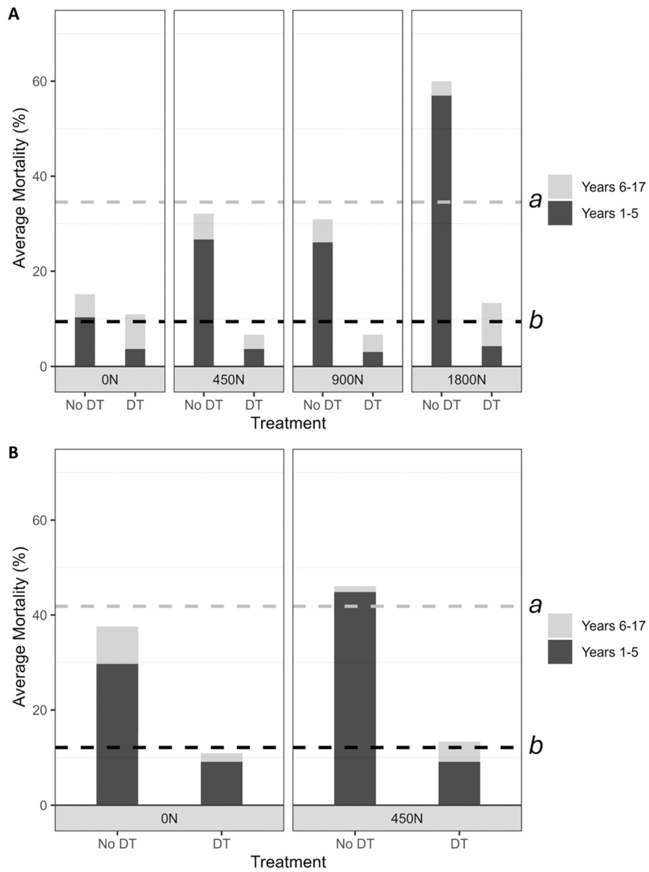

Fig. 3. Average tree mortality in % for each treatment combination at Hagfors (A) and Nissafors (B) during years 1–5 and 6–17 years, respectively. No DT = no disc trenching, DT = disc trenching, 0 N = no N-fertilization, 450 N = fertilized with 450 kg N per hectare, 900 N fertilized with 900 kg N per hectare and 1800 N = fertilized with 1800 N per hectare. Dotted lines refer to average mortality for DT (black followed by b) and no DT (light grey followed by a), where the different letters a and b indicates a significant difference.

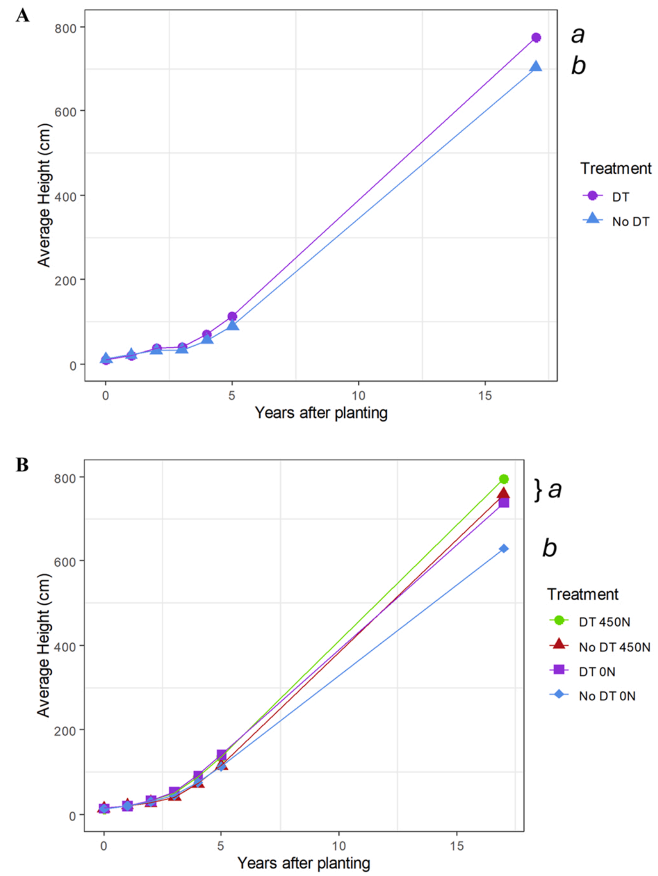

Fig. 4. Average tree height (cm) with DT or no DT across all N-fertilization treatments at Hagfors (A), and for the combination of fertilization and MSP at Nissafors (B). For both sites values are shown up to 17 years after planting. DT = disc trenching, 0 N = no fertilization, 450 N = 450 kg of N added in total). Letters a and b show statistical differences between treatments.

while the lowest was found in the no DT subplots fertilized with 450 N (690 cm).

At Nissafors, there was a significant effect on the average tree height after both N-fertilization and DT (Table 2). Fertilization with 450 N as well as DT increased tree height. There was also a tendency towards an interaction between the treatments. The highest mean height of 790 cm was found after DT and 450 N, while the lowest, 640 cm, was found with no DT and 0 N (Fig. 4B).

A significant effect of DT on individual tree volume was observed at Hagfors, but no effect of N-fertilization or treatment interactions were found (Table 2). Disc trenching increased individual tree volume, 0.0279 m^3 without DT and 0.0321 m^3 with DT. The greatest volume of individual trees was found after DT with 1800 N and the lowest with no DT and 0 N (Fig. 5A). At Nissafors, there was no significant effect on individual tree volume of N-fertilization, DT or their interaction (Fig. 5B).

3.2. Subplot tree growth (per hectare values)

No significant effect of N-fertilization was found on the number of stems or total tree stem volume per subplot when converted to volume per hectare (Table 3). MSP, on the other hand, had a significant effect on both stem number and total tree volume per hectare at Hagfors and Nissafors. No significant interactions between N and MSP treatments were found.

Due to lower mortality, the number of stems per hectare was higher after DT (Fig. 6). At Hagfors, the treatments' average stem number varied from 1522 to 2121 stems per hectare with no DT, while the corresponding numbers for the DT treatment varied from 2166 to 2333 per hectare. Some natural regeneration occurred on the sites adding to the number of surviving planted stems. The largest number of naturally regenerated stems was found in subplots with no DT combined with 1800 N, 318 trees ha^{-1}, presumably due to the large mortality that occurred in that treatment during the first five years after planting. At Nissafors, DT showed a similar pattern as in Hagfors with a higher stem number, ranging from 1348 stems with no DT to 2227 with DT (Fig. 6). At Nissafors, the DT treatment had a higher presence of natural regeneration, almost double that when compared to no DT.

As a result of more stems and larger individual trees, subplots with DT had significantly higher volume than subplots with no DT (Fig. 7). The natural regeneration did not contribute to the total volume to a large extent except for at Hagfors in the treatment 1800 N with no DT.

3.3. Ground vegetation at Hagfors

Ground vegetation 17 years after final felling and MSP at Hagfors was dominated by *Calluna vulgaris* (L.), *Vaccinium myrtillus* L., and *Vaccinium vitis-idaea* L., all members of the Ericaceae family. There was a sporadic occurrence of *Deschampsia flexuosa* (L.) Trin. and *Lutzula pilosa* (L.) Willd. The bottom layer was mainly dominated by mosses and lichens such as *Hylocomium splendens* (Hedw.) Schimp., *Pleurozium schreberi* (Brid.) Mitt., *Cetrarica islandica* (L.) Ach., *Cladonia rangiferina* (L.) Weber, *Cladonia arbuscula* (Wallr.) Flot., *Cladonia stellaris* (Opiz)

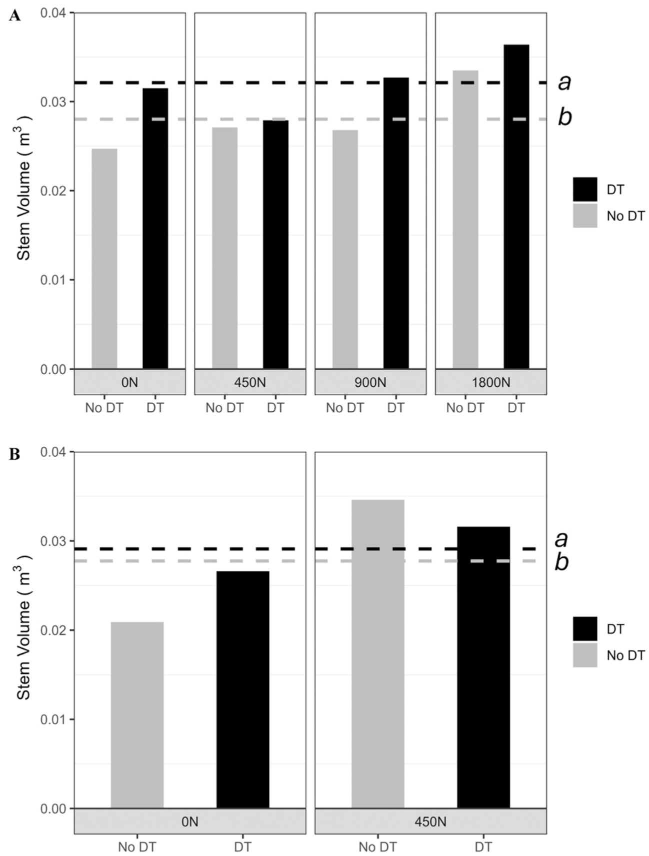

Fig. 5. Mean stem volume (m^3) for individual trees at Hagfors (A) and Nissafors (B) in the different treatment combinations. Dotted lines refer to average stem volume for DT (black followed by a) and no DT (light grey followed by b), where the different letters a and b indicate a significant difference.

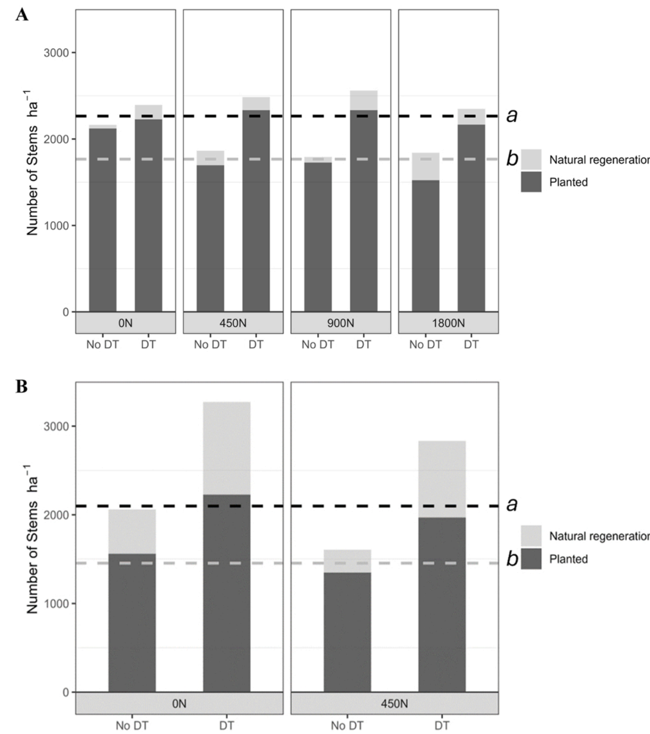

Fig. 6. Number of planted and naturally regenerated trees per hectare in the different treatment combinations at Hagfors (A) and Nissafors (B). Dotted lines refer to average number of planted stems for DT (black followed by a) and no DT (light grey followed by b), where the different letters a and b indicate a significant difference.

Table 3
p-values according to the mixed linear model (Eq. (3)) for each treatment on subplot growth parameters (stem number and total tree volume per hectare) at Hagfors and Nissafors. N = N-fertilization treatment (0 N, 450 N, 900 N and 1800 N at Hagfors, and 0 N and 450 N at Nissafors), MSP = MSP treatment (No DT and DT), and N × MSP = interaction between N-fertilization and MSP.

	p-value			
	Hagfors		Nissafors	
Factor	Stems	Volume	Stems	Volume
N	0.3736	0.5141	0.4126	0.3213
MSP	**0.0024**	**< .0001**	**0.0481**	**0.0274**
N × MSP	0.2883	0.5773	0.9257	0.4970

Ponzar & Vezda and *Dicranum* spp. The occurrence of species having a coverage of more than 1 % of the area, as well as the total coverage of both Ericaceous species and bottom layer species, was statistically analyzed, and results showed that MSP had a significant impact on all species except for *D. flexuosa* (Tables 6 and 7). *V. vitis-idaea* was negatively impacted by MSP, with the lowest coverage found in the furrow. The lichen *C. rangiferina* was affected both by MSP and previous N-fertilization (Table 4). The coverage was reduced to almost half for the soil disturbance type between furrows, one eighth for tilt and one sixth for furrow compared with no DT (Table 5). Furthermore, the coverage of *C. rangiferina* decreased with increased fertilization rates, and there was an interaction effect between N-fertilization and MSP (Table 4, Fig. 8). Species coverage that were increased by DT were *C. vulgaris* and, to some extent, also *V. myrtillus* and *H. splendens*. The coverage of *H. splendens* was positively affected by previous fertilization with a coverage of 10.7 %, 17.2 % and 14.9 % after 0 N, 450 N and 900 N, respectively, and 27.8 % after 1800 N, which was significantly different from the previously mentioned N treatments. For the Ericaceous species, the coverage of *C. vulgaris* was higher and *V. vitis-idaea* lower 17 years after the disturbance, especially in the tilt.

3.4. Ground vegetation at Nissafors

Fewer species were found in the field and bottom layers at Nissafors when compared to Hagfors 17 years after final felling and MSP. *V. vitis-idaea* dominated all plots regardless of previous N-fertilization but decreased slightly on the plots that were disturbed by MSP, while *V. myrtillus* increased, especially in the tilt and between furrows (Tables 6 and 7). Although not significant ($p = 0.057$), the coverage of *V. myrtillus* tended to increase after N-fertilization with a coverage of 10.4 % and 17.4 % for 0 N and 450 N, respectively. In contrast to Hagfors, no increase of *C. vulgaris* was detected after disturbance made by MSP at Nissafors; however, its total abundance was also rather sparse. No bottom layer species, mosses or lichens were present at Nissafors except for some sparse occurrence on one of the plots.

3.5. Light reduction

No significant effect of previous N-fertilization was found on light reduction at either site ($p = 0.95$). The light reduction was larger in the DT subplots at both sites ($p < 0.01$) (Table 8).

4. Discussion

The Hagfors and Nissafors sites provided a unique opportunity to investigate the long-term effects of different silvicultural treatments and carry-over effects across two tree generations. In the previous stand at Hagfors, Jacobsson and Pettersson (2010) analyzed the tree growth

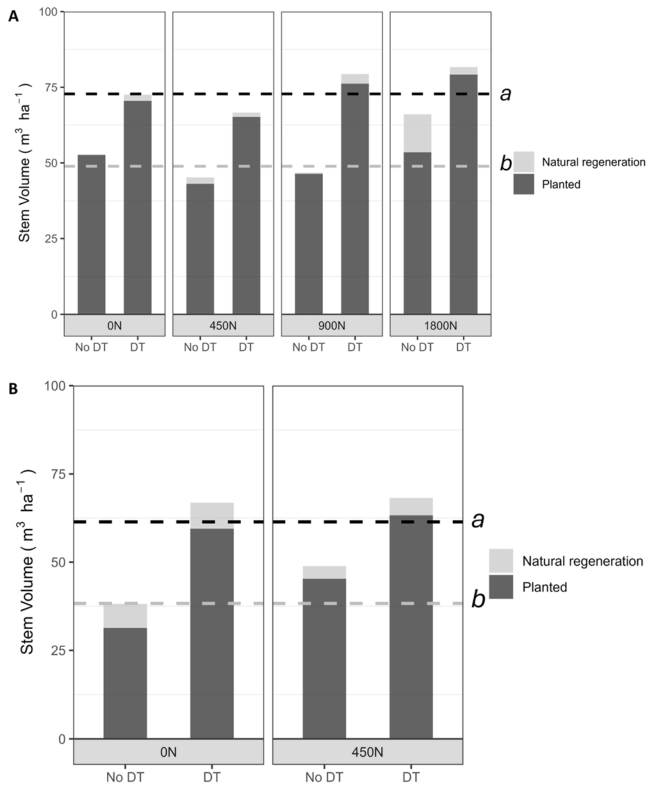

Fig. 7. Stem volume per hectare for both planted trees and naturally regenerated trees at Hagfors (A) and Nissafors (B). Dotted lines refer to average stem volume of planted trees for DT (black followed by a) and no DT (light grey followed by b), where the different letters a and b indicate a significant difference.

Table 4
p-values for ground vegetation species having a coverage greater than 1 % at Hagfors 17 years after MSP in the different treatments. N = N-fertilization treatment (0 N, 450 N, 900 N and 1800 N), MSP = MSP treatment (in this case the soil disturbance types no DT, between furrows, tilt, and furrow), and N × MSP = interaction between N-fertilization and MSP.

	Effect (p-value)		
Species	N	MSP	N × MSP
V. vitis-idaea	0.4529	**< .0001**	0.1151
C. vulgaris	0.9959	**< .0001**	0.8181
V. myrtillus	0.8969	**0.0089**	0.5003
D. flexuosa	0.1744	0.4074	0.4334
H. splendens	**< .0001**	**0.0020**	0.0841
C. rangiferina	**0.0125**	**< .0001**	**0.0083**
Ericaceous spp.	0.2494	**< .0001**	0.5933
Bottom layer*	0.1959	**< .0001**	0.0631

* Bottom layer includes all moss and lichen species found on the ground.

response following N-fertilization over approximately 20 years after the first fertilization. N-fertilization led to an increased growth for all treatments compared to the 0 N treatment, however there were no significant differences between the treatments with N addition. In the study covering the establishment phase, previous fertilization had only minor effects on the planted seedlings, but DT increased both survival and growth (Johansson et al., 2013). The field vegetation biomass was higher in the no DT subplots, indicating that DT favored seedling growth at the expense of the ground vegetation. Based on those results, we hypothesized that no effects of previous fertilization were found after clear-felling, neither for tree growth nor field vegetation composition. Seventeen years after planting, a few effects were found on the trees of previous fertilization, and the effects found could partly be explained by

Table 5
Coverage (%) of the ground vegetation species with a coverage greater than 1 % at Hagfors 17 years after MSP for different soil disturbance types across all N-fertilization levels. Row-wise values followed by different letters indicate significant differences at $p < 0.05$.

Species	No DT	Between furrows	Tilt	Furrow
V. vitis-idaea	42.8 a	20.1 bc	27.9 b	10.5c
C. vulgaris	4.2 a	30.6 b	42.1 b	36.8 b
V. myrtillus	1.3 a	4.3 b	4.0 b	1.7 ab
D. flexuosa	1.3 a	1.0 a	0.3 a	0.7 a
H. splendens	13.4 a	18.8 ab	13.2 a	25.1 b
*C. rangiferina**	30.1 a	16.9 b	3.9c	6.0c
Ericaceous spp.	49.6 a	56.9 a	74.3 b	50.1 a
Bottom layer**	46.4 a	37.3 ab	19.8 b	32.4 b

* NB! A significant interaction between NxMSP was detected (Fig. 8).
** Bottom layer includes all moss and lichen species found on the ground.

Table 6
p-values for each treatment on the coverage of the dominating species in the ground vegetation at Nissafors 17 years after MSP. N = N-fertilization treatment (0 N and 450 N), MSP = MSP treatment (no DT, between furrows, tilt, and furrow), and N × MSP = interaction between N-fertilization and MSP.

	p-value			
Factor	*V. vitis-idaea*	*C. vulgaris*	*V. myrtillus*	Ericaceous spp.
N	0.1584	0.5400	0.0573	0.2913
MSP	**0.0002**	0.2978	**0.0028**	**< .0001**
N × MSP	0.9900	0.3676	0.8871	0.9070

Table 7
Coverage (%) of the ground vegetation species with a coverage greater than 1 % at Nissafors for different soil disturbance types 17 years after MSP across all N-fertilization treatments. Row-wise values followed by different letters indicate significant differences at $p < 0.05$.

Species	No DT	Between furrows	Tilt	Furrow
V. vitis-idaea	66.33 a	35.42 bc	50.81 ab	30.86c
C. vulgaris	0.89 a	3.31 a	1.64 a	4.72 a
V. myrtillus	5.72 a	22.31 b	21.61 b	5.86 a
Ericaceous spp.	74.61 a	61.03 b	74.06 a	41.44c

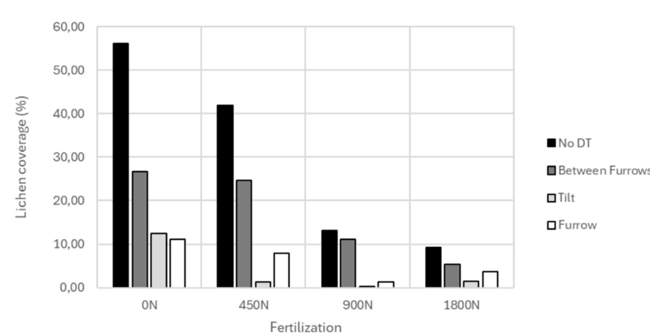

Fig. 8. Coverage of *C. rangiferina* at Hagfors 17 years after MSP for different soil disturbance types (i.e., no DT, between furrows, tilt, and furrow) and N-fertilization treatments (0 N, 450 N, 900 N and 1800 N).

other causes rather than previous fertilization. At Hagfors, the increased mortality in fertilization treatments without DT relates back to the establishment phase where, particularly one plot representing the 1800 N treatment, experienced high mortality (59 %), but higher mortality rates were also found in the 450 N and 900 N treatments. One could speculate that higher mortality after fertilization could be a result of more competing ground vegetation and interacting effects with vegetation and damaging agents such as pine weevils and large

Table 8
Reduction in PAR (%) at the forest floor as compared to open field at Hagfors and Nissafors by fertilization treatment.

Fertilization	Hagfors		Nissafors	
	No DT	DT	No DT	DT
0 N	70 %	84 %	56 %	79 %
450 N	55 %	81 %	54 %	80 %
900 N	78 %	86 %		
1800 N	53 %	83 %		

herbivores, as shown and discussed in Johansson et al. (2013). Initially, more grass (mainly *D. flexuosa*) was found on these plots but, after 17 years, only 1 % of the ground vegetation consisted of *D. flexuosa*. Competition from grass is seen as one of the major problems when regenerating clear-cuts in Sweden (Nilsson and Örlander, 1999) but, as the stand ages, this competition seems to diminish. It is also known that more vegetation, especially grass, increases the likelihood of pine weevil damage (Petersson et al., 2006).

A similar argument regarding competition could be applied for the effect of fertilization on individual tree height at Nissafors. This effect was most profound in the 450 N treatment without DT where high mortality rates occurred in the establishment phase. This resulted in fewer stems, and consequently reduced competition among the remaining stems. In stands of the same age but with different spacing, there are differences in competitive status that changes the allometry of trees (Mäkelä and Vanninen, 1998). One possible explanation could thus be that the plots were mostly composed of dominant trees 17 years after clear-felling, with few trees of lower heights in the co-dominant and suppressed tree layers. Although not significant, the trees in the no DT treatment and 450 N also had the greatest individual stem volume.

It is however a bit surprising that no effects of previous fertilization on tree growth were found, not even for a total addition of 1800 N. A drawback regarding our experiment is that the higher dosages were not repeated at Nissafors. A lack of fertilization response on tree growth could be connected to the removal of logging residues before establishing the new generation. Several studies have shown that a substantial amount of N is removed in whole tree harvest, potentially leading to reduced production later in the rotation (Thiffault et al., 2011; Merilä et al., 2014). Thus, there are several possible explanations to the lack of response to previous fertilization, revealing the complexity around possible interactions that occur between fertilization and silvicultural measures applied, site characteristics, species etc. which can lead to inconsistent responses as shown in other studies (Binkley and Reid, 1984; Pinno et al., 2012).

Regarding the field vegetation composition, there were significant effects of previous fertilization, contrary to our hypothesis H1. The largest effect was found at Hagfors on *C. rangiferina,* where the coverage decreased dramatically from more than 50 % in areas with no DT to less than 10 % after 1800 N. Since *C. rangiferina* is an important food source for reindeers, the potential negative impact of forestry measures on its distribution must be considered. Over the years, there has been a decline in forests with a high abundance of lichens, affecting the potential for reindeer husbandry (Sandström et al., 2016). Species that, on the other hand, increased after previous fertilization were *H. splendens* at Hagfors and consequently, fertilization affected the bottom layer composition by increasing the coverage of mosses and decreasing the coverage of lichens. At Nissafors, *V. myrtillus* increased after fertilization, somewhat contradictory to results found by Strengbom and Nordin (2008). Perhaps this increase can be explained by a relatively low inherent site fertility, where lichens and *V. vitis-idaea* are indicator species, and that fertilization caused a shift towards species indicating slightly higher site fertility.

The hypothesis that DT increased tree growth, both for individual trees and on a subplot level, could not be rejected. At both sites, mortality rates decreased, and growth of individual trees increased following DT, resulting in both more remaining trees due to higher survival and, in some cases, larger trees on the subplots, and thus also greater stem volumes. Although the effect on mortality was greatest in the establishment phase in the first five years after planting, it is important to confirm that this effect remains over time. The number of stems was larger after DT at both sites, due to the higher survival rate of planted trees. Natural regeneration can, in some cases, replace eventual losses. At both sites, broadleaved species and spruces were removed but the naturally regenerated pines were saved. At Hagfors, the number of naturally regenerated pine was low and, despite a larger number of naturally regenerated trees at Nissafors, the naturally regenerated pine trees were small, and did not contribute much to the total stand volume. At Hagfors, positive growth effects were found both on the individual trees and on subplot level but, at Nissafors, no effects on individual tree volume were found. Jakubowski et al. (2025) also found an increase in growth in a Scots pine stand 17 years after furrowing (similar to our disc trenching treatment). The average heights reported by Jakubowski et al. (2025) are in line with the averages of our study, but they achieved slightly greater volumes per hectare as an effect of denser stands. Effects on growth parameters on single trees can be affected by several factors, as discussed above, such as improved site conditions resulting from the treatments but also the structure of the stand in terms of spacing, crown structure and competition between dominant, co-dominant and supressed trees (Nilsson and Albrektson, 1993). More trees usually result in more standing volume, but it is important to follow the development of the stand over time and eventually apply appropriate thinnings if the end goal is larger individual trees. The importance of early establishment success on further development of a stand has been shown in other long-term studies (Hjelm et al., 2019; Jonsson et al., 2022). An investment in site preparation, in this case disc trenching, may lead to stands with a higher economic value and result in a higher likelihood of reaching the end goals (Hawkins et al., 2006; Ahtikoski et al., 2010).

A successful regeneration with more and larger stems per hectare influences not only the tree volume but also environmental factors such as light conditions at the forest floor. The light measurements indicated reduced light above the forest floor. This was probably caused by a denser tree canopy layer after disc trenching, which in turn may have affected the ground vegetation. The species composition and coverage of the ground vegetation were significantly affected by disc trenching at both Hagfors and Nissafors. At Hagfors, a clear reduction of *C. rangiferina* and *V. vitis-idaea* was seen, with *C. vulgaris* becoming the dominant species. The reduction of *C. rangiferina* was highest in the areas that had previously been disturbed during DT, i.e. the furrows and the tilts. This is also where the increase in *C. vulgaris* was highest, indicating that not only the light conditions but also the soil disturbance carried out 17 years ago impacted these species. A reduced variation in ground vegetation species composition due to denser stands has been shown in other studies (Hedwall et al., 2011). Nissafors was a slightly poorer site as regards tree production with less species abundance than Hagfors, but significant effects of disc trenching were also seen here. *V. vitis-idaea* was replaced by *V. myrtillus,* which could indicate a slight increase in soil fertility after disc trenching. The increase was highest in the tilt and between furrows. During the first years after planting, more field layer vegetation biomass was found in the plots with no DT, almost double the amount compared to plots with DT (Johansson et al., 2013). No large differences in biomass were found between furrow, tilt and between furrows. Similarly, a study from Ontario, Canada, showed that the more intense silvicultural treatments in the establishment phase, the stronger were the effects on the understory plant community with lower vegetation coverage and low taxonomic and functional diversity (Santala et al., 2025). This study was performed six years after harvest, but one can expect the differences to remain. In our study, 17 years after disc trenching, the lowest coverage of most species was found in the furrows. The removal of the organic layer down to the mineral soil had a large impact on the ground vegetation, even a substantial time after DT was carried out, both by removing initial vegetation but also by improving seedling growth and thus competition. Since the seedlings were planted in the furrows, the competition from the seedlings, and eventually the trees, had an impact. Interestingly, there was a large difference in the vegetation composition between the plots without DT and the soil disturbance type between furrows. One might expect those areas to be more similar, but apparently the disturbance from the machinery affected the whole plot, not only the area directly affected by the discs, and the initial differences in field layer vegetation biomass were also preserved over time. In our study, it should be noticed that the distance between the furrows was narrower than commonly applied in practical forestry, and the disturbed area therefore somewhat larger.

Contrary to hypothesis H4, a few interactions between previous fertilization and MSP were detected. The most pronounced interaction effect was found at Hagfors for *C. rangiferina*, which decreased after both disc trenching and previous fertilization. No such interactions were detected in the study covering the first five years at Hagfors and Nissafors (Johansson et al. 2013). It should be noted that the two sites in this experiment were average to poor in terms of soil fertility. Bognounou et al. (2024) found that soil scarification negatively affected the understory plant community in a hardwood forest in Quebec, Canada, and that the negative effects increased in combination with nutrient addition. This site was also in the boreal zone, but on other types of soils, and only after 4 years. Thus, studies of other types of forest ecosystems are essential, not only to study the short-term effects but also long-term effects since the impact might change over time.

In conclusion, disc trenching increased the volume production of stemwood biomass in the stands over the longer term, but the disturbance also affected the ground vegetation. It is therefore important to find methods that create disturbance of a level sufficient for adequate seedling establishment and further tree growth, but with reduced negative effects on the ground vegetation. Disc trenching applied in continuous rows disturbs a considerable proportion of the ground surface area (Sikström et al. 2020). Patch-wise methods, such as soil inversion and mounding, could be better alternatives to ensure tree growth with less influence on the ground vegetation (Nordin et al., 2022). More studies are needed to follow the development of forest regenerations that have undergone different regeneration treatments, and it is important not only to look at the development of the planted trees, but also the forest ecosystem as a whole and how silvicultural practices might affect it. As stressed by Thiffault et al. (2025), more research initiatives including the long-term perspective are needed to conduct sustainable forestry.

CRediT authorship contribution statement

Eva Ring: Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Lars Högbom:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Edzus Romans:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Karin Hjelm:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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