Silva Fennica vol. 56 no. 4 article id 10762
Category: research article
https://doi.org/10.14214/sf.10762

SILVA FENNICA

http://www.silvafennica.fi
ISSN-L 0037-5330 | ISSN 2242-4075 (Online)
The Finnish Society of Forest Science

Karri Uotila[1], Jaana Luoranen[1], Timo Saksa[1], Tiina Laine[2] and Juha Heiskanen[1]

Long-term growth response of Norway spruce in different mounding and vegetation control treatments on fine-textured soils

Uotila K., Luoranen J., Saksa T., Laine T., Heiskanen J. (2022). Long-term growth response of Norway spruce in different mounding and vegetation control treatments on fine-textured soils. Silva Fennica vol. 56 no. 4 article id 10762. 20 p. https://doi.org/10.14214/sf.10762

Highlights

- Spot and ditch mounding methods favoured spruce sapling development on fine-textured soils.
- Inverted and unprepared plots showed the weakest growth.
- Vegetation control suppressed the growth differences between site preparation methods.
- Vegetation control reduced the density of resprouts after early cleaning.

Abstract

Mechanical site preparation (MSP) is a common practice that precedes the planting of Norway spruce (*Picea abies* (L.) H. Karst.) in Nordic forests. Mounding has become the most used method in spruce planting in recent years. This study examined the effects of different mounding treatments (spot and ditch mounding, inversion, unprepared control with or without herbicide application) and a mechanical vegetation control (MVC) treatment done 3–4 years after planting on the post-planting growth of spruce container seedlings and their development to saplings during the first 11–13 years on two forest till soils in central Finland, one on flat terrain and other on a southwest slope. On these fine-textured soils the spot and ditch mounding methods favoured spruce saplings development. Inversion and unprepared plots showed weakest growth. On the site with flat terrain, 11 years post planting, spruce saplings were 78–144 cm (38–80%) taller and their breast height diameters were 11–13 mm (60–74%) thicker for ditch or spot mounding than for inversion or herbicide treatment. On the site with sloped terrain the differences were minor between the MSP treatments. MVC improved spruce height growth on sites which did not have intensive MSP, especially on control saplings planted on unprepared soil in herbicide and inversion treatments. On the flat terrain, MVC reduced the density of resprouts to be removed later in pre-commercial thinning. As a conclusion, spot or ditch mounding favoured the growth of spruce over inversion especially on flat terrain with fine-textured soil.

Keywords boreal forest; establishment; fine-textured soils; mechanical vegetation control; plantation; regeneration; scarification; site preparation; tree growth
Addresses [1]Natural Resources Institute Finland (Luke), Natural resources, Juntintie 154, FI-77600 Suonenjoki, Finland; [2]Metsä Forest, Revontulenpuisto 2, FI-02100 Espoo, Finland
E-mail karri.uotila@luke.fi
Received 9 June 2022 **Revised** 7 December 2022 **Accepted** 14 December 2022

1 Introduction

Norway spruce (*Picea abies* (L.) H. Karst.) is the most planted tree species in boreal forests of northern Europe (Peltola et al. 2019; Sikström 2020). Nowadays mechanical site preparation (MSP) commonly precedes spruce planting since it has been found to facilitate the planting work and expedite the survival and early growth of planted seedlings (Ritari and Lähde 1978; Örlander et al. 1990; Sutton 1993; Hallsby and Örlander 2004; Boateng et al. 2006; Nilsson et al. 2010; Wallertz and Malmqvist 2013; Wallertz et al. 2018; Hjelm et al. 2019; Sikström et al. 2020). Mounding has shown better plantation establishment than patch scarification or disc trenching (Hallsby and Örlander 2004; Saksa et al. 2005; Kankaanhuhta et al. 2009; Korhonen et al. 2010; Uotila et al. 2010; Saksa 2011; Sikström et al. 2020), and it is currently one of the mostly used methods in Fennoscandia (Peltola et al. 2019). The recent upsurge of mounding started by promising results of Swedish and Finnish studies in the late 1970s (Sutton 1993). Mounding started to gain more popularity in the 1990s and become the most widely used site preparation method only after the early 2000s, e.g. in Finland (Laine et al. 2019). Thus, information on the long-term effects of mounding methods have only become recently available.

In all mounding methods, humus and mineral soil layers are inverted or mixed (Örlander et al. 1990; Sutton 1993; Örlander et al. 1998; Heiskanen et al. 2013), but there are some principal differences between different mounding methods. In ditch mounding, mineral soil from short ditches is placed on the undisturbed single humus layer beside the ditch. In inversion, the dug-up soil is re-laid inverted into the same pit. In spot mounding, the dug-up soil is placed inverted on undisturbed soil next to the pit, forming a double humus layer beneath the mineral soil.

Soil temperature and nitrogen availability from humus layer, along with less damage from ground vegetation and pine weevils (*Hylobius abietis* L.) after MSP have been reported to increase post-planting seedling growth. (Örlander et al. 1998; Örlander and Nilsson 1999a; Nordborg 2001; Nordborg et al. 2003; Heiskanen and Viiri 2005; Smolander and Heiskanen 2007; Nilsson et al. 2010; Luoranen et al. 2017; Luoranen and Viiri 2021). MSP may also affect the soil water status and on subsequent post-planting seedling growth (Söderström et al. 1978; Örlander et al. 1990; Munson et al 1993; Grossnickle 2000; Knapp et al. 2008). MSP may also have negative effects on seedling performance. In exposed bare mineral soil seedlings are prone to frost heave damage in fine-textured soil (Heiskanen et al. 2013). The risk of winter damage can increase in very high (over 30 cm) mounds (Lindström and Troeng 1995), but in typical modern mounds (average height 10 cm) the risk is minimal (Luoranen et al. 2022a). Overall, the damage risks are lower in prepared soil and the survival of the seedlings is better than in unprepared soil (Sikström et al. 2021). Mineral soil also improves the germination of unwanted deciduous trees (Raulo and Mälkönen 1976; Uotila et al. 2010; Johansson et al. 2013; Uotila et al. 2014; Laine et al. 2020; Sikström et al. 2020), which subsequently require clearing operations for the competing deciduous trees (Uotila et al. 2012; Uotila and Saksa 2021).

On fine-textured soils in boreal forests of northern Europe the survival and growth of planted spruce seedlings have been reported to be worse than on coarser soils regardless of the use of mounding (Miina and Saksa 2006; Saksa and Kankaanhuhta 2007; Heiskanen et al. 2016). Reasons for the varying plantation success may follow from occurrence of soil waterlogging, drought, pine weevils, voles, and competing vegetation, which can vary among MSP methods and influence seedling growth and damage (Heiskanen et al. 2013).

Few studies or surveys have examined the post-planting performance of seedlings planted with different mounding methods. Laine et al. (2020), Hallsby and Örlander (2004), or Johansson et al. (2013) did not find any differences in the height of conifer seedlings between inversion and spot mounding. Örlander et al. (1998) found that conifer saplings grew better with inversion compared to spot mounding. Only Örlander et al. (1998) and Johansson et al. (2013) studied the response of the trees 10 or more years after planting. Sikström et al. (2020) carried out a meta-analysis on different MSP methods, but consistent growth differences between mounding methods were not found.

Vegetation control (weeding) means protecting small saplings (Taylor 1945), e.g. by using herbicides, or by trampling, scything or cutting ground vegetation or naturally established trees from the vicinity of the saplings. Vegetation control has been shown to increase survival and growth of planted seedlings, but the research has focused on arable land (Siipilehto 2001; Hytönen and Jylhä 2005; Jylhä and Hytönen 2006; Hytönen and Jylhä 2013). The information available on the effects of mechanical vegetation control (MVC) on spruce on northern European boreal forests sites is scarce. Competition from ground vegetation is typically much lesser on forest sites than on former agricultural lands (Hytönen et al. 2009).

This study deepens the knowledge of the long-term (over 10 years) development of spruce trees after different mounding treatments and adds ditch mounding to the compared treatments. Furthermore, our study includes within site replicates, which in long-term studies have been earlier included only by Örlander et al. (1998). Our aim was to i) compare the height and diameter growth of planted and survived saplings following different MSP treatments (spot mounding, ditch mounding and inversion, as well as examining unprepared control spots with and without herbicide application), and ii) the effects of MVC on growth parameters and survival rates of planted spruces during 11 or 13 years after planting on two fine-grained forest till soils in central Finland. We also studied if there were any effects of MSP treatment or MVC on the height and density of resprouts. MSP can also impact on survival rate of planted seedlings, especially in the very first years after establishment. The survival rate of the seedlings in the studied stands has been reported earlier by Heiskanen et al. (2013).

2 Materials and methods

2.1 Study sites

The study sites were located on sloped terrain in Suonenjoki (62°65´N, 27°10´E) and on flat terrain with periodic soil wetness (increased wetness can be expected to prevail after snowmelt in spring and rainy periods in summer) in Pieksämäki (62°38´N, 27°29´E) in central Finland. Both sites were typical spruce sites (mesic heath forest, *Myrtillus* type; Cajander 1949) on silty, frost susceptible till soil. Soil type is podzol according to FAO/WRB classification system. The study sites were site prepared with an excavator in spring 2007 (Suonenjoki) and autumn 2008 (Pieksämäki) after clear cutting the previous winter. Both sites also underwent slash removal between the clear cutting and site preparation. Two-year-old standard grown, local origin Plantek 81F container seedlings were planted in spring 2007 (Suonenjoki) and 2009 (Pieksämäki). Seedlings were treated against pine weevil feeding damages by 0.05% deltamethrin solution. Spot mounding formed slight elevations consisting of a mineral soil layer on top of a double humus layer (Fig. 1). In ditch mounding, mineral soil from short ditches (not leading water away) was placed on the undisturbed single humus layer beside the ditch. In inverted spots, the dug-up soil was re-laid inverted into the same pit with the mineral soil uppermost. Herbicide treatment was applied in the second growing season (27 June 2008 in Suonenjoki, 10 June 2010 in Pieksämäki) by spraying 50 cm around the seedlings with glyphosate in 1.2% concentration (Glyfonova Bio, Cheminova A/S, Lemvig, Denmark). Seedlings were covered by an upside-down bucket during spraying. The site preparation treatments resulted in almost 2000 planting spots ha^{-1} in Suonenjoki and in slightly sparser spot positions in Pieksämäki. Within plots, the soil treatment spots were randomly positioned and the plots were

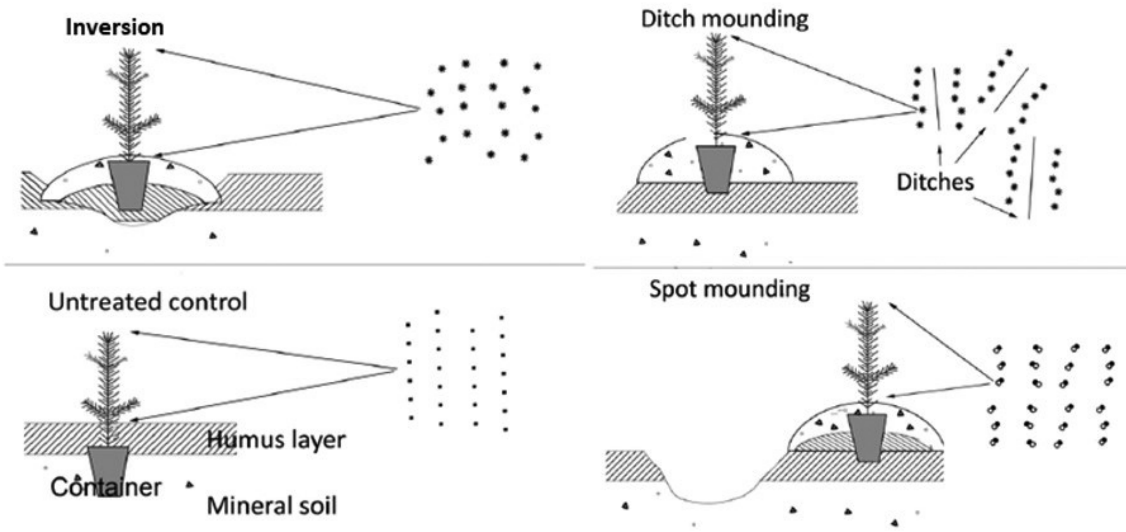

Fig. 1. Schematic illustration for the site preparation treatments of ditch and spot mounding, inversion and untreated control drawn from aside (single seedling) and above (multiple seedlings).

randomly assigned into each block (Fig. 2). Both sites had 4 replicates of each site preparation treatments. The study sites, meteorological data, and used planting and site preparation treatments are described in more detail by Heiskanen et al. (2013).

The main plots (site-preparation treatment, 20 m × 32 m) were split into sub plots (20 × 16 m) that underwent MVC or an untreated control treatment which was applied at Suonenjoki in August 2010 and in Pieksämäki in August 2011. On MVC sub plots the vegetation was scythed from the vicinity (~ 50 cm radius) of the spruce saplings.

Furthermore, excess and smothering broadleaved trees were removed from the stands in early cleaning (see cleaning, Taylor 1945). Early cleaning was carried out in each treatment and control plots in Suonenjoki in August 2011 and in Pieksämäki in August 2016.

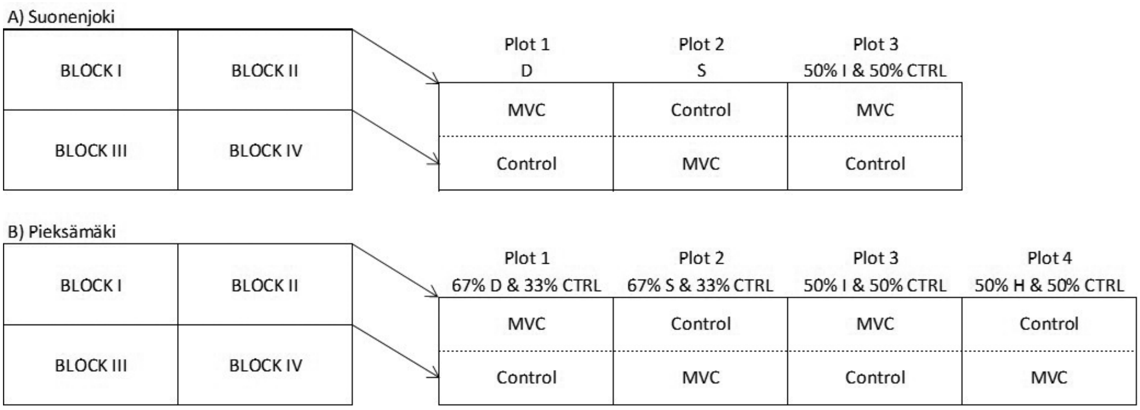

Fig. 2. Schematic graph of the study design A) Suonenjoki and B) Pieksämäki sites in Finland. The percentage of initial planting spots in each plot is shown next to the abbreviation of site preparation methods in plots containing two site preparation methods (mounding or herbicide, and control). Soil preparation plot is split in to sub plots according to two mechanical vegetation control methods (MVC and control). Size of a sub plot with edge area is 20 × 16 m (320 m^2), and the circular sample taken from the center of each sub plot is 50 m^2. Abbreviations; D = ditch mounding, S = spot mounding, I = inversion, CTRL = unprepared soil, H = Herbicide treatment after planting.

2.2 Seedling and sapling measurements

The planted seedlings were measured for height (mm) and vigour in the autumn after planting for five years in Suonenjoki (2007–2011) and three years in Pieksämäki (2009–2011) as described by Heiskanen et al. (2013). In addition to the height and vigour, also the collar diameter (at 2 cm height) of the seedlings was measured in the third and fifth year, respectively in Pieksämäki and Suonenjoki. In April–May 2020 the stands were remeasured at the ages of 13 and 11 years. Circular sample plots (50 m^2) were taken from the centre of each sub plot (MVC treatment). However, on ditch mounded plots, the samples were located aside from the ditches because ditches were on small clusters, and they were not initially planted with spruce seedlings. Each planted spruce sapling on a circular sample plot was measured for height and three years' height growth to within 5 cm accuracy and diameter at breast height at 5 mm accuracy. The total number of observations were 218 in Suonenjoki and 381 trees in Pieksämäki (Table 1). Furthermore, each naturally established broadleaved tree was counted from the circular sample plot and their mean height was approximated with a tape measurer to within 10 cm accuracy. These were mainly resprouts from early cleaning and are hereafter referred to as resprouts.

Table 1. Observations of spruce saplings in different treatments in Suonenjoki and Pieksämäki sites in south-boreal forest in Finland. The target share indicates the targeted share of planted seedlings on a prepared point or between them in unprepared control points (CTRL) within plots. The p-value is the result of binomial test of equality of the proportion (50%) of measured saplings between mechanical vegetation controlled (MVC) and untreated control plots.

		Suonenjoki Observations					Pieksämäki Observations			
	Target share	MWC	Control	Total	p-value	Target share	MWC	Control	Total	p-value
Inversion plots										
Mound	1/2	18	20	38	0.871	1/2	41	35	76	0.567
CTRL	1/2	7	5	12	0.774	1/2	16	16	32	1.000
Spot mounding plots										
Mound	1/1	43	37	80	0.576	2/3	36	28	64	0.382
CTRL						1/3	11	4	15	0.119
Ditch mounding plots										
Mound	1/1	46	42	88	0.749	2/3	46	35	81	0.266
CTRL						1/3	6	10	16	0.754
Herbicide plots										
Herbicide						1/2	42	28	70	0.120
CTRL						1/2	7	20	27	0.263
Total		114	104	218	0.542		205	176	381	0.151

2.3 Data analyses

We had three different approaches to analysing the effects of site preparation treatments on the height and diameter of the seedlings or saplings. First, the height development of the spruce trees from establishment to the last measurement was analysed with linear mixed model as a response of the stand age and the treatments.

The response variable was a natural logarithm of the height of the planted spruce trees (cm). The explanatory variables were the natural logarithm of the stand age (years) as a continuous variable, MSP, MVC treatment (0 = untreated control, 1 = MVC), and full interactions between them. A transformation was carried out for the stand age [ln(age + 9)] in the analysis to optimize the model fit and shape of the growth curve. However, it was back-transformed when representing the results. In the growth model for Suonenjoki random variables included the block, sub block nested within a block, stand age as a factor nested within a block, the MSP nested within a block, stand age as a factor nested within MSP and block, stand age as a factor nested within all the former random variables, and tree. A sub block was used to separate the inversion treatment from other MSP treatments in Suonenjoki, because inverted plots also had control saplings planted in unprepared soil. In Pieksämäki, all MSP treatments included control saplings, so for that reason sub blocks were dropped from the Pieksämäki growth model.

Second, the annual height growth was also analysed with a mixed model. The response variable was the annual height growth of the spruce saplings (cm). The explanatory variables were MSP and MVC treatments. No interactions were included (MSP and MVC interaction was found to be significant only in one out of 16 instances). Random variables included the block, MSP nested within a block, MVC nested within a block and the MSP. In these analyses we examined the differences between individual years and growth differences between the treatments at the later stage (11–13 years) of the study. Third, a similar modelling approach was used to test the treatment effects on the spruce height and diameter ($d_{1.3}$) for the last measurements taken at the sites, and on the height (cm) and density (trees ha^{-1}) of resprouts. The MVC level was dropped from the random variables at this stage. No interactions were included in these analyses. Between groups differences were tested with a Tukey HSD test.

One more test was done to analyse the effect of MVC on the survival rate of the spruce saplings. This was done with a binomial test.

The data was analysed with statistical software R version 4.0.2. (Venables and Smith 2021). The Lme4-package and the lmer-function was used in mixed modelling, and the biom.test-function was used in binomial test.

3 Results

3.1 The effect of site preparation or mechanical vegetation control on height growth

Spruce saplings on different MSP and MVC treatments had different growth patterns, and there were significant differences (Table 2). Generally, growth was the highest for those sapling which had undergone ditch and spot mounding treatments and was the lowest for those that had undergone herbicide and inversion treatments. However, MVC suppressed the differences between MSP treatments. The results varied also between sites.

The differences between MSP methods were the most apparent in Pieksämäki, when MVC was not done (Fig. 3, middle row). The best growth was for those saplings which had undergone ditch mounding, and then for spot mounding, inversion and herbicide treatment ($p < 0.001$ MSP×age).

Table 2. Mixed models for the height of spruce saplings at the Suonenjoki and Pieksämäki sites in south-boreal forest in Finland. The response variable is the natural logarithm of the sapling height in centimetres. The CTRL refers to control saplings planted in unprepared soil between seedlings undergoing different site preparation (MSP, ref. Inversion) treatments including application of seedling surroundings with glyphosate (Herbicide). MVC = mechanical vegetation control, DitchM = ditch mounding, SpotM = spot mounding.

Predictors	Pieksämäki Ln(height)			Suonenjoki Ln(height)		
	Estimates	std. Error	p-values	Estimates	std. Error	p-values
(Intercept)	–4.089	0.273	**<0.001**	–3.460	0.189	**<0.001**
MSP [DitchM]	–1.380	0.344	**<0.001**	–0.603	0.207	**0.004**
MSP [SpotM]	–0.842	0.335	**0.012**	–0.079	0.207	0.704
MSP [Herbicide]	1.462	0.405	**<0.001**			
MSP [DitchMCTRL]	–0.620	0.390	0.112			
MSP [SpotMCTRL]	0.033	0.486	0.946			
MSP [InversionCTRL]	0.012	0.351	0.972	0.411	0.284	0.148
MSP [HerbicideCTRL]	0.928	0.341	**0.006**			
MVC	0.440	0.247	0.076	–0.067	0.204	0.744
Ln(Age+9)	3.172	0.097	**<0.001**	3.115	0.068	**<0.001**
MSP [DitchM] × MVC	–0.100	0.333	0.764	0.488	0.256	0.057
MSP [SpotM] × MVC	0.078	0.329	0.813	–0.130	0.258	0.616
MSP [Herbicide] × MVC	–1.351	0.409	**0.001**			
MSP [DitchMCTRL] × MVC	0.416	0.460	0.366			
MSP [SpotMCTRL] × MVC	–0.407	0.495	0.410			
MSP [InversionCTRL] × MVC	0.010	0.358	0.978	–0.312	0.389	0.423
MSP [HerbicideCTRL] × MVC	–1.889	0.422	**<0.001**			
MSP [DitchM] × Ln(Age+9)	0.623	0.121	**<0.001**	0.246	0.074	**0.001**
MSP [SpotM] × Ln(Age+9)	0.413	0.118	**<0.001**	0.025	0.074	0.739
MSP [Herbicide] × Ln(Age+9)	–0.730	0.145	**<0.001**			
MSP [DitchMCTRL] × Ln(Age+9)	0.206	0.139	0.138			
MSP [SpotMCTRL] × Ln(Age+9)	0.034	0.171	0.844			
MSP [InversionCTRL] × Ln(Age+9)	–0.040	0.124	0.748	–0.196	0.101	0.052
MSP [HerbicideCTRL] × Ln(Age+9)	–0.433	0.120	**<0.001**			
MVC × Ln(Age+9)	–0.183	0.086	**0.034**	0.003	0.072	0.964
(MSP [DitchM] × MVC) × Ln(Age+9)	0.019	0.116	0.868	–0.184	0.091	**0.044**
(MSP [SpotM] × MVC) × Ln(Age+9)	–0.034	0.115	0.767	0.095	0.092	0.300
(MSP [Herbicide] × MVC) × Ln(Age+9)	0.618	0.146	**<0.001**			
(MSP [DitchMCTRL] × MVC) × Ln(Age+9)	–0.102	0.163	0.530			
(MSP [SpotMCTRL] × MVC) × Ln(Age+9)	0.186	0.173	0.281			
(MSP [InversionCTRL] × MVC) × Ln(Age+9)	0.083	0.126	0.512	0.217	0.137	0.114
(MSP [HerbicideCTRL] × MVC) × Ln(Age+9)	0.822	0.149	**<0.001**			
Random Effects						
σ^2	0.042			0.031		
τ_{00}	0.011 $_{Block:MSP:Age\_f}$			0.003 $_{Block:Sub\_block:MSP:MVC:Age\_f}$		
	0.069 $_{Tree}$			0.035 $_{Tree}$		
	0.006 $_{Block:Age\_f}$			0.002 $_{Block:MSP:Age\_f}$		
	0.014 $_{Block:MSP}$			0.005 $_{Block:Age\_f}$		
	0.001 $_{Block}$			0.000 $_{Block:MSP}$		
				0.001 $_{Block:Sub\_block}$		
				0.000 $_{Block}$		

Applying MVC suppressed the differences between the MSP treatments ($p < 0.001$), but the order between the treatments remained the same. Control seedlings planted on unprepared soil grew more slowly than their corresponding alternatives for all mounding methods, but not herbicide treatment (Fig. 3, middle vs bottom row). Differences were small between control saplings even when MVC was not applied and became even smaller, or negligible, when it was applied (Fig. 3, bottom row). MVC especially increased the growth of control saplings planted on unprepared soil which had undergone herbicide (Fig. 3, HerbicideCTRL) or inversion (Fig. 3, InversionCTRL)

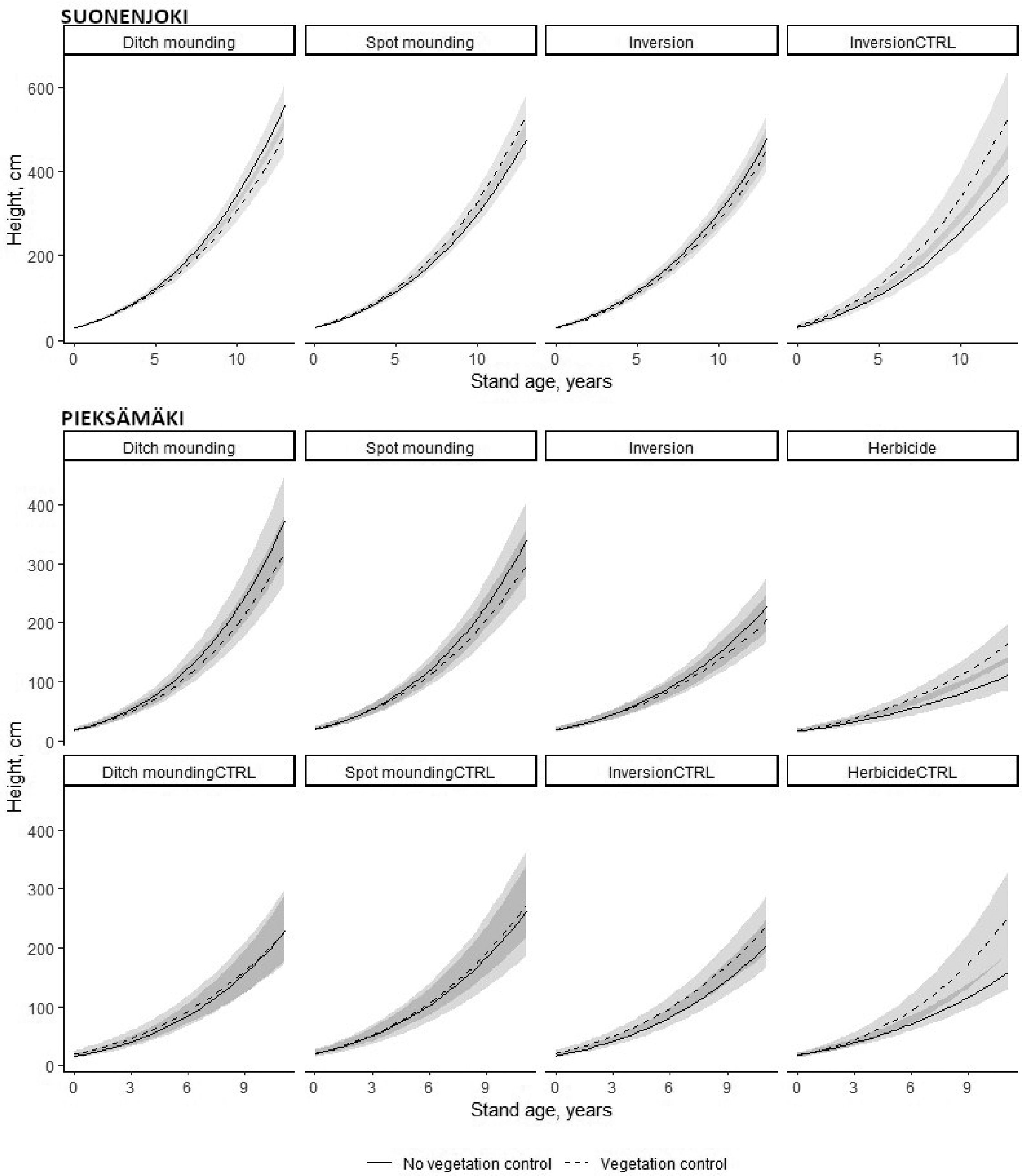

Fig. 3. Height development of spruce saplings in south-boreal forest in Finland at the Suonenjoki and Pieksämäki sites, respectively during the first 13 and 11 years after establishment according to site preparation and mechanical vegetation control (MVC) treatments. Lines represent the estimated median of the population and the transparent grey ribbon ±95%CI. When the ribbons are darker grey, CIs between MVC treatments overlaps each other. CTRL refers to control saplings planted in unprepared soil between the saplings planted on prepared soil.

treatments. The effective period of MVC was one year in Pieksämäki, until early cleaning was applied throughout the site.

In Suonenjoki, differences in the height growth of the spruce saplings were significant (p = 0.004 MSP×age) but rather small between MSP methods when MVC was not done. MVC evened out the differences even more (p = 0.001 MSP×MVC×Age), as it especially increased the growth of the control saplings (Fig. 3, top row). The effective time of MVC was five years in Suonenjoki, until early cleaning was applied throughout the site.

In Suonenjoki, growth differences between MSP treatments in different years were small and inconsistent. Statistically significant differences were found only during the first three years after establishment, when ditch and spot mounding had small advantage over other methods (Fig. 4).

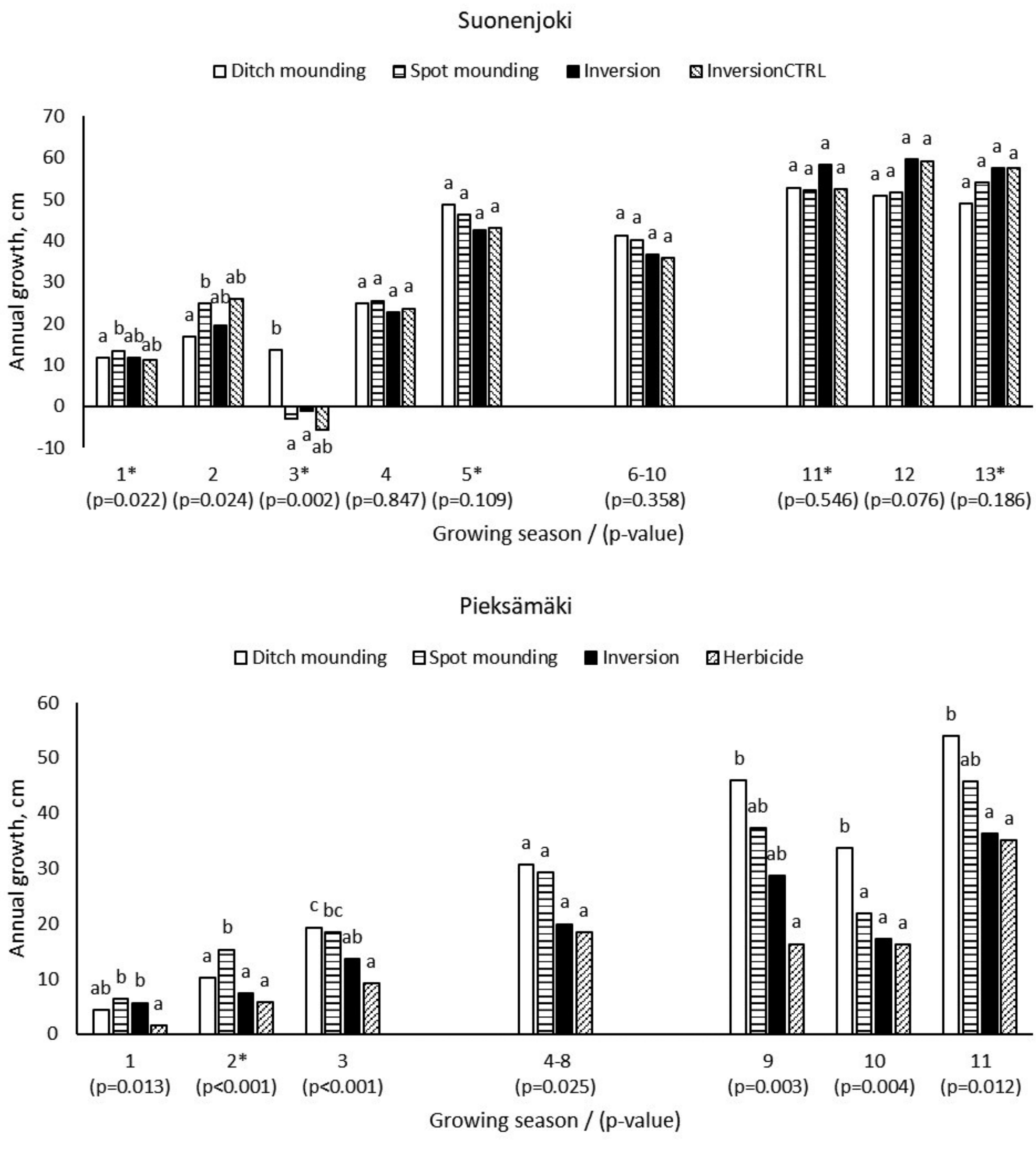

Fig. 4. The annual height growth of planted spruce saplings in south-boreal forest in Finland at the Suonenjoki and Pieksämäki sites in different growing seasons. The letters (a, b, c) represent significant differences in the Tukey HSD test at a confidence level of 95% within a single group of bars. (* variation of random factors on the main plot level was small and the random effect in the analyses had singular fit, which may affect reliability of p-values).

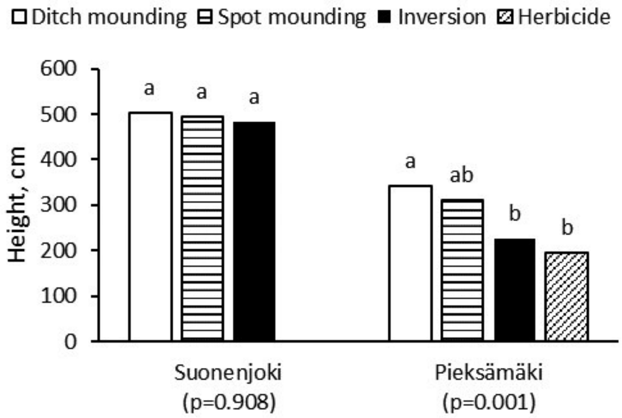

Fig. 5. The mean height of spruce saplings 13 and 11 years after establishment respectively at the Suonenjoki and Pieksämäki sites in south-boreal forest in Finland. The letters (a, b) represent significant differences in the Tukey HSD test results at a confidence level of 95% within one site.

The third growing season was exceptional at the Suonenjoki site due to seedling damage. The mean growth of the stand for those saplings which had undergone spot mounding, inversion and control treatments was negative (Fig. 4), only for those saplings which had undergone ditch mounding did the seedlings show positive growth.

In Pieksämäki, ditch mounding and spot mounding yielded consistently higher growth than inversion or herbicide treatment, and on many occasions the differences were statistically significant (Fig. 4). Moreover, inversion yielded consistently higher growth than the use of herbicides, but the difference was statistically significant only in the first growing season.

At the end of the experiment the sapling heights differed between MSP treatments at Pieksämäki ($p=0.001$). The saplings were 116–147 cm (51–76%) taller after ditch mounding than after inversion or herbicide treatment (Fig. 5). In Suonenjoki, however, the differences were not statistically significant ($p=0.908$). MVC treatment did not cause significant differences to the height of the spruce saplings at either Suonenjoki ($p=0.830$) or Pieksämäki ($p=0.560$).

3.2 The effect of site preparation or mechanical vegetation control on diameter

The treatment effect on the diameter was tested at collar height (2 cm) in 3- or 5-years old stands or at breast height (1.3 m) in 11- or 13-years old stands. In Pieksämäki, MSP treatments had a statistically significant effect both 3 ($p<0.001$) and 11 ($p=0.003$) years after establishment. The spruce saplings favoured ditch and spot mounding. At the age of 11, those saplings which had undergone ditch mounding rather than herbicide treatment were 23 mm thicker. Even though the difference in the diameter of the saplings was quite large between those saplings which had undergone inversion and other mounding methods (15–19 mm), it was not statistically significant. Statistically significant differences were found also at Suonenjoki ($p=0.009$, Fig. 6) but only when the stand age was 5 years old as those saplings which had undergone ditch mounding rather than inversion were 5.2 mm thicker.

At Suonenjoki, MVC (4th season) treatment had a significant effect on the diameter of spruce saplings (Fig. 6). Before MVC, in 0–3 year old stands, the difference in collar diameter of spruce was under 0.3 mm and it was not statistically significant ($p=0.132$). Two years later, the spruce saplings were 2.6 mm thicker for those saplings which had undergone MVC treatment than the

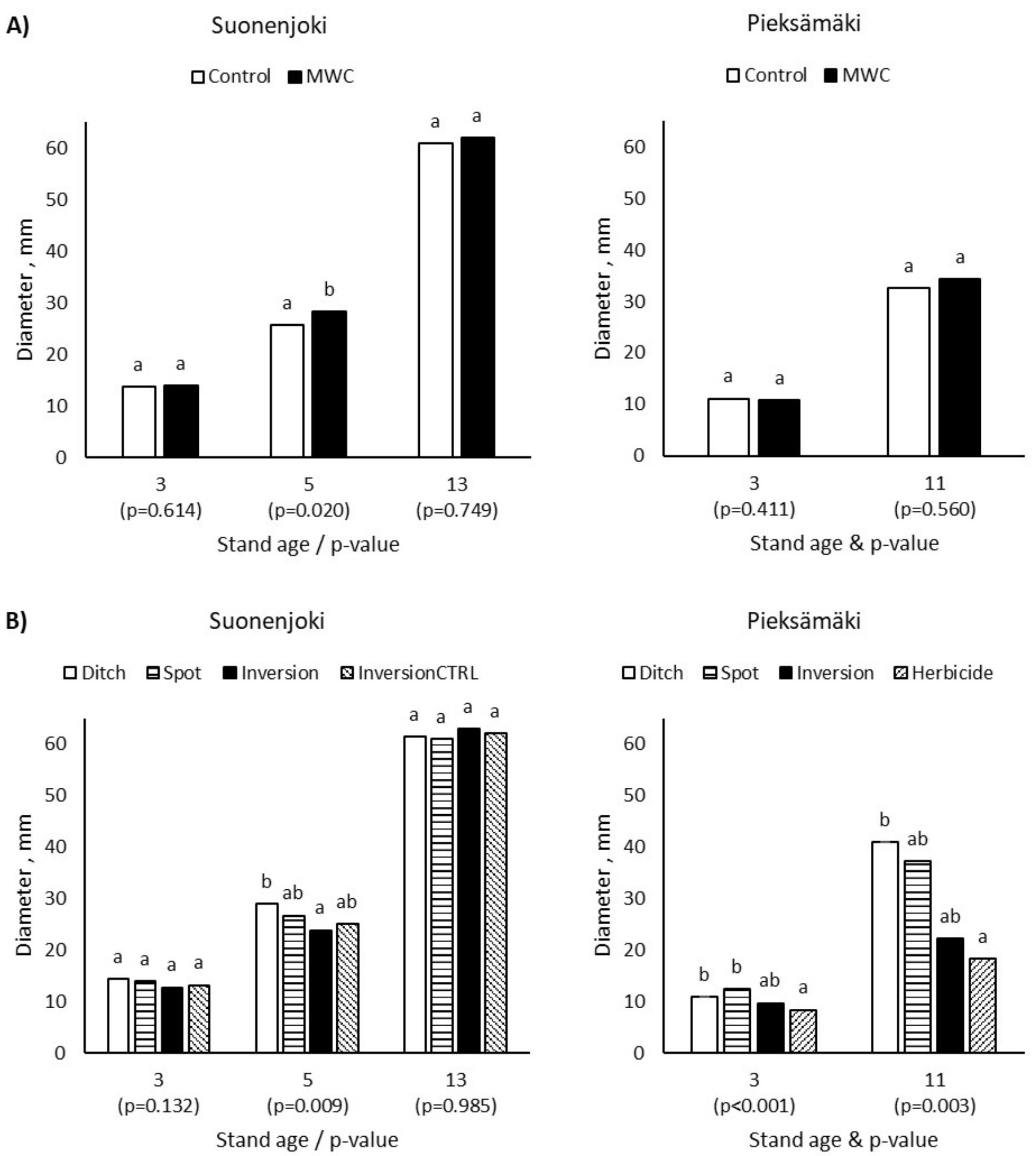

Fig. 6. The mean collar diameter of spruce saplings in 3- or 5-year-old stands or the mean diameter at breast height in 11- or 13-year- old stands in south-boreal forest in Finland at the Suonenjoki and Pieksämäki sites according to A) mechanical vegetation control (MWC) or B) site preparation treatments. The letters (a, b) represent significant differences in the Tukey HSD test at a confidence level of 95% within one age category. Inversion/CTRL are control saplings on inversion plots.

untreated control (p = 0.009). However, at the last measurement, in 13 year old stands, the effect of MVC treatment was no longer significant for the breast height diameter (p = 0.749). At Pieksämäki, MVC did not have a significant effect on the diameter of the planted spruce trees, although saplings on MVC treatment had grown slightly better between 4–11 years (Fig. 6).

3.3 The effect of site preparation or mechanical vegetation control on resprouts

Resprouts were measured at the last measurement in 11- and 13-years old stands, respectively in Pieksämäki and Suonenjoki. At that stage, all the treatments were already early cleaned after MVC. Thus, the observed trees were resprouts from the cleaning. Neither MSP or MVC treatment had statistically significant effect on the height of resprouts in either Suonenjoki (MSP $p=0.843$, MVC $p=0.200$) or Pieksämäki (MSP $p=0.442$ and MVC $p=0.360$).

However, at Suonenjoki, ditch mounding reduced the density of resprouts by 9 024 trees ha^{-1} or 47% compared to combined inversion and control treatment (Fig. 7, $p=0.034$). Spot mounding did not differ significantly from ditch mounding or inversion. At Pieksämäki, the herbicide treatment had the lowest density of resprouts and spot mounding the highest, but the differences between MSP methods were not statistically significant ($p=0.368$).

MVC had significant effect on the density of resprouts at Pieksämäki ($p=0.004$, Fig. 7). MVC reduced the density of resprouts by 4400 trees ha^{-1}, which was a 43% decrease compared to the mean estimated density of 10 260 trees ha^{-1} in control. Although MVC reduced the density of resprouts by 1100 trees ha^{-1} also at Suonenjoki, the difference was not statistically significant there ($p=0.685$).

3.4 Effect of mechanical vegetation control on the survival rate of spruce saplings

The effect of MVC treatment on the survival rate of the spruce saplings was tested in 11- and 13-years old stands, respectively in Pieksämäki and Suonenjoki. In general, more surviving saplings were found on the MVC plots. However, the proportion of observed saplings did not significantly differ from the expected 50% between MVC treatments, not even within any of the MSP treatments (Table 1).

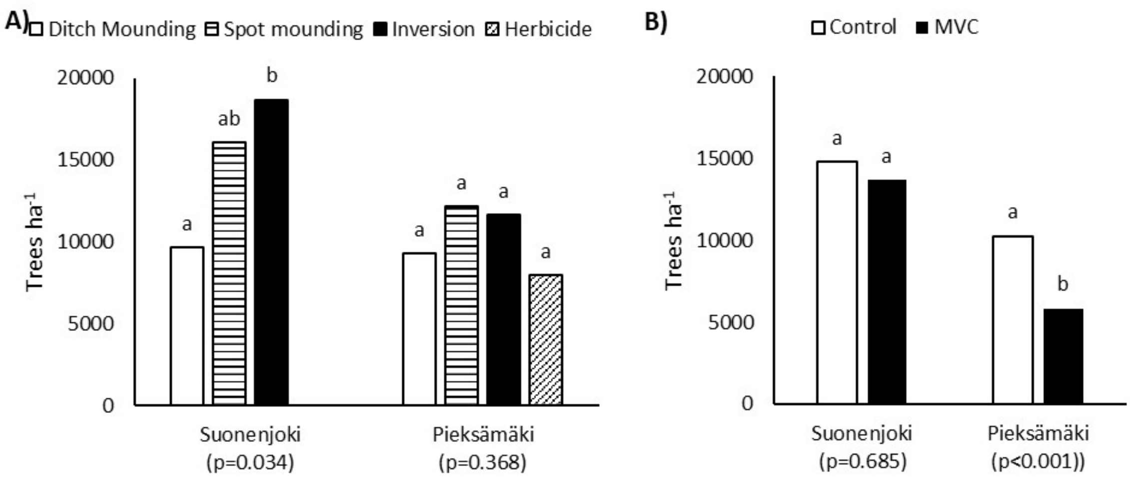

Fig. 7. The density of the resprouts in south-boreal forest in Finland at the age of 11 at Pieksämäki and at the age of 13 at Suonenjoki for those saplings that had undergone A) site preparation and B) mechanical vegetation control treatments (MVC). The letters (a, b) represent significant differences within site in the Tukey HSD test at a confidence level of 95%.

4 Discussion

In this study, we found that on long-term (> 10 years), on fine-textured soil and on flat sites, the growth of spruce saplings was favoured by ditch or spot mounding rather than inversion, using herbicides or planting in unprepared soil. At 11 years, inversion led to a growth disadvantage of 2–5 years compared to those saplings that had been planted using ditch or spot mounding. Nonetheless, growth on the control or herbicide treatment plots was even poorer than on the inversion plots. This study extends the earlier findings from the same site to consider longer time periods (Heiskanen et al. 2013). On flat terrain with fine-textured soil with periodic wetness, ditch or spot mounding can improve growing conditions in the long term, as was also found by Heiskanen et al. (2016).

On the sloped terrain of Suonenjoki, the differences in height, height growth or diameter of the spruce saplings were much lesser for those saplings which had undergone mounding methods than in Pieksämäki. Inversion and spot mounding did not have any significant differences in Suonenjoki. Ditch mounding achieved significantly better height growth than inversion, but between the years the growth differences were inconsistent. Significant growth differences were found only during the first three years or size differences during the first five years, but not later on. Inversion did not provide significantly better growth compared to the control in Suonenjoki.

MSP has commonly been reported to result in a better survival rate and increased growth of planted seedlings compared to seedlings in unprepared soil in Nordic forests (Örlander et al. 1996; Hallsby and Örlander 2004; Saksa et al. 2005; Kankaanhuhta et al. 2009; Hjelm et al. 2019; Sikström et al. 2020; Luoranen et al. 2022b). Kankaanhuhta et al. (2009) found MSP to be the most important factor explaining improved regeneration results when planting spruce in Finnish privately-owned forests and mounding was found to produce better results than patching and disc trenching. In a meta-analysis of planting studies, Sikström et al. (2020) found that MSP increases the sapling height by 10–25% 10–15 years after planting.

Some earlier planting studies have suggested better seedling survival and growth for saplings planted using inversion techniques than with mounding in Sweden and Finland (Örlander et al. 1998; Heiskanen and Viiri 2005; Heiskanen and Rikala 2006). Örlander et al. (1998) found that conifer saplings were significantly taller after inversion compared to spot mounding ten years after planting. According to Örlander et al. (1998), differences between observed MSP became detectable during the third growing season and increased towards the end of the study period. However, older inversion methods used in Örlander et al. (1998) may have been more intensive than their modern counterparts used in our study. On the other hand, in a meta-analysis of planting studies, Sikström et al. (2020) did not find statistically significant differences in sapling height due to the mounding methods. Neither did Laine et al. (2020) in the height of conifer seedlings when comparing inversion (56 cm) and spot mounding (57 cm) three growth seasons after planting, nor did Hallsby and Örlander (2004) five years after planting (inversion 46 cm, spot mounding 42 cm), and nor did Johansson et al. (2013) 18 years after planting (inversion 413–430 cm, spot mounding 424 cm).

Variability in the mounding results may derive from soil conditions. Low-positioned inverted spots with a fine soil texture can suffer from occasional waterlogging and coolness according to Heiskanen et al. (2013, 2016). As they pointed out, the differences in planting success for varying mounding methods are affected by the variability of the sites (hydrology, fertility) and years (weather, damage). Slope prevents waterlogging and can limit the disadvantages of planting on unprepared or only mildly prepared soils. The southwest slope is also better positioned for sunshine to warm the site than flat sites, which may furthermore decrease the benefit of increased temperature of elevated planting spot of mounding (Nilsson et al. 2010). Mounding is commonly applied prior to planting of container grown spruce seedlings on fine-grained till soils that are susceptible to frost heave. Different site preparation methods, typically disc-trenching or patching, are used on other soil types.

In this study, slashes were removed from the studied sites before soil preparation. Slash removal can facilitate soil preparation and improve quality of mounds (Saarinen 2006; Saksa et al. 2018). However, benefits are minor in excavator-based mounding. Retained slashes release slowly nutrients to the soil, and because of that, slash removal may have short- or long-term growth effects (Wall 2008; Wall and Hytönen 2011; Jacobsen et al. 2015). However, the effect of nutrient balance would likely be quite similar in any MSP. For example, Hjelm et al. (2019) did not find slash removal to have any long-term effects on conifer growth in disc-trenched sites. Thus, we do not expect slash removal to have large effect on the results between MSP or MVC treatments, not at least when mounding is excavator-based. On forwarder-based mounding, on the other hand, slash retention may strongly affect quality of mounding (Saksa et al. 2018), and thus it may impact especially short-term growth of spruce.

In this study, growth pattern of spruce saplings in their third growing season was somewhat peculiar in Suonenjoki, as there was negative mean growth for all but those saplings which had undergone ditch mounding treatment. The number of saplings damaged by herbivores, mainly pine weevils and voles was noticed to be especially high that year, and the proportion of seedlings damaged by voles was slightly lower for saplings which had been planted in ditch mounds than had undergone other MSP treatments (Heiskanen et al. 2013). Damage caused by voles was the most obvious reason for the negative growth. During the third year, growth in the saplings that had undergone ditch mounding was significantly higher than for those which had undergone other treatments, which gives a reason to suspect that ditch mounding may protect seedlings from herbivore damage as has been speculated also by Huitu et al. (2013).

Herbicide treatment yielded the lowest growth for spruce saplings of all the soil preparation treatments at Pieksämäki and was lower than the controls. There was more pine weevil feeding damage especially for those saplings which had undergone herbicide treatment, but also for those which had undergone the control treatments (Heiskanen et al. 2013). Pine weevil feeding damage, even slight damage, reduces seedling growth (Långström and Hellqvist 1989; Luoranen et al. 2017) and probably affected the seedlings growth also here. The other, reason for reduced growth for the saplings which had herbicide treatment might be contamination damage from the herbicide. Spruce has been considered quite tolerant to glyphosate (Lund-Høie 1983; Kogan and Allister 2010; Wendel et al. 1984). However, the tolerance depends on time and conditions of application. Elongating saplings in warm summer conditions are highly susceptible to glyphosate (Lund-Høie 1983), and needle damage may affect the later growth of the seedlings (Långström and Hellqvist 1989). The saplings were briefly covered with an upside-down bucket during the spraying application of glyphosate, but the seedlings still had apparent contamination damage from the application done in the middle of the summer. Herbicide application may be more suitable when applied before planting or then in few years after, once the trees are taller, or when the trees are already winter hardened and not so susceptible to herbicides (Boateng et al. 2006). According to former studies, repeated or even one-off herbicide treatment could be an effective alternative to MSP (Munson et al. 1993; Örlander and Nilsson 1999b; Boateng et al. 2006; Löf et al. 2006; Cole et al. 2018).

MVC had a positive effect on the growth of spruce saplings which had undergone herbicide treatment, and control saplings on unprepared soil in plots which had undergone herbicide and inversion treatments. However, with more intensive MSP methods (ditch and spot mounding) MVC did not improve the growth of the saplings, not even the growth of the control saplings in unprepared soil between the mounds. It seems that for these treatments, the control saplings also benefitted from MSP. There is little information available on the effects of MVC on spruce on forest sites, which typically have less competition from ground vegetation. Though, Siipilehto and Lyly (1995) found that herbicide treatment or mulching did not improve the growth of Scots pine on reforestation sites. On arable land, vegetation control has been found to improve growth or survival of different tree species (Siipilehto 2001; Hytönen and Jylhä 2005, 2013; Jylhä and Hytönen 2006), including the shade tolerant spruce (Siipilehto 2001; Jylhä and Hytönen 2006; Hytönen and Jylhä 2008). According to our results, MVC seems to be especially important when MSP has not been done on a site.

MVC heavily reduced (43%) the density of resprouts at Pieksämäki. This finding is important to silviculture because high densities of resprouts add to high pre-commercial thinning costs and may also lead to extra pre-commercial thinning. There are some indications that juvenile stand management, in which excess trees are cut in forest stands, typically reduces the density of trees later (Uotila et al. 2014). Such a strong response between MVC and number of resprouts years after the treatment is surprising. Especially when the stands were early cleaned later (and this was done also for the control plots). However, there are some indications that repeated cuttings (MVC, early cleaning, pre-commercial thinning) may decrease sprouting ability or survival of re-sprouted broadleaves (Johansson and Lundh 2009). It is also known that the timing of cutting and weather conditions during and before the cutting can have a large effect on sprouting (Mikola 1942; Johansson and Lundh 2009; Uotila and Saksa 2021). Nonetheless, if density of broadleaved trees reduces over each cutting, several less expensive cutting for smaller trees may be a better option than one expensive cutting for larger trees. It is good to find that the density of resprouts was also lower (8%) in Suonenjoki after MVC treatment, even though the difference was non-significant.

The density of resprouts was much lower for those saplings which had undergone ditch mounding than other mounding methods at the Suonenjoki site. Typically exposed mineral soil increases the natural establishment of trees (Raulo and Mälkönen 1976; Uotila et al. 2010; Johansson et al. 2013; Laine et al. 2020). It should be acknowledged that initially, when the stand was established, it was decided not to plant seedlings around ditches. Thus, our sample plots did not locate near ditches, which because of the exposed mineral soil should be a good seedbed for naturally emerging trees. It is possible though, that on dryish, sloped terrains like on the Suonenjoki site, the extra drainage of the ditches may also reduce seed germination. The density of resprouts was also lower on ditch mounding plots in Pieksämäki than on spot mounding or inversion plots, but the difference was not significant. Furthermore, Laine et al. (2020) suggested that less exposed mineral soil and subsequently less naturally regenerated broadleaves may be achieved by using inversion methods rather than spot mounding, which may improve the growth of conifer seedlings on the long-term. In this study, we did not find statistically significant differences between inversion and spot mounding on the sprout density. However, the sites have undergone 1–2 juvenile stand management operations after MSP, which have had an impact on the resprout density.

There are a handful of previous studies of different mounding methods on the development of planted stands (Örlander et al. 1998; Hallsby and Örlander 2004; Heiskanen and Viiri 2005; Heiskanen and Rikala 2006; Johansson et al. 2013; Laine et al. 2020). Only a few extend to time periods after the first decade (Örlander et al. 1998; Johansson et al. 2013), and to our knowledge, inversion in Örlander et al. (1988) did not represent a modern method of application of the MSP method by excavator. Our results represent the current mounding methods used in Finland in practice, and the results can be generalized on fine-textured soil types planted with spruce seedlings on southern and central Finland and in similar conditions in other northern boreal forests.

To conclude the results of the present study, inversion showed poorer growth compared to spot or ditch mounding on fine-textured soils on flat terrain. Inversion was the only MSP method of the study that did not show a clear improvement over the saplings on unprepared soil on such conditions. However, in more favourable conditions which do not benefit from extra drainage, inversion provided comparable growth results to spot mounding. Herbicide treatment showed the poorest growth in the study. Thus, herbicide treatment should not be applied as an alternative in site preparation, not at least when there is a high risk of damage to adjacent spruce seedlings. MVC applied in 3rd or 4th season had only minor effect on the growth of spruce on MSP sites, but on the other hand, it may be a necessary treatment on sites without MSP. Moreover, on flat terrain MVC lowered the density of resprouts quite heavily.

Declaration of openness of research materials, data, and code

The data, code, research materials and data are available upon requests from Natural Resources Institute Finland. Data and materials can be acquired from karri.uotila@luke.fi, juha.heiskanen@luke.fi, or jaana.luoranen@luke.fi and code from karri.uotila@luke.fi. Study or analysis plan is not preregistered.

Authors' contributions

Substantial contributions to the conception of research question and design of the work (KU (final measurements), JH (planting, measurements), JL (weed control, final measurement), TS (weed control, intermediate measurements, final measurements), and TL (measurements); or the acquisition, analysis, and interpretation of data and results (KU); AND Scientific writing of the work (KU) or revising it critically for sound and intellectual content (JH, JL, TS, TL); AND Final approval of the version to be published (all); AND Accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved (all).

Acknowledgements

We would like to thank Janne Kaseva from his support in statistical analyses. We would like to also thank Juhani Salonen and Kari Kautto from their valuable help in measuring the experiments.

Funding

The project was funded by Natural Resources Institute Finland.

References

Boateng JO, Heineman JL, McClarnon J, Bedford L (2006) Twenty year responses of white spruce to mechanical site preparation and early chemical release in the boreal region of northeastern British Columbia. Can J For Res 36: 2386–2399. https://doi.org/10.1139/x06-197.

Cajander AK (1949) Forest types and their significance. Acta For Fen 56, article id 7396. https://doi.org/10.14214/aff.7396.

Cole E, Lindsay A, Newton M, Bailey JD (2018) Eight-year performance of bareroot Douglas-fir and bareroot and plug western larch Seedlings following herbicide applications, northeast Oregon, USA. New For 49: 791–814. https://doi.org/10.1007/s11056-018-9653-5.

Grossnickle SC (2000). Ecophysiology of northern spruce species. The performance of planted seedlings. NRC Research Press, Ottawa.

Hallsby G (1995) Field performance of outplanted Norway spruce: effects of organic matter amendments and site preparation. Can J For Res 25: 1356–1367. https://doi.org/10.1139/x95-148.

Hallsby G, Örlander G (2004) A comparison of mounding and inverting to establish Norway spruce on podzolic soils in Sweden. Forestry 77: 107–117. https://doi.org/10.1093/forestry/77.2.107.

Heiskanen J, Rikala R (2006) Root growth and nutrient uptake of Norway spruce container seedlings planted in mounded boreal forest soil. For Ecol Manage 222: 410–417. https://doi.org/10.1016/j.foreco.2005.10.047.

Heiskanen J, Viiri H (2005) Effects of mounding on damage by the European pine weevil in planted Norway spruce seedlings. North J Appl For 22: 154–161. https://doi.org/10.1093/njaf/22.3.154.

Heiskanen J, Saksa T, Luoranen J (2013) Soil preparation method affects outplanting success of Norway spruce container seedlings on till soils susceptible to frost heave. Silva Fenn 47, article id 893. https://doi.org/10.14214/sf.893.

Heiskanen J, Sutinen S, Hyvönen J (2015) Effects of light exposure in freezing temperatures on winter damage to foliage of Norway spruce container seedlings in mid and late winter: Pilot experiments in open field. J For Sci 61: 35–44. https://doi.org/10.17221/97/2014-JFS.

Heiskanen J, Saksa T, Hyvönen J (2016) Effects of mounding and soil clay content on post-planting success of Norway spruce. For Ecol Manage 378: 206–213. https://doi.org/10.1016/j.foreco.2016.07.044.

Hjelm K, Nilsson U, Johansson U, Nordin P (2019) Effects of mechanical site preparation and slash removal on long-term productivity of conifer plantations in Sweden. Can J For Res 49: 1311–1319. https://doi.org/10.1139/cjfr-2019-0081.

Huitu O, Rousi M, Henttonen H. (2013). Integration of vole management in boreal silvicultural practices. Pest Manag Sci 69: 355–361. https://doi.org/10.1002/ps.3264.

Hytönen J, Jylhä P (2005) Effects of competing vegetation and post-planting weed control on the mortality, growth and vole damages to *Betula pendula* planted on former agricultural land. Silva Fenn 39: 365–380. https://doi.org/10.14214/sf.374.

Hytönen J, Jylhä P (2008) Fifteen-year response of weed control intensity and seedling type on Norway spruce survival and growth on arable land. Silva Fenn 42: 355–368. https://doi.org/10.14214/sf.242.

Hytönen J, Jylhä P (2013) Long-term effect of weed control on survival and growth of silver birch planted on arable land. Balt For 19: 170–178.

Hytönen J, Kiljunen N, Poteri M (2009) Finland. In: Willoughby I, Balandier P, Bentsen NS, Mac Carthy N, Claridge J (eds) Forest vegetation management in Europe: current practice and future requirements. European co-operation in science and technology (COST) Office, pp 25–32.

Jacobsen S, Högbom L, Ring E, Nohrstedt H-O (2017) The distribution of logging residues and its impact on seedling establishment and early plant growth in two Norway spruce stands. Scan J For Res 32: 134–141. https://doi.org/10.1080/02827581.2016.1194456.

Johansson T, Lundh E-K (2008) Försök med upprepad röjning av björk och sälg. [Trials with repeated cleaning of birch and sallow]. SLU, Department of energy and technology. Report 004.

Johansson K, Nilsson U, Örlander G (2013) A comparison of long-term effects of scarification methods on the establishment of Norway spruce. Forestry 86: 91–98. https://doi.org/10.1093/forestry/cps062.

Jylhä P, Hytönen J (2006) Effect of vegetation control on the survival and growth of Scots pine and Norway spruce planted on former agricultural land. Can J For Res 36: 2400–2411. https://doi.org/10.1139/x06-053.

Kankaanhuhta V, Saksa T, Smolander H (2009) Variation in the results of Norway spruce planting and Scots pine direct seeding in privately-owned forests in southern Finland. Silva Fenn 43: 51–70. https://doi.org/10.14214/sf.217.

Knapp BO, Wang GG, Walker JL (2008). Relating the survival and growth of planted longleaf pine seedlings to microsite conditions altered by site preparation treatments. For Ecol Manag 255: 3768–3777. https://doi.org/10.1016/j.foreco.2008.03.013.

Kogan, M, Alister, C (2010) Glyphosate use in forest plantations. Chil J Agric Res 70: 652–666. https://doi.org/10.4067/S0718-58392010000400017.

Laine T, Kankaanhuhta V, Rantala J, Saksa T (2020) Effects of spot mounding and inverting on growth of conifers, exposed mineral soil and natural birch regeneration. Silva Fenn 54, article id 10369. https://doi.org/10.14214/sf.10369.

Lindstrom A, Troeng E (1995) Temperature variations in planting mounds during winter. Can J For Res 25: 507–515. https://doi.org/10.1139/x95-057.

Löf M, Rydberg D, Bolte A (2006) Mounding site preparation for forest restoration: survival and short term growth response in *Quercus robur* L. seedlings. For Ecol Manag 232: 19–25. https://doi.org/10.1016/j.foreco.2006.05.003.

Lund-Høie K (1983) The influence of temperature on the phytotoxic effect of glyphosate on Norway spruce (*Picea abies* L.). Crop Prot 2: 409–416. https://doi.org/10.1016/0261-2194(83)90061-3.

Luoranen J, Viiri H (2021) Comparison of the planting success and risks of pine weevil damage on mineral soil and drained peatland sites three years after planting. Silva Fenn 55 article id 10528. https://doi.org/10.14214/sf.10528.

Luoranen J, Viiri H, Sianoja M, Poteri M, Lappi J (2017) Predicting pine weevil risk: effects of site, planting spot and seedling level factors on weevil feeding and mortality of Norway spruce seedlings. For Ecol Manag 389: 260–271. https://doi.org/10.1016/j.foreco.2017.01.006.

Luoranen J, Riikonen J, Saksa T (2022a) Factors affecting winter damage and recovery of newly planted Norway spruce seedlings in boreal forests. For Ecol Manage 503, article id 119759. https://doi.org/10.1016/j.foreco.2021.119759.

Luoranen J, Laine T, Saksa T. (2022b) Field performance of sand-coated (Conniflex®) Norway spruce seedlings planted in mounds made by continuously advancing mounder and in undisturbed soil. For Ecol Manag 517, article id 120259. https://doi.org/10.1016/j.foreco.2022.120259.

Miina J, Saksa T (2006) Predicting regeneration establishment in Norway spruce plantations using a multivariate multilevel model. New For 32: 265–283. https://doi.org/10.1007/s11056-006-9002-y.

Mikola P (1942) Koivun vesomisesta ja sen metsänhoidollisesta merkityksestä. [Sprouting of birch and the silvicultural importance of it]. Acta For Fenn 50. https://doi.org/10.14214/aff.7356.

Munson AD, Margolis HA, Brand DG (1993) Intensive silvicultural treatment: impacts on soil fertility and planted conifer response. Soil Sci Soc Am J 57: 246–255. https://doi.org/10.2136/sssaj1993.03615995005700010043x.

Nilsson U, Luoranen J, Kolström T, Örlander G, Puttonen P (2010) Reforestation with planting in northern Europe. Scand J For Res 25: 283–294. https://doi.org/10.1080/02827581.2010.498384.

Nordborg F (2001) Effects of site preparation on soil properties and on growth, damage and nitrogen uptake in planted seedlings. Acta Uni agric Suec Silv 195: 1–11.

Nordborg F, Nilsson U, Örlander G (2003) Effects of different soil treatments on growth and net nitrogen uptake of newly planted *Picea abies* (L.) Karst. seedlings. For Ecol Manag 180: 571–582. https://doi.org/10.1016/S0378-1127(02)00650-3.

Örlander G, Nilsson U (1999a) Effect of reforestation methods on Pine weevil (*Hylobius abietis*) damage and seedling survival. Scand J For Res 14: 341–354. https://doi.org/10.1080/02827589950152665.

Örlander H, Nilsson U (1999b) Vegetation management on grass-dominated clearcuts planted with Norway spruce in southern Sweden. Can J For Res 29: 1015–1026. https://doi.org/10.1139/

x99-071.

Örlander G, Gemmel P, Hunt J (1990) Site preparation: a Swedish overview. FRDA Report 105: 1–61.

Örlander G, Hallsby G, Gemmel P, Wilhelmsson C (1998) Inverting improves establishment of *Pinus contorta* and *Picea abies*— 10-year results from a site preparation trial in Northern Sweden. Scand J For Res 13: 160–168. https://doi.org/10.1080/02827589809382972.

Peltola, A Ihalainen, A, Mäki-Simola, E Sauvula-Seppälä, T Torvelainen, J, Uotila, E Vaahtera, E Ylitalo, E (2019) Finnish forest statistics. Natural Resources Institute Finland, Helsinki. http://urn.fi/URN:ISBN:978-952-326-856-2.

Raulo J, Mälkönen E (1976) Koivun luontainen uudistuminen muokatulla kangasmaalla. [Natural regeneration of birch (Betula verrucosa hrh. and B. pubescens Ehrh.) on tilled mineral soil]. Folia For 252. http://urn.fi/URN:ISBN:951-40-0197-4.

Ritari A, Lähde E (1978) Effect of site preparation on physical properties of the soil in a thick-humus spruce stand. Commun Inst for Fenn 92. http://urn.fi/URN:NBN:fi-metla-201208286003.

Saarinen V-M (2006) The effects of slash and stump removal on productivity and quality of forest regeneration operations—preliminary results. Biomass Bioenergy 30: 349–356. https://doi.org/10.1016/j.biombioe.2005.07.014.

Saksa T (2019) Maanmuokkauksen historia ja kehitys. [History and development of mechanical site preparation]. In: Laine T, Luoranen J, Ilvesniemi H (eds) Metsämaan muokkaus: kirjallisuuskatsaus maanmuokkauksen vaikutuksista metsänuudistamiseen, vesistöihin sekä ekologiseen ja sosiaaliseen kestävyyteen. Luonnonvara- ja biotalouden tutkimus 58/2019. Natural Resources Institute Finland (Luke), Helsinki, pp. 8–9. http://urn.fi/URN:ISBN:978-952-326-813-5.

Saksa T, Kankaanhuhta V (2007) Metsänuudistamisen laatu ja keskeisimmät kehittämiskohteet Etelä-Suomessa. [Quality and the main develoment needs of forest regenration in Southern Finland]. Metsänuudistamisen laadun hallinta -hankkeen loppuraportti. Metsäntutkimuslaitos, Suonenjoen yksikkö. http://urn.fi/URN:ISBN:978-951-40-2040-7.

Saksa T, Miina J, Haatainen H, Kärkkäinen K (2018). Quality of spot mounding performed by continuously advancing mounders. Silva Fenn 52, article id 9933. https://doi.org/10.14214/sf.9933.

Siipilehto J (2001) Effect of weed control with fibre mulches and herbicides on the initial development of spruce, birch and aspen seedlings on abandoned farmland. Silva Fenn 35: 403–414. https://doi.org/10.14214/sf.577.

Siipilehto J, Lyly O (1995) Weed control trials with fibre mulch, glyphosate and terbuthylazine in Scots pine plantations. Silva Fenn 29: 41–48. https://doi.org/10.14214/sf.a9196.

Sikström U, Hjelm K, Holt Hanssen K, Saksa T, Wallertz K (2020) Influence of mechanical site preparation on regeneration success of planted conifers in clearcuts in Fennoscandia – a review. Silva Fenn 54, article id 10172. https://doi.org/10.14214/sf.10172.

Smolander A, Heiskanen J (2007) Soil N and C transformations in two forest clear-cuts during three years after mounding and inverting. Can J Soil Sci 87: 251–258. https://doi.org/10.4141/S06-028.

Söderström V, Bäcke J, Byfalk R, Jonsson C (1978) Comparison between planting in mineral soil heaps and after some other soil treatment methods. SLU, Department of Silviculture, Research Notes 11.

Sutton RF (1993) Mounding site preparation: a review of European and North-American experience. New For 7: 151–192. https://doi.org/10.1007/BF00034198.

Taylor WL (1945) Weeding and cleaning. Forestry 19: 27–32. https://doi.org/10.1093/forestry/19.1.27.

Uotila K, Saksa T (2021) Cost-efficient pre-commercial thinning: effects of method and season of early cleaning. Silva Fenn 55, article id 10507. https://doi.org/10.14214/sf.10507.

Uotila K, Rantala J, Saksa T, Harstela P (2010) Effect of soil preparation method on economic result of Norway spruce regeneration chain. Silva Fenn 44: 511–524. https://doi.org/10.14214/sf.146.

Uotila K, Rantala J, Saksa T (2012) Estimating the need for early cleaning in Norway spruce plantations in Finland. Silva Fenn 46, article 919. https://doi.org/10.14214/sf.919.

Uotila K, Saksa T, Rantala J, Kiljunen N (2014) Labour consumption models applied to motor-manual pre-commercial thinning in Finland. Silva Fenn 48, article id 982. https://doi.org/10.14214/sf.982.

Venables WN, Smith DM (2021) An introduction to R.

Wallertz K, Malmqvist C (2013) The effect of mechanical site preparation methods on the establishment of Norway spruce (*Picea abies* (L.) Karst.) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) in southern Sweden. Forestry 86: 17–78. https://doi.org/10.1093/forestry/cps065.

Wallertz K, Björklund N, Hjelm K, Petersson M, Sundblad L-G (2018) Comparison of different site preparation techniques: quality of planting spots, seedling growth and pine weevil damage. New For 49: 705–722. https://doi.org/10.1007/s11056-018-9634-8.

Wendel GW, Kochenderfer JN (1984) Aerial release of Norway spruce with Roundup in the Central Appalachians. Nort J Appl For 1: 29–32. https://doi.org/10.1093/njaf/1.2.29.

Total of 64 references.