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Successful spruce regenerations – impact of site preparation and the use of variables from digital elevation models in decision-making?

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ABSTRACT

Various site preparation methods are used in Swedish forestry. However, some methods can lead to unnecessary disturbance, which could be avoided by using variables from digital elevation models in management decisions. The current study aimed to investigate how different site preparation methods, and their intensities, affect Norway spruce (*Picea abies* (L.) Karst.) regeneration. Additional aims were to clarify how these methods affect soil disturbance and vegetation development, along with how variables from digital elevation models could be used in silvicultural decision-making. Experimental sites were established in southern Sweden to assess five different site preparation treatments with different planting densities: (1) conventional disc trenching 2500 seedlings/ha (DT2500); (2) low intensity disc trenching 1250 seedlings/ha (LDT1250); (3) low intensity disc trenching 2500 seedlings/ha (LDT2500); (4) low-intensity patch-wise 1250 seedlings/ha (PW1250); and (5) patch-wise 2500 seedlings/ha (PW2500). Site preparation intensity had no effect on seedling growth and, survival or vegetation development; the tested treatments differed in terms of soil disturbance. Planting spot properties and weather conditions influenced the seedling performance. DTW and slope could not substantially explain either seedling growth or survival. The results indicate that the choice of site preparation method should consider flexibility when planting while adapting the level of disturbance accordingly.

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KEYWORDS
Disturbance; depth-to-water; Norway spruce; regeneration; site preparation

Introduction

The use of mechanical site preparation before planting is one of the most common practices in Swedish forestry and is applied in close to 90% of regeneration efforts in the southern counties (Bergquist et al. 2017). It is critical to create a suitable planting environment for seedlings when regenerating a clear-cut area (Thiffault and Jobidon 2006; Hébert et al. 2014; Wallertz et al. 2018). For this reason, mechanical site preparation is often used, with the main benefits being the suppression of competing vegetation (Nilsson and Örlander 1999; Mallik and Kravchenko 2016) and the creation of planting spots which give seedlings the best possible opportunity to overcome numerous risks to survival (Langvall et al. 2001; Petersson et al. 2005; Heiskanen et al. 2013; Luoranen et al. 2017). Mechanical site preparation also promotes growth by creating planting spots which alter the environmental conditions on a given site (Sutton 1993; Burton et al. 2000; Hansson et al. 2018; Hjelm et al. 2019). This can be achieved through various methods (Löf et al. 2012; Sikström et al. 2020) that employ either continuous, e.g. disc trenching (Burton et al. 2000), or intermittent, e.g. inversion or mounding (Sutton 1993; Johansson et al. 2013a), site preparation.

Site preparation creates suitable planting spots, and hence can increase the amount of natural regeneration along with survival of planted coniferous seedlings (Karlsson and Nilsson 2005; Lehtosalo et al. 2010; Saursaunet et al. 2018). This can create a mixture of coniferous and deciduous trees in the future stand (Nilsson et al. 2006), which is often required for different certification schemes (FSC, 2020; PEFC, 2020). Mixed forests can also be advantageous for biodiversity and to increase resilience towards different risks (Felton et al. 2010; Hahn et al. 2021; Huuskonen et al. 2021). However, an increased amount of natural regeneration can be a disadvantage in later stages of stand development due to increased competition between the naturally regenerated and planted seedlings, which will increase pre-commercial thinning costs (Ahtikoski et al. 2010; Uotila et al. 2010). Though most studies that focuses on natural regeneration within the disturbed area, the area in between is seldom taken into account. Additionally, even if site preparation proves to be effective in controlling competing vegetation (Thiffault and Jobidon 2006; Löf et al. 2012) the decolonization of disturbed areas is a relatively fast process that gives seedlings a relatively short period of time when they are free from competition (Nilsson and Örlander 1999; Archibold et al. 2000; Haeussler et al. 2017). Site preparation can also affect other site characteristics beyond seedling establishment, with these effects sometimes being negative. For example, it can result in possible damage to cultural remains (Dolk Fröjd and Norrman 2007; SFA 2021), influence recreational values (Karjalainen 2006) and alter the vegetation composition (Archibold et al. 2000; Haeussler et al. 2017; Cardosso et al. 2020). The chosen method influences how large of an area will be disturbed, with patch-wise methods having a less significant effect than

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continuous methods (Strömgren et al. 2017; Sikström et al. 2020). On the other hand, continuous methods usually provide a greater number of available planting spots (Örlander et al. 1990; Wallertz et al. 2018). In Sweden, seedlings are usually planted in a square design of 2×2 m with around 2500 seedlings per hectare, and the site preparation method is commonly adapted accordingly. However, research has shown that planting design has very little effect on future coniferous forest growth (Ara et al. 2021), providing opportunities for more focus on the choice of a suitable planting spot regardless of planting design. A more flexible approach that integrates site preparation method, planting spot selection and planting design could therefore minimize the amount of overall soil surface disturbance and simultaneously meet the requirements of seedling establishment (Sikström et al. 2020).

On average, a clear-cut in southern Sweden ranges between 4 and 10 ha and is usually treated as one unit even though clear-cuts are rarely homogenous. Site variation within a clear-cut can affect the result of regeneration efforts and could provide a basis for diversified management on a smaller scale (Skovsgaard and Vanclay 2013; Holmström et al. 2019). It is possible to determine terrain variations across a site by processing high resolution (i.e. 2×2 meters) digital elevation models (DEM). Terrain variation within a site can be of interest when explaining differences in seedling growth (Henneb et al. 2019). Similarly, hydrological conditions can be displayed in high-resolution raster maps to indicate where in the landscape wet and moist areas can be found (Murphy et al. 2011; White et al. 2012; Ågren et al. 2015). Previous studies have also shown that the depth-to-water (DTW) index can be used on the landscape level to predict the regeneration of field vegetation and the regrowth of forest stands following large disturbances (Nijland et al. 2015; Van Rensen et al. 2015). High-resolution (2×2 m) DTW-maps are also useful for the explanation of seedling survival on a smaller scale within stands (Holmström et al. 2019). The understanding of how a clear-cut varies in different aspects that are known to affect seedling survival and growth can therefore be valuable for making well-grounded regeneration decisions.

In this study, an experiment designed to investigate the long-term effects of various site preparation methods, seedling number and seedling spacing was used. A long-term goal of the experiment is to study the development of the forest composition over time in terms of tree species composition, vegetation cover and forest growth. The layout of the experiment made it possible to look at the spatial variation of the clear-cut in smaller areas of 32×32 m in different aspects. The objective was to investigate how different site preparation methods and their intensities affect growth and survival of Norway spruce (*Picea abies* (L.) Karst.) seedlings, and how these methods impact soil disturbance and vegetation development. Additionally, the value of variables from DEMs, such as soil moisture maps and slope rasters, in explaining regeneration results and how these could be used in regeneration planning was evaluated. It was hypothesized that:

(1) With an availability of suitable planting spots, there is no difference in seedling growth and survival between disc trenching and patch-wise site preparation treatments.
(2) Site preparation intensity influences the extent of soil disturbance, which increases field vegetation cover and natural regeneration.
(3) DTW and slope rasters can be used to explain the growth and survival of planted spruce seedlings.

Materials and methods

Experimental design

The experiment included two sites in southern Sweden, Fänneslunda in the province of Västergötland and Tagel in the province of Småland (Table 1). Fänneslunda and Tagel sites were clear-felled in the winter of 2016 and 2017, respectively, and established in the spring and early summer of the following year. Slash residue was removed from the clear-cuts prior to establishment. In Fänneslunda, precipitation during the growing season (April–October) varied between 465 and 636 mm, while mean temperatures varied between 10.8 and 13.2°C. In Tagel, precipitation during the growing season varied between 319 and 489 mm, while mean temperatures varied between 11.7°C and 13.6°C. A longer dry period occurred between June and July in 2018 at both sites with only 80 mm of rain in Fänneslunda and 28 mm of rain in Tagel. (SMHI 2020).

Two different site preparation methods, disc trenching and patch-wise soil inversion, were applied to five 32×32 m treatment plots. Disc trenching was performed using a Bracke T26 (Bracke Forest, Bräcke, Sweden) mounted on a forwarder and patch-wise soil inversion with Karl-Oscar (BSM Verkstads AB, Alvesta, Sweden) mounted on an excavator. To create different levels of disturbance and planting densities, the number of rows after disc trenching or the number of patches in patch-wise soil inversion varied within the treatment plots. This resulted in five treatment

Table 1. Information about the two study sites.

Site	Fänneslunda	Tagel
Year of establishment	2017	2018
Latitude (°N)	57.854228	57.049462
Longitude (°E)	13.136115	14.394866
Altitude (m a.s.l.)	219	233
DTW-range (cm)	76.58–719.29	37.84–364.65
Slope-range (°)	3.95–7.27	1.85–4.74
Percipitation (mm)[a]		
1990–2020	580.2	479.9
2017	636.4	
2018	465.6	319.1
2019	533.9	489.1
2020		437.9
Mean temperature (°C)[b]		
1990–2020	11.0	11.5
2017	10.8	
2018	13.2	13.6
2019	11.6	11.8
2020		11.7
Stoniness (%)[c]	39	61

[a]Recorded precipitation at the nearest weather station (SMHI 2020) during the growing season (April–October) for each year within the study period and the mean precipitation during the latest climate period (1990–2020).
[b]The mean air temperature recorded at the nearest weather station (SMHI 2020) during the growing season (April-October) for each year during within the study period and the mean air temperature during the latest climate period (1990–2020).
[c]Average proportion of times stones were encountered on a depth of 20 cm.

combinations, which were repeated across three blocks at each site: (1) conventional disc trenching with 2 m between double rows and a planting spacing of 2 m within rows (2500 seedlings/ha) (DT2500), (2) low-intensity disc trenching with 6 m between double rows and a planting spacing of 2 m within rows (1250 seedlings/ha) (LDT1250), (3) low-intensity disc trenching with 6 m between double rows and a planting spacing of 1 m within rows (2500 seedlings/ha) (LDT2500), (4) low-intensity patch-wise site preparation resulting in 1250 spots/ha with a spacing of approximately 3 m between the patches (PW1250), and (5) patch-wise preparation resulting in 2500 spots/ha with a spacing of approximately 2 m between patches (PW2500) (Figure 1). Since the patch-wise treatments created various planting spots, the best possible spot was chosen at the time of planting. An optimal spot was characterized as an elevated spot of pure mineral soil, in the furrow after disc trenching, and in the middle of the patch of pure mineral soil after soil inversion.

The seedling material used in this experiment consisted of genetically improved containerized cuttings of Norway spruce grown at Skogforsk's nursery in Ekebo, Sweden. Although cuttings were used, they will hereafter be referred to as seedlings. The different planting densities used in the treatments resulted in either 256 seedlings/plot (treatment 1, 3, and 5) or 128 seedlings/plot (treatment 2 and 4). A total of 5640 seedlings were used in the experiment, 2907 in F and 2733 in T. Following planting, the seedlings were protected against pine weevil (*Hylobius abietis* L.) with insecticide treatments, Imprid Forest (active substance acetamiprid) in Fänneslunda and Merit forest (active substance imidacloprid) in Tagel. Insecticide treatments were repeated in spring one year after planting for further protection. Due to a large number of dead seedlings in Tagel after the dry summer of 2018, the site was supplementary planted in the spring of 2019 with all of the dead seedlings replaced. The plant material used in 2019 were also cuttings of the same origin as the ones planted in 2018.

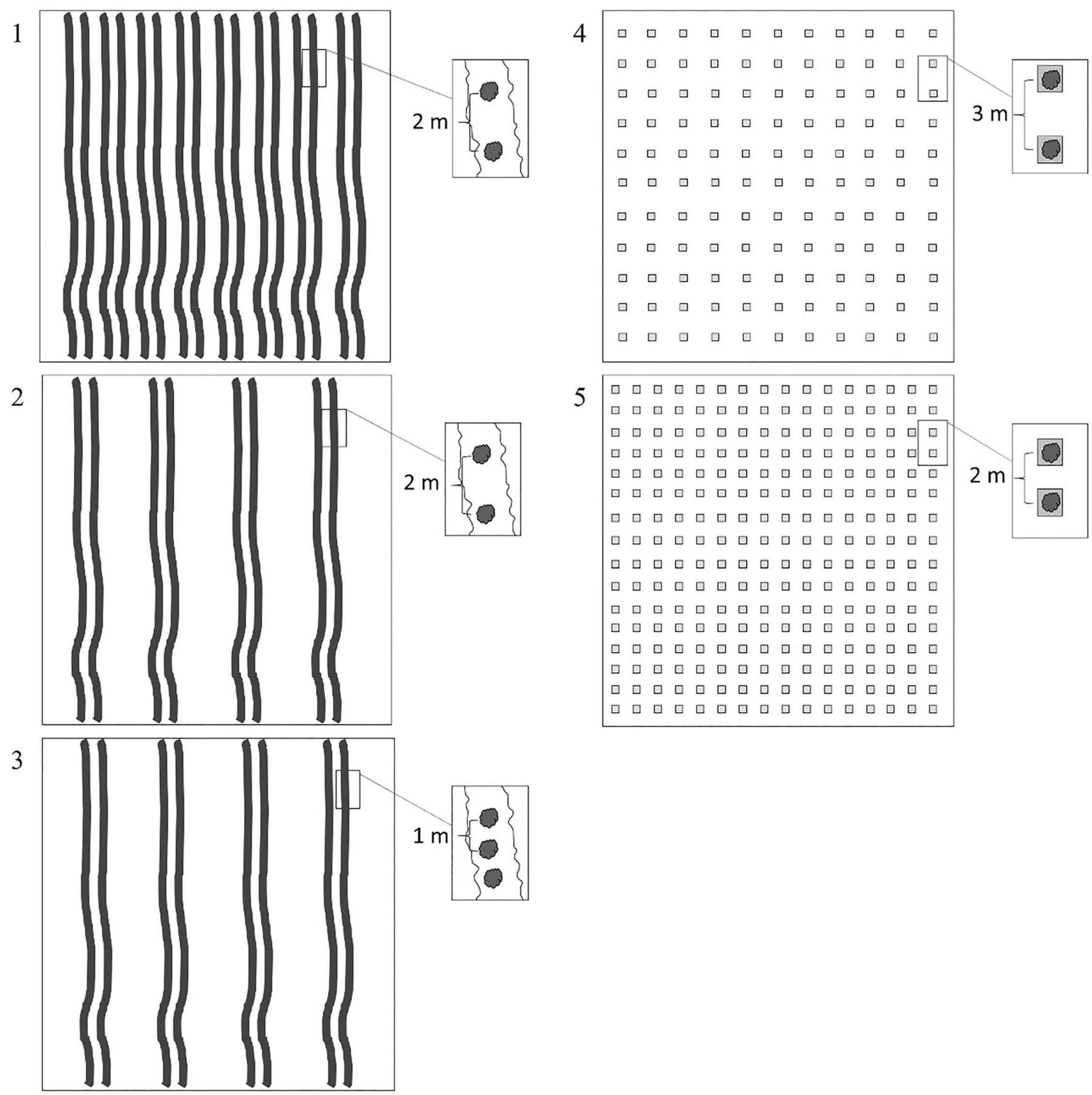

Figure 1. The design of the different site preparation treatments which were tested in the study. (1) DT2500, Conventional disc trenching, (2) LDT1250 Low-intensity disc trenching with sparse planting, (3) LDT2500, Low-intensity disc trenching with dense planting, (4) PW1250, Low-intensity patch-wise site preparation, (5) PW2500, Patch-wise site preparation.

Field measurements

Seedling height above the soil surface and the length of the leading shoot were measured after the first three growing seasons in October (Fänneslunda: 2017–2019, Tagel: 2018–2020). Seedling damage was also assessed at these three occasions based on a seven-level scale: 0 = No damage; 1 = Negligible damage; 2 = Slightly damaged (reduced growth but not smaller than the previous year); 3 = Severe damage (reduced growth and smaller than the previous year); 4 = Lethal damage (expected to die the following year); 5 = Dead; and 6 = Missing. The cause of damage, e.g. drought, damage by pine weevil or browsing, was also registered. When the cause of damage could not be determined, it was noted as unknown damage.

Planting spot type and soil type were assessed based on the environment within a 10 cm radius of each seedling. These assessments were done after the first growing season in Tagel and after the second growing season in Fänneslunda. Planting spot type was divided into three classes: 0 = No site preparation; 1 = Furrow/hole/patch; 2 = Mound/berm/inverted planting spot. For schematics of the planting spot types see Sikström et al. (2020). Soil type was divided into four classes: 0 = No site preparation; 1 = Disturbed humus; 2 = Mix of humus and mineral soil; and 3 = Bare mineral soil. A majority of the seedlings, approximately 90%, were planted in the soil type bare mineral soil regardless of site preparation treatment. Planting spot type differed between treatments where seedlings planted in furrow/hole/patch were most common in the DT2500, LDT1250, and LDT2500 treatments (94% in Fänneslunda and 93% in Tagel). In PWP1250 and PWP2500 planting spot type varied more resulting in seedlings being planted both in furrow/hole/patch and mound/berm/inverted planting spots (Figure 2).

Additionally, the percentage of field vegetation cover in a 30 cm radius around each seedling was visually assessed after each growing season. The numbers of naturally regenerated deciduous and coniferous seedlings within the same radius were also registered after each growing season.

A total of six circular plots with a radius of 1.78 m were placed systematically across a diagonal transect in each treatment plot. The first circular plot was placed at a distance of 3.5 m into the treatment plot and with the remaining five circular plots placed every 7 m. These circular plots were used to

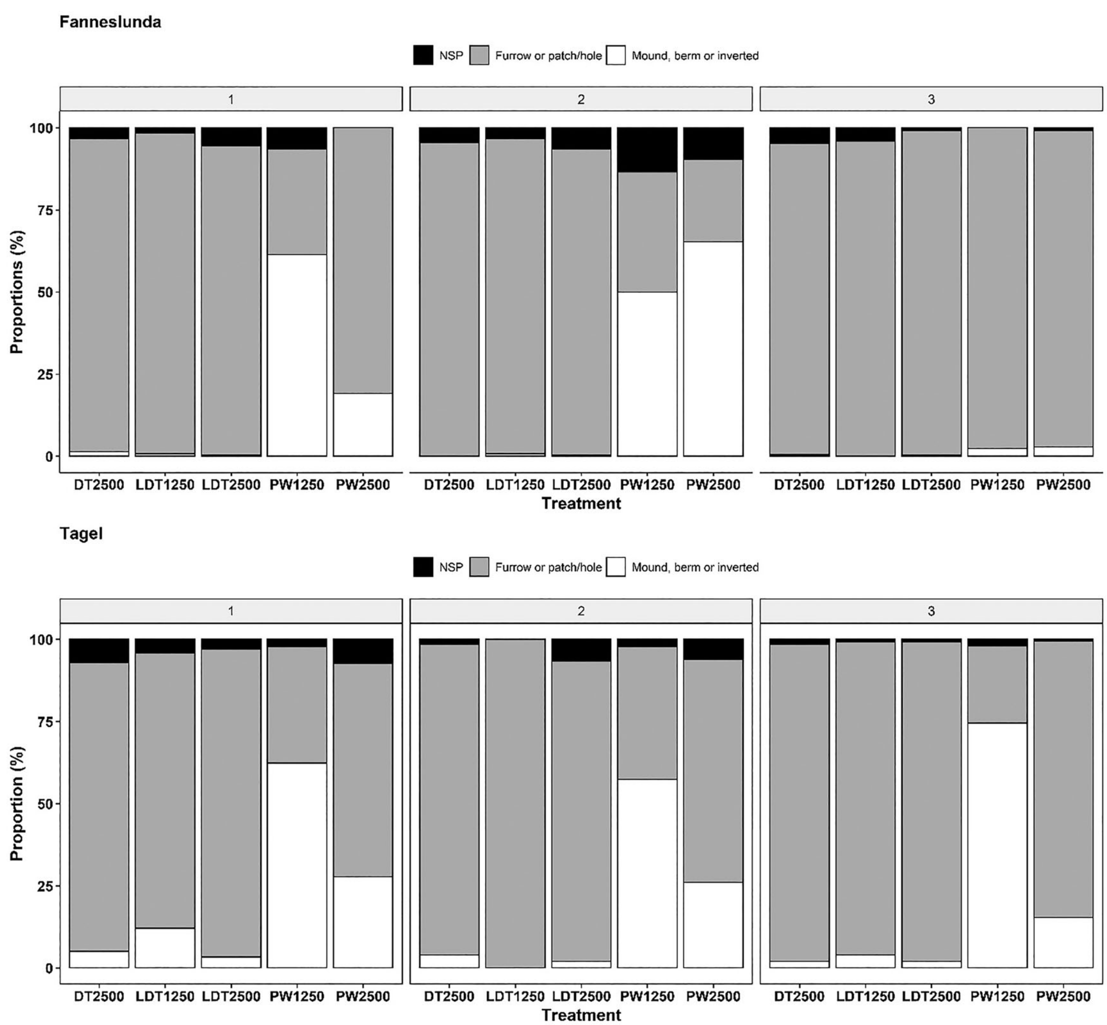

Figure 2. Proportion of seedlings planted in different planting spots across the various treatments and blocks within the two sites. DT2500, Conventional disc trenching; LDT1250 Low intensity disc trenching with sparse planting; LDT2500, Low intensity disc trenching with dense planting; PW1250, Low intensity patch-wise site preparation; PW2500, Patch-wise site preparation. NSP stands for no site preparation.

inventory stoniness and soil disturbance following the different site preparation treatments after the first growing season. Soil disturbance was determined by visually assessing the percentage of coverage by five disturbance classes, (1) bare mineral soil (BMS), (2) mineral soil on top of humus (MSOH), (3) mineral soil mixed with humus (MSH), (4) disturbed humus (DH), and (5) undisturbed (U). Stoniness was assessed by pushing a metal rod into the ground to a depth of 20 cm at three randomly chosen spots in each circular plot, i.e. a total of 18 per treatment plot. The number of times the pin hit a stone was recorded, after which the total amount of hits per treatment plot was divided by 18 to express the stoniness of the plot (Berg and Wickström 1982). Stoniness varied between the blocks in both sites and averaged 39% in Fänneslunda and 61% in Tagel (Table 1). The circular plots were also used to count the number of naturally regenerated coniferous and deciduous seedlings, and to visually assess field vegetation cover after each growing season. This was done to capture not only the regeneration within the planting spots but also the area in between which was not as affected by the site preparation treatment. There was no distinction made between field vegetation cover and naturally regenerated seedlings that was present before and after site preparation when counting and assessing.

Variables from DEMs

Estimated soil moisture data was obtained from a DTW-raster (2×2 m resolution), available at the Swedish Forest Agency (SFA). The values in a DTW-raster are based on models which calculate where water accumulates in the landscape based on topographical variation and values can range from 0 mm to more than 1000 mm where the closer to 0 the wetter it is (Murphy et al. 2008, 2011; Ågren et al. 2015). Based on the applied treatment plots, the mean pixel value per each 32×32 m plot was calculated and extracted using ArcGIS Pro (Esri, West Redlands, CA). A similar process was used to extract the mean slope value for each treatment plot from a slope-raster (2×2 m resolution). All of the DTW-values were log-transformed (eDTW) before used in the models.

Data analysis

Growth was estimated as the accumulated length of the leading shoot across three years. Mortality was defined as the number of seedlings represented in damage class 5 after three growing seasons. To analyze the effect of planting spot type on growth, a mixed-effects model (Equation (1)) with planting spot type as a fixed effect and block as a random effect, was constructed using the lme function from the R statistical package nlme (Pinheiro et al. 2021).

$$Y_{ik} = \mu + b_k + \omega_i + \varepsilon_{ik} \qquad (1)$$

where Y_{ik} = response variable (growth), μ = the overall mean, b_k = block effect (random), (k = 1,.., 3), ω_i = fixed effect of the i:th planting spot type (i = 1, … , 3) and ε_{ik} = the random error.

To test the effects of planting spot type on mortality a generalized mixed-effects model (Equation (2)), where mortality (η) was assumed a binomial distribution, with a logit link function was constructed using the glmer function in the R statistical package LmerTest (Kuznetsova et al. 2017), an add-on to the lme4 package (Bates et al. 2015). Similar to the previous model planting spot was used as a fixed effect and block as a random effect. The models were used for both sites separately.

$$\mathrm{logit}(\eta_{ik}) = \log\left(\frac{\eta_{ik}}{1-\eta_{ik}}\right) = \mu + b_k + \omega_i + \varepsilon_{ik} \qquad (2)$$

The parameters are the same as in Equation (1).

When testing the site preparation treatments and the effect of eDTW and slope on growth and mortality, mean growth and mortality were calculated for each treatment plot after the third growing season and fitted in a mixed-effects model, using the same R function as Equation (1), with site preparation treatment, eDTW and slope as fixed effects and block as a random effect. The following model was used for both sites separately.

$$Y_{ik} = \mu + b_k + \alpha_i + (b\alpha) + \beta_{ik} + \Phi_{ik} + \varepsilon_{ik} \qquad (3)$$

The terms are as follows: Y_{ik} = response variable (growth or mortality), μ = the overall mean, b_k = block effect (random), (k = 1,.., 3), α_i = fixed effect of the i:th site preparation treatment (i = 1, … , 5), β = fixed effect of slope, Φ = fixed effect of eDTW, $b\alpha$ = interaction term between block and site preparation, ε_{ik} = the random error.

The soil disturbance classes BMS, MSOH, MSH, and DH were combined to investigate how site preparation treatment contributed to soil disturbance. Plot means were calculated to compare the difference between site preparation treatments in the following ANOVA model:

$$Y_{ik} = \mu + b_k + \alpha_i + \varepsilon_{ik} \qquad (4)$$

where the parameters are the same as described for Equation (3). The same model was used to compare the field vegetation cover and the number of naturally regenerated seedlings per hectare (circular plots of 1.78 m radius), as well as naturally regenerated seedlings and field vegetation cover at planting spot level (30 cm radius) across plots representing the two site preparation treatments after the third growing season.

Whenever significant differences in the response variable for the planting spot type or site preparation method was detected a Tukey post-hoc test was conducted. Differences were deemed significant when $p < 0.05$. The proportional variables field vegetation cover, soil disturbance and mortality were logit transformed to meet assumptions of normality and homogeneity when needed.

Results

Seedling responses

Mortality

There were large between-site differences in seedling mortality (Figures 3 and 4). In Fänneslunda, average mortality was 10%, while average mortality in Tagel 49%. A majority of the seedlings died after the exceptionally dry and warm growing season of 2018 (5% in Fänneslunda and 34% in Tagel). The seedling death in Fänneslunda was mainly explained by drought (45%) or unknown damage (50%), with the remaining 5% due to pine weevil damage. In Tagel, the predominant cause of death was drought (71%) followed by unknown damage (25%) and pine weevil damage (4%).

Seedling mortality was significantly affected by the planting spot type in both Fänneslunda ($p < 0.05$) and Tagel ($p < 0.05$). The highest mortality rate after three growing seasons was observed in the no site preparation treatment (on average 24% in Fänneslunda and 66% in Tagel) and the mound/berm/inverted classes (on average 24% in Fänneslunda and 68% in Tagel). Seedlings planted in the class furrow/hole/patch class had a larger chance of surviving compared to the other two classes with on average mortality rates of 7% an 45% in Fänneslunda and Tagel respectively (Figure 3).

Site preparation treatment had no significant effect on seedling mortality in Fänneslunda, moreover, neither slope nor DTW exerted any significant effect on mortality (Table 2). The two patch-wise treatments showed a slightly higher mortality rate than the three disc trenching treatments, although this difference was not statistically significant (Figure 4). A similar result was observed in Tagel, i.e. site preparation treatment, DTW, or slope did not significantly affect seedling mortality (Table 2). Although the difference was not statistically significant, the PW1250 treatment showed a noticeably higher mortality rate (77%) than any of the other site preparation treatments. The mortality rates for treatments DT2500, LDT1250, LDT2500, and PW2500 were 51%, 45%, 44%, and 41%, respectively.

Growth

It was clear that growth differed between sites, with a generally higher growth in Fänneslunda (overall average 387 mm) than in Tagel (overall average 247 mm). Planting spot type significantly affected the growth in both Fänneslund ($p < 0.05$) and Tagel ($p < 0.05$) after three growing seasons. In Fänneslunda, the seedlings planted in the furrow/hole/patch grew better than the seedlings planted in the mound/berm/inverted but similarly to the seedlings planted in no site preparation. However, in Tagel seedlings planted in the mound/berm/inverted spots grew better than the seedlings planted in the furrow/hole/patch but grew similarly to seedlings planted in no site preparation spots (Figure 3).

Growth was found to be significantly affected by site preparation treatment in Fänneslunda after three growing seasons, but not in Tagel (Table 2). In Fänneslunda, LDT1250 had the highest growth, followed by LDT2500. PW1250 had the lowest growth, although the average value was only significantly lower than what was observed for DT2500 and LDT1250 (Figure 4). In Tagel, no differences in growth were observed across the site preparation treatments after three growing seasons. Nevertheless, LDT2500 and PW2500 showed the highest growth, with LDT1250 resulting in the lowest growth (Figure 4).

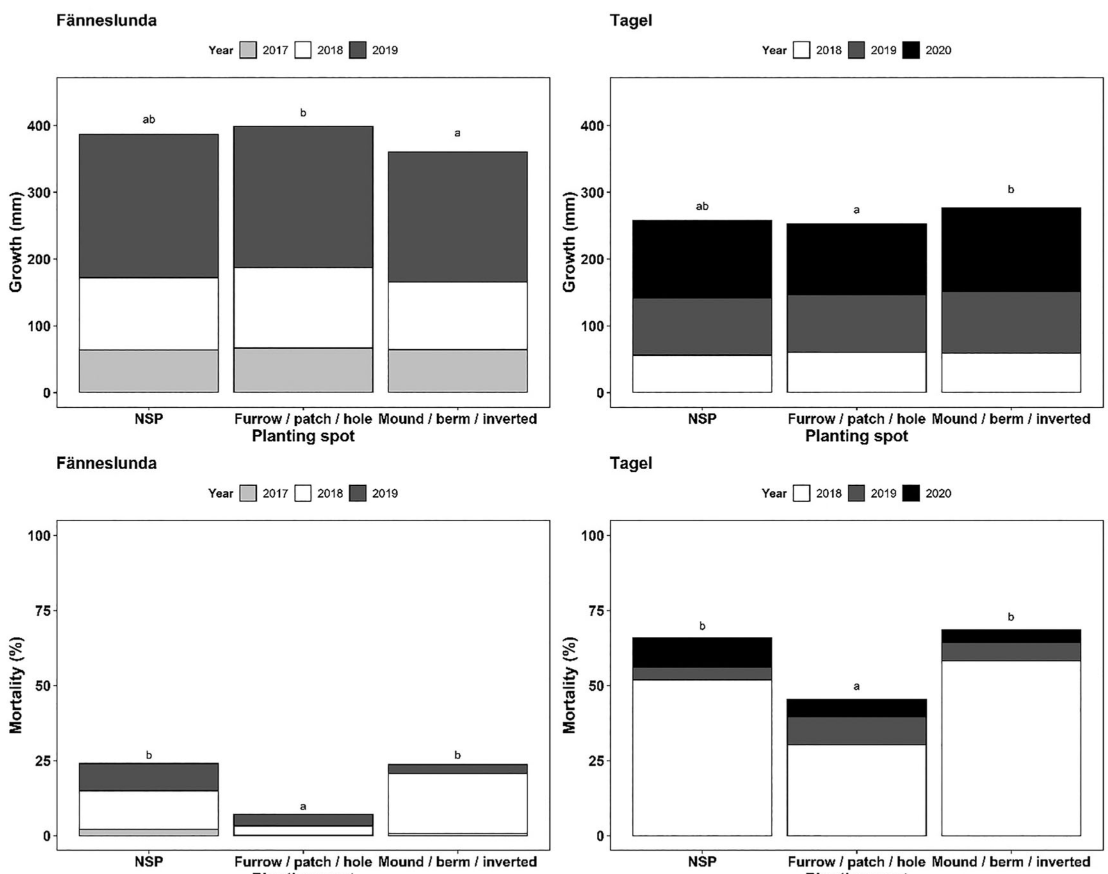

Figure 3. Growth, displayed as the total leading shoot growth, across different planting spot types and study sites split by year. The mortality rates of the seedlings after three growing seasons across the different planting spot types and study sites split by year illustrated below. Letters indicates significant difference between planting spot types. NSP stands for no site preparation.

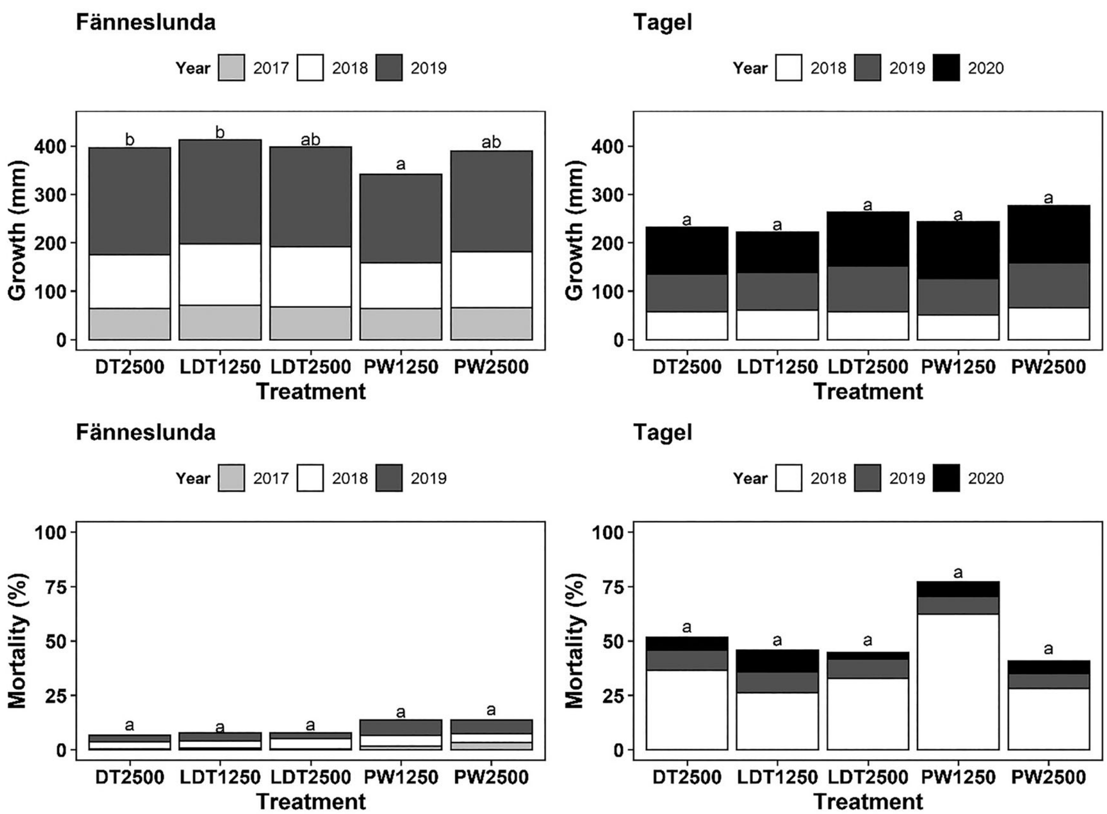

Figure 4. Growth, displayed as the total leading shoot growth, across different soil preparation treatments and study sites split by year. The mortality rates of the seedlings after three growing seasons across the different soil preparation treatments and study sites split by year are illustrated below. Letters indicate significant difference between site preparation treatments. DT2500, Conventional disc trenching; LDT1250, Low-intensity disc trenching with sparse planting; LDT2500, Low-intensity disc trenching with dense planting; PW1250, Low-intensity patch-wise site preparation; PW2500, Patch-wise site preparation.

It was also evident that DTW had a significantly negative effect on growth in Fänneslunda (Figure 5), but this dynamic was not observed in Tagel (Table 2). This suggests that growth reduces as depth to ground water increases. In Tagel, DTW did not significantly affect growth. It is notable to mention that DTW showed a larger range in Fänneslunda than in Tagel, with DTW values in Fänneslunda generally showing drier conditions relative to what was observed in T (Figure 5).

Slope did not significantly affect growth after three years at either of the sites. The range for slope, just like DTW, differed between the sites, where Fänneslunda had a more distinct slope compared to Tagel (Figure 5). To be noted is that DTW and slope did not show any effect on growth or mortality of the supplementary planted seedlings in Tagel either.

Table 2. The results (*p*-values) following analysis of variance for the fixed effects on growth and mortality after three growing seasons for Fänneslunda and Tagel.

p-value Site	Effect	Growth	Mortality
Fänneslunda	Trt	**0.0287**	0.0729
	eDTW	**0.0075**	0.9839
	Slope	0.0901	0.0594
Tagel	Trt	0.0901	0.1491
	eDTW	0.2646	0.2202
	Slope	0.0913	0.1484

Notes: Treatment = the five site preparation treatments, eDTW = the logarithmic value of the estimated DTW, and Slope = slope angle in degrees. Each site was analyzed separately. Statistically significant effects ($p < 0.05$) are illustrated in **bold.**

Field vegetation cover and natural regeneration

Circular plots

In Fänneslunda, the site preparation methods did not significantly affect field vegetation cover after three growing seasons. The average field vegetation cover across the treatments was 81%. Furthermore, no significant between-treatment differences in the amount of natural regeneration after three growing seasons were observed in Fänneslunda (Table 3). The LDT2500 treatment showed the highest amount of naturally regenerated seedlings (on average 4171 seedlings per ha), while the fewest were observed in the PW1250 treatment (on average 500 seedlings per ha). Deciduous species dominated in the naturally regenerated seedlings across all site preparation treatments. In Tagel, site preparation treatment did not significantly affect field vegetation cover or natural regeneration after three growing season (Table 3), with average field vegetation cover reaching 60%. The DT2500 treatment showed the highest amount of natural regeneration after three growing seasons (on average 6667 seedlings per ha), while the least natural regeneration was observed in the LDT1250 treatment (on average 2444 seedlings per ha). Once again, deciduous seedlings predominated the naturally regenerated seedlings across all site preparation treatments in Tagel.

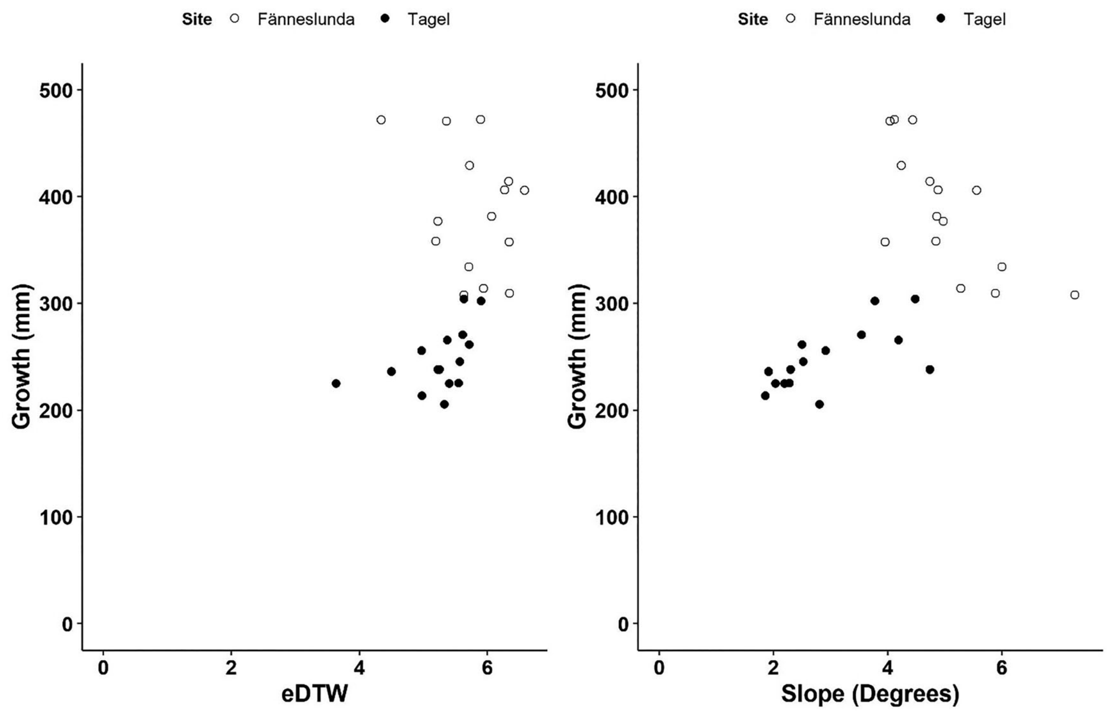

Figure 5. Effect of slope and eDTW on growth in sites Fänneslunda and Tagel. The graph on the left illustrates the relationship between eDTW and growth after three growing seasons. Hollow dots represent values from Fänneslunda while the filled dots represents values from Tagel. The graph on the right illustrates the relationship between slope and growth after three growing seasons. Hollow dots represent values from Fänneslunda while filled dots represents values from Tagel.

Planting spot level

At the planting spot level, site preparation treatment did not significantly affect field vegetation cover after three growing seasons in either Fänneslunda or Tagel. In Fänneslunda, the field vegetation cover reached an average of 77%, with the PW2500 treatment (average 85%) and DT2500 treatment (average 70%) showing the greatest and least ingrowth around the seedling, respectively. In Tagel, LDT1250 showed the most ingrowth (an average of 70%) while the DT2500 treatment (58%) showed the least ingrowth (Table 3). Overall, the average field vegetation coverage across the site preparation treatments after three growing seasons was 63%.

It could not be determined whether site preparation treatment had any significant effect on natural regeneration in the planting spots in either Fänneslunda or Tagel. The amount of natural regeneration in the planting spots varied depending on the site, with Fänneslunda showing less regeneration (on average 983 seedlings per ha) than Tagel (on average 2 098 seedlings per ha).

Table 3. The average amount of natural regeneration, along with the proportion of deciduous seedlings as well as field vegetation cover after three growing seasons in Fänneslunda and Tagel for each site preparation treatment on both a circular plot level and planting spot level.

Circular plots

	Fänneslunda			Tagel		
Trt	Nat. reg.	Decid (%)	Veg. Cov. (%)	Nat. reg.	Decid (%)	Veg. Cov. (%)
DT2500	2447	73	76	6667	98	51
LDT1250	1556	96	86	2444	100	57
LDT2500	4171	97	79	3389	95	62
PW1250	500	78	76	3500	100	71
PW2500	2331	95	89	5667	97	60

Planting spot level

	Fänneslunda			Tagel		
Trt	Nat. reg.	Decid (%)	Veg. Cov. (%)	Nat. reg.	Decid (%)	Veg. Cov. (%)
DT2500	1345	86	70	3034	96	58
LDT1250	701	98	81	1510	96	70
LDT2500	1667	97	70	3109	96	64
PW1250	280	89	79	750	98	59
PW2500	920	97	85	2087	98	65

Notes: The natural regeneration results are displayed as seedlings per hectare, while the proportion of deciduous seedlings is expressed in percentage. Field vegetation cover is displayed as the percentage of cover. Trt = Site preparation treatment, Nat reg. = Natural regeneration/hectare, Decid = Proportion of deciduous seedlings, Veg. Cov. = Field vegetation cover.

Soil disturbance

Soil disturbance was significantly affected by site preparation treatment at both sites (Figure 6). DT2500 resulted in the highest levels of largest soil disturbance and differed significantly from the other treatments at both sites with 33% of the disturbed area in Fänneslunda and 54% in Tagel. The rest of the site preparation treatments resulted in disturbance rates ~20% in Fänneslunda and between 25% and 30% in Tagel. The disturbed area was mostly represented by the BMS and DH classes, which accounted for around 60–80% of the disturbance caused by various site preparation treatments. The soil disturbance rate was generally higher in Tagel than Fänneslunda, nevertheless similar patterns in soil disturbance were observed across the site preparation treatments at both sites.

Discussion

Disc trenching and patch-wise treatments only differed marginally in terms of seedling growth. This result may not necessarily be connected to the methods but rather be

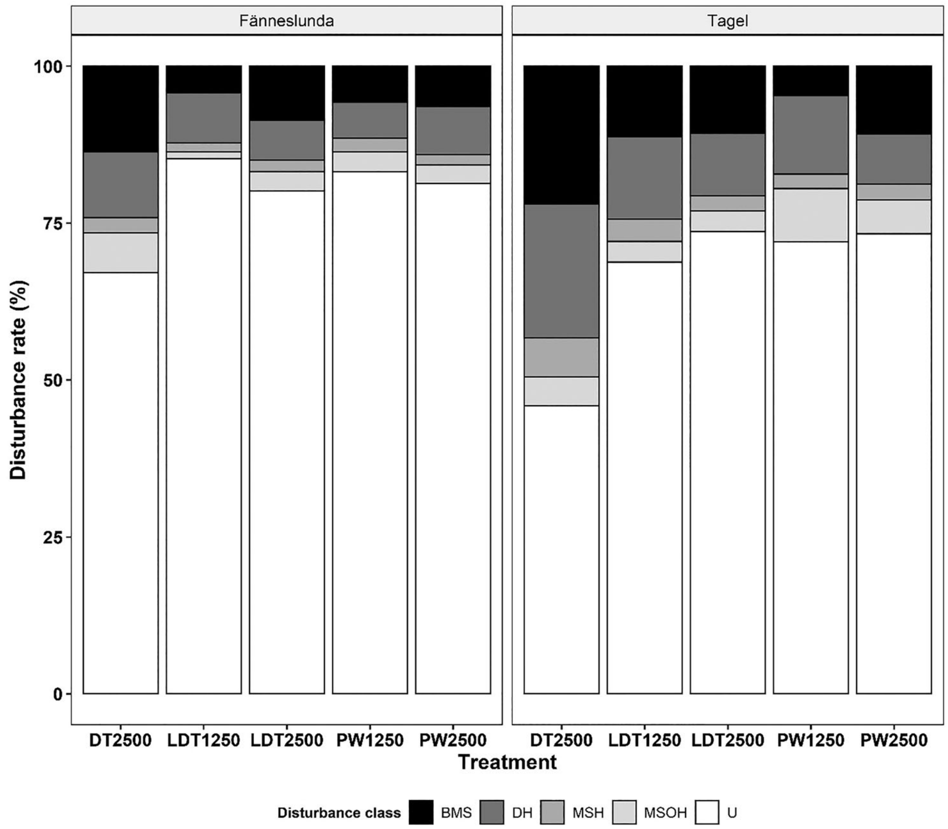

Figure 6. Soil disturbance rate across the different site preparation methods in Fänneslunda and Tagel. Different letters indicate significant differences between site preparation methods. DT2500, Conventional disc trenching; LDT1250, Low-intensity disc trenching with sparse planting; LDT2500, Low-intensity disc trenching with dense planting; PW1250, Low-intensity patch-wise site preparation; PW2500, Patch-wise site preparation. BMS: Bare mineral soil; DH: Disturbed humus; MSH: Mineral soil mixed with humus; MSOH: Mineral soil on top of humus; U: Undisturbed.

explained by the availability and selection of planting spots. (Figure 3). The different treatments apply different approaches to create an adequate amount of planting spots. Previous studies have shown the benefits of both types of methods (Johansson et al. 2013a; Hébert et al. 2014; Hjelm et al. 2019) for example patch-wise methods provide flexibility, but the properties of the planting spots may vary depending on site conditions (Wallertz et al. 2018). Disc trenching often create more homogenous planting spots and perform well at most sites leading to a large area of disturbance where planting spots are plentiful (Sikström et al. 2020). Seedlings in Fänneslunda grew better in the furrow/hole/patch but the seedlings planted in Tagel grew better in the mound/berm/inverted spots (Figure 3). Site-specific properties and planting year variation could be an explanation for the differing results between planting spot types (Sikström et al. 2020; Häggström et al. 2021). A difference in growth between planting spot types in this study further implies the importance of selecting suitable planting spots to adapt to different site conditions.

The site preparation treatments did not differ significantly in terms of seedling mortality. Once again, the selection of planting spot could partly explain this finding. The disc trenching treatments created homogenous planting spots, whereas the patch-wise treatments resulted in more variation between planting spots (Figure 2). This could explain why the patch-wise treatments resulted in higher mortality, which was more evident in Tagel, since more seedlings were planted in mounds/berms/inverted spots (Figure 3). The seedling mortality rate observed in Tagel was probably connected to annual variations in precipitation and temperature, as the first growing season was exceptionally dry and warm (Table 1) limiting water availability in elevated planting spots during the crucial establishment phase (Örlander et al. 1990; Spittlehouse and Childs 1990). These types of weather variations can increase stress among seedlings, which may progress to a point at which the seedlings can no longer tolerate the lack of water (Margolis and Brand 1990). Hence, the choice of planting spot is important as it may enable seedlings to withstand harsh conditions. However, differing precipitation from year to year could alter what properties are more important for survival (Spittlehouse and Childs 1990; Häggström et al. 2021). Therefore, a decision that seems appropriate in one part of a clear cut could be less appropriate in another year. The observation that the seedlings in Fänneslunda were less affected by the dry summer, even though seedlings in mounds/berms/inverted spots were more likely to die, than the seedlings in Tagel highlights how important the conditions of the planting year are for the ability of seedlings to manage harsh conditions. Therefore, it is important to have a variety of planting spots to choose from (Wallertz et al. 2018).

As expected, the DT2500 treatment resulted in a larger area of disturbance than the other treatments. This confirms previous findings that the disc trenching methods disturbs larger areas compared to the patch-wise methods that are used in Swedish forestry (Strömgren et al. 2017; Wallertz et al. 2018; Sikström et al. 2020). However, the tested patch-wise treatments did not differ in terms of disturbance eventhough they aimed to create different amounts of planting spots (Figure 6). The execution of the patch-wise treatments may be one explanation. Although the amount of planting spots differed, the excavator may have moved in a similar pattern in all of the tested treatments and caused a similar level of disturbance, which was reflected in the amount of disturbed humus (Figure 6). Further studies are needed to get more knowledge regarding which type of disturbance results from site preparation. Intermittent methods, like the patch-wise method used in this study, result in scattered disturbance, which may be favorable in terms of precise action and, minimizes the unnecessary area of disturbance. Continuous methods, even those described as less intensive, still lack flexibility and create long furrows that traverse the clear-cut,.causing a large amount of disturbance, with some of the disturbed areas not utilized as planting spots. This could be perceived as unnecessary when considering potential unwanted disturbance to ecological, recreational and cultural values (Karjalainen 2006; Dolk Fröjd and Norrman 2007; Cardosso et al. 2020; SFA 2021). Thus, the selection of site preparation methods should consider not only tolerance of disturbed areas, but also the pattern of disturbance.

The field vegetation quickly recovered after three growing seasons across all of the site preparation treatments (Table 3), which demonstrates how rapidly competing vegetation recovers in southern Sweden. Similar results have been reported for multiple site preparation treatments (Archibold et al. 2000; Johansson et al. 2013b; Floistad et al. 2018). In addition, no significant effect of site preparation treatment could be found on the amount of natural regeneration neither, on planting spot level or circular plot level. This is in contrary with other studies where disturbance promoted natural regeneration (Hanssen et al. 2003; Lehtosalo et al. 2010; Holmström et al. 2017; Saursaunet et al. 2018). The spatial distribution of seed sources could have influenced the results (Karlsson et al. 2002; Holmström et al. 2017; Saursaunet et al. 2018), providing an explanation to the lack of difference in natural regeneration on a circular plot level. Therefore, it is important to highlight the scale on which natural regeneration was measured. Most studies focuses on the disturbed area only which disregards the areas inbetween, leading to the risk of overlooking the amount of natural regeneration on a site level. Although no significant effect of site preparation could be found on either level, the observed amount of natural regeneration differed depending on the approach where more natural regeneration was registered in the circular plot (Table 3). Thus, natural regeneration should be taken into account to gain an understanding of how the stand will develop over time and to plan for future management e.g. pre-commercial thinning.

In this study, DTW showed different effects on growth depending on the site, i.e. seedlings in Fänneslunda were negatively affected as DTW increased, while no effect was recorded in Tagel (Figure 4). Shifts in water availability could be an explanation for the decline in growth in Fänneslunda (Margolis and Brand 1990). However, DTW was generally high in Fänneslunda, which suggests that water was most likely not a limiting factor for growth. It has previously been reported that DTW loses explanatory power at high values due to the difficulty in estimating moisture classes in between wet and dry (Ågren et al. 2015). Hence, in such sites, factors (e.g. rain fall, air temperature, soil texture) other than topography most likely determine water availability causing insecurity in using DTW to explain seedling growth or mortality. Furthermore, the DTW-raster used in this study displays estimated soil moisture conditions based on a predetermined normal setting (Murphy et al. 2008; Ågren et al. 2015). Therefore, the dry conditions in 2018 may have influenced the fact that no significant effect of DTW on growth was observed in Tagel, which was not the case for Fänneslunda, since site conditions were altered due to weather factors. Using maps with better accuracy could provide better estimates of soil moisture as well as adequately reflect the reality of the sites. Machine learning options that have been developed for all of Sweden takes more factors other than topography into account (e.g. landscape variabilities such as run-off and soil texture), which will increase the accuracy of the classification of wet areas in comparison to the DTW-raster used in this study (Lidberg et al. 2020; Ågren et al. 2021). These developments may improve the ability to use estimated soil moisture to make informed silvicultural decisions, but more research is needed to understand the benefits and limitations of these tools within forest regeneration.

Based on the analysis performed no significant effect of slope on growth or mortality could be found. Though, small-scale variations could not be properly detected with this study design. Mean values of every raster cell within a treatment plot were used thus hindering evaluation of small topographical changes that can influence seedlings performance (Burney et al. 2007). Also factors that limits the effectiveness of site preparation, such as stoniness (Wallertz et al. 2018), could have made the process of creating enough planting spot more complicated. Even though variations on a small scale are hard to identify with slope and DTW, they can be useful to identify areas with less suitable conditions, e.g. wet areas and steep slopes. They can also be useful in experimental set-ups, like block designs, that need to consider belowground variation.

Conclusions

In general, site preparation methods did not demonstrate significantly different results in terms of growth or survival. Instead, the most important factor for seedling growth and survival were the planting spot itself and the weather factors during the planting year. As such awareness and flexibility when planting, which will ensure the selection of good planting spots, are key to adapting to site conditions and succeeding in regeneration efforts. Site preparation intensity did influence the extent of soil disturbance, as well as the disturbance pattern, both of which are of importance for future stand management. Moreover, the disturbed area was quickly recolonized by field vegetation and natural regeneration. This highlights that natural regeneration should always be considered in forest regeneration planning. In this study, DTW and slope, did not substantially contribute to explaining growth or mortality in the study sites. When analysing how DTW and slope can be used in the future the appropriate scale should be taken into consideration depending on the information that is sought after. Further improvements in variables from DEMs, i.e. better accuracy and information on numerous metrics, could make them useful tools in forest regeneration planning and experimental design, however, at present more information is needed about their limitations and how they are applicable to forest regeneration.

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