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Early growth of planted Norway spruce and Scots pine after site preparation in Sweden

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ABSTRACT
Norway spruce (*Picea abies* (L.) H. Karst) and Scots pine (*Pinus sylvestris* L.) have different site preferences, but silvicultural recommendations for their regeneration at planting (including site preparation) are often the same. Thus, there is a clear need for greater understanding of species-specific interactions between site preparation and site properties. To meet this need, the species' growth and survival have been monitored at both fertile and poor sites in northern and southern Sweden. At each of these sites, effects of three types of site preparation – removed humus (RH), deep soil cultivation (DSC) and control (C, no site preparation) – were compared. Results show that Scots pine grew more rapidly initially than Norway spruce, and DSC site preparation promoted growth of both species. However, on poor sites there was a delay in growth responses. In addition, removal of organic material in the RH treatment caused a sustained growth check of Norway spruce, but not for Scots pine. This study confirms that it is beneficial to use site preparation as it increases the survival of both species and may increase growth. However, site preparation methods that reduce the amount of organic material in the planting spots should be avoided for Norway spruce.

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Introduction

Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst) are the dominant tree species in commercial Swedish forestry, accounting for 39% and 41% of the total standing volume in Swedish forests, respectively (SLU 2018). However, their growth patterns and site preferences differ substantially. Norway spruce is a late-successional species with slow early growth and late mean annual increment (MAI) culmination (Engelmark and Hytteborn 1999). There is also often a growth check of Norway spruce during the establishment phase, usually in the first 1–3 years after planting. The effect is strongest in the second year after planting, as its growth depends on conditions in the previous year (Grossnickle 2000). Early growth of Norway spruce can be particularly slow, especially in the harsher conditions in northern Sweden (Björkman 1953; Bergh et al. 1999; Nilsson et al. 2012). In contrast, Scots pine is a pioneer species that initially grows rapidly, and less quickly in later stages. Scots pine is naturally promoted with recurrent low to medium intensity fires, and has poor tolerance of prolonged suppression in shady conditions. Norway spruce dominates at sites that seldom or never burn and where gaps (enabling release of suppressed trees) are regularly created by uprooting or stem breakage (Engelmark and Hytteborn 1999).

Generally, Norway spruce is considered to grow better than Scots pine in mesic sites and in intermediate to high fertility (Albrektson et al. 2012). However, even in such sites Scots pine may become the dominant tree species after a major disturbance (Engelmark and Hytteborn 1999). Scots pine outperforms Norway spruce in nutrient-poor sites and sites with coarse-textured soils that do not hold water well (Öyen and Tveite 1998; Engelmark and Hytteborn 1999; Heiskanen and Mäkitalo 2002; Helmisaari et al. 2009). Generally, Scots pine also grows faster than Norway spruce in the cold climate of northern Sweden, and vice versa in the milder conditions in southern Sweden (Ekö et al. 2008). However, in controlled experiments, Scots pine has outperformed Norway spruce at an intermediate site in central Sweden (Holmström et al. 2018), and grown slightly better at two fertile sites in southern Sweden (Drössler et al. 2018).

Many different factors that influence survival and growth may arise when a forest is in its regenerating phase (Burdett 1990), and thereby also reducing financial returns. Slow early growth is a major concern, due to the importance of seedlings growing quickly after planting, to minimize the time they are most sensitive to biotic and abiotic stress factors, such as frost, competing vegetation, pine weevils, and browsing (Nilsson et al. 2010). Effects of these factors can be mitigated by site preparation (Nilsson et al. 2010), and/or by use of chemical herbicides or fertilizers (Thiffault et al. 2017). In boreal forests of both Scandinavia and elsewhere, site preparation by some form of scarification promotes the establishment of new stands and generally reduces rotation lengths (Thiffault et al. 2017). Thus, 92% of

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all planted forest land in Sweden is scarified (SFA 2014), usually by mounding or disc trenching (Nilsson et al. 2010).

Site preparation improves site conditions by for example reducing competition for nutrients (Thiffault et al. 2004), frost risk (Langvall et al. 2001; Simard et al. 2003) and competing ground vegetation (Thiffault et al. 2005; Johansson et al. 2013), while increasing nutrient mineralization (Örlander et al. 1990; Lebel et al. 2008), water availability (Löf et al. 2012), soil temperatures (Nilsson and Örlander 1999; Thiffault et al. 2013) and improving aeration on wet sites (Ritari and Lähde 1978; Kabrick et al. 2005). However, it may also have negative effects, such as reducing nutrient concentrations (Munson et al. 1993; Hallsby 1995), or frost heaving (Sahlén and Goulet 2002; Heiskanen et al. 2013).

Important insights have been obtained in the cited studies, and numerous other investigations, regarding growth characteristics and various aspects of the site preferences of Scots pine and Norway spruce. However, more information about factors that influence the species' early growth is required, to facilitate choices of material in the regeneration phase (one of the most important silvicultural decisions and the start of a long-term commitment) and optimize site preparation treatments. More specifically, detailed comparative information is required about the two species' growth responses at sites with a wide range of conditions. Thus, in the study presented here, the early growth and survival rates of Scots pine and Norway spruce were monitored following three treatments – removed humus (RH), deep soil cultivation (DSC) and no site preparation (C, control treatment) – at four sites spanning large fertility and geographical gradients in Sweden. The main purpose was to investigate differences in the two species' responses to the site preparation treatments, and possible species-specific site-treatment interactions. The following specific hypotheses were tested:

(1) Scots pine has higher early growth than Norway spruce, especially in low-fertility sites.
(2) Norway spruce has stronger early growth-responses than Scots pine to site preparation treatments.

Material and methods

Experimental design

The hypotheses were tested in trials replicated at four sites described in Table 1, selected (based on site indices) to represent fertile and poor sites in northern and southern Sweden. Locations of the sites (designated NorthPoor, NorthFertile, SouthPoor and SouthFertile, respectively) are shown in Figure 1. The trials in northern Sweden were established in June 2011, while those in southern Sweden were established in April and June 2012. The previous crop was harvested during the winter before planting, at all sites except SouthPoor, where it was harvested a year earlier.

Site preparation treatments

At all sites, a split-plot design with four blocks was applied. In the north, each block was 13 × 41 m, and each block was divided into three main plots of the size 13 × 11 m, with a 4 m undisturbed buffer zone between the main plots, in which one of three treatments was applied over the entire main plot (i.e. not spot-wise). In the main plots, the inner 7 × 8 m areas were used for planting, creating a second 4–5 m

Table 1. Description of the four trial sites.

Local name	NorthPoor Vindeln	NorthFertile Hössjö	SouthPoor Sävsjöström	SouthFertile Klåveröd
Altitude (m)	200	170	220	180
Latitude	64°13´N	63°48´N	56°59´N	56°02´N
Longitude	19°46´E	19°49´E	15°29´E	13°11´E
Mean annual precipitation (mm)[a]	669.8	583.1	596.6	872.6
Mean annual temperature (°C)[b]	3.5	4.5	7.1	9.0
Temperature sum[c]	881	946	1320	1388
Field vegetation type[d]	Bilberry	Low herbs	Bilberry	No field vegetation
Soil moisture	Mesic	Mesic	Mesic	Mesic
Soil texture[d]	Sandy till	Sandy-silty till	Sandy-silty till	Clay-silty till
Soil type[e]	Orthic podzol	Orthic podzol	Orthic podzol	Eutric Cambisol
Site index[f]	T20	G21	T26	G35
MAI (m^3 ha^{-1} $year^{-1}$)[g]	3.7	4.6	6.8	13.3
Previous crop	Scots pine	Norway spruce	Scots pine	Norway spruce
Previous stand harvest date	Winter 10–11	Winter 10–11	Winter 10–11	Winter 11–12
Soil preparation date	10 June 2011	13 June 2011	16 May 2012	14 March 2012
Planting date	22 June 2011	23 June 2011	6–7 June 2012	25 April 2012
Provenance Scots pine	Fp-625 Dal T8		Fp-606A Gotthardsberg	
Provenance Norway spruce	Fp-130 Domsjöänget		Fp-501 Bredinge	

[a](SMHI 2019)
[b]Average annual values recorded at the closest weather stations for the years 2011–2016 in the North and 2012–2016 in the south. Weather stations: Vindeln-Vindeln/Sunnansjönäs (149,120), Hössjö-Umeå Flygplats (140,480) for temperature, and Hössjö-Röbäcksdalen (140,490) for precipitation; Sävsjöström-Kosta Mo (65,510) for temperature, and Sävsjöström-Älghult (75,010) for precipitation; Klåveröd-Helsingborg (62,040) for temperature, and Klåveröd-Gillastig (63,010) for precipitation.
[c]Day-degrees >5°C calculated according to Morén and Perttu (1994), without correction with respect to continentality and maritimity. (using TS = 4.922–60.4* lat −0.837* alt).
[d]According to Hägglund and Lundmark (1987).
[e]FAO-UNESCO, Soil map of the world (Anon 1981).
[f]Site index derived from site properties as the height of the dominant trees (m) after 100 years for Scots pine (T) or Norway spruce (G) according to to Hägglund and Lundmark (2007).
[g]Mean annual increment derived from site index from site properties according to Hägglund and Lundmark (2007).

Figure 1. Locations of the four sites. 1 = NorthPoor, 2 = NorthFertile, 3 = SouthPoor and 4 = SouthFertile.

buffer zone to the edge of the treated main plot. The size of main plots and inner areas varied between the two regions (they were slightly smaller in southern Sweden). The treatments were: control (C, no site preparation); removed humus (RH, i.e. removal of the organic layer in the entire plot leaving a top layer consisting of bare mineral soil); and deep soil cultivation (DSC, inverting the entire soil profile to a depth of 60 cm, burying the topsoil under 10–20 cm of mineral soil). Each of the site preparation treatments was applied in the spring or early summer using an excavator that operated from outside the plots to avoid soil compaction. The two sites in southern Sweden were fenced to prevent browsing damage, but at the northern sites fencing was not needed.

Nursery preparation

The planting material consisted of provenances considered to be well adapted to the respective sites (Table 1), provided by the Forestry Research Institute of Sweden (Skogforsk). All the seedlings were sown in containers and raised in a greenhouse, following a conventional growing scheme. Seedlings grown in southern Sweden were kept a few weeks longer in the greenhouse than those grown in northern Sweden (3 and 4 weeks longer, for Norway spruce and Scots pine respectively) before planting to increase their size. All Scots pine seedlings were raised with a short-day (8 h) treatment, to promote a second flush. Average heights of the Scots pine and Norway spruce seedlings at planting were 55 and 104 mm, respectively, in the north, while in the south they were 80 and 247 mm, respectively.

Planting

Containerized Norway spruce and Scots pine seedlings were randomly interplanted at all sites with 1 m spacing in the inner 7 × 8 m areas of the main plots. In each plot, 20 or 29 seedlings of each species were planted in the northern and southern sites, respectively. All 2352 seedlings were planted with a conventional planting depth, i.e. the entire container was a few cm under the soil surface. Each seedling was treated with Merit Forest WG insecticide (active substance Imidacloprid, Bayer AB - Bayer CropScience) to provide protection against pine weevil (*Hylobius abietis*) at planting, then re-treated in the first spring in the northern trials, and both the first spring and autumn in the southern trials.

Field measurements

Immediately after planting, before the first growing season, initial dimensions (height from the ground, diameter at ground level, and length of the leading shoot) of every seedling were measured. Subsequently, measurements were acquired after every growing season until 2016 (except 2014, the fourth growing season, in northern Sweden).

Damage was registered in the following seven classes: 0 = undamaged, 1 = negligible damage, 2 = slightly damaged (reduced growth, but not shorter than in the previous year), 3 = damaged (reduced growth, shorter or similar height as in the previous year), 4 = lethally damaged (expected to die during the following year), 5 = dead, and 6 = dead during the previous year. In addition, the cause of the damage or mortality was registered, if detectable (e.g. browsing, competing vegetation, frost, fungi, insects (except pine weevil), pine weevil, rodents or waterlogging). Unfortunately, damage and mortality data from the first and second growing seasons in the north were lost.

Percentage cover of field vegetation cover was assessed visually during the growing season in 2016 (i.e. during the fifth growing seasons in the south and sixth in the north), in eight 1 m^2 squares along a diagonal transect across each plot, giving a total of 32 assessed 1 m^2 squares per site preparation and site (384 in total). Field vegetation cover was recorded by species in 10% classes, with single presence of a species set as 1%.

Soil temperature was recorded at each site between 7th July and 3rd October, the first year and the first two years of the study period in the northern and southern sites, respectively. Recordings were hourly by data loggers (HOBO Water Temp Pro v2) buried 10 cm below the soil surface in each plot, in total 152,064 observations were collected, from which daily mean temperatures were calculated from the acquired data.

Statistical analyses

The seedlings' stem volumes were calculated using the formula for volume of a cone (Equation (1)):

$$\text{Stem volume} = \frac{\text{Height} \times \text{Basal area}}{3} \tag{1}$$

Mean total stem volume, leading shoot length and mean mortality of seedlings of each species in each plot and species (excluding those in damage classes >3) were then calculated and used in ANOVA of site-specific effects of the treatments on each species' growth. For this purpose, a mixed-effect model was constructed using the R statistical package lmerTest (Kuznetsova et al. 2017), an add-on to the lme4 package (Bates et al. 2015), treating blocks as a random effect, and both site preparation and species as fixed effects.

The following split-plot model was used separately for each site and year:

$$y_{ijk} = \mu + b_k + \alpha_i + \delta_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{2}$$

where y_{ijk} is the response variable (growth in total stem volume, leading shoot length, or mortality) of the kth replicate of site preparation treatment (C, RH or DSC) i, and species j. The other terms are defined as follows: μ = overall mean b = block (random) effect, (k = 1, … ,4) α_i = fixed effect of the ith site preparation treatment (i = 1, … ,3) δ_{ik} = site preparation treatment experimental error β_j = fixed effect of the jth split-plot species (j = 1,2) $(\alpha\beta)_{ij}$ = interaction between site preparation and species ε_{ijk} = split-plot experimental error (species experimental error)

When significant differences in the response variables were detected, the significant differences were identified by Tukey's *post hoc* test.

Effects of the treatments on field vegetation cover were analyzed using average cover values for the plots, and day-degree values (based on temperatures when daily mean temperature exceeded 5°C) were summed per block and plot, and used for soil temperature analyses.

In addition, the effects of the field vegetation cover and soil temperature were analyzed using the following model (with notation described above):

$$y_{ik} = \mu + b_k + \alpha_i + \varepsilon_{ik} \tag{3}$$

Again, when significant between-treatment differences were detected, the significant differences were identified by Tukey's *post hoc* test.

The explanatory variables of growth parameters were log-transformed to meet homogeneity of variance requirements for ANOVA when needed. Proportion variables were for the same reason transformed when needed according to Bartlett (1937), after which all frequencies were arcsine square-root transformed (Zar 1984). In all analyses, differences were deemed significant if $p < 0.05$.

Results

Growth

Leading shoot growth

Leading shoot growth patterns varied across sites and species and were significantly affected by site preparation and species within sites during most years (Table 2, Figures 2–3). There were significant differences in leading shoot growth between species every year at all sites except in the first year at the northern sites. Significant site preparation effects on leading shoot growth were detected in the third year at both southern sites, the second year at the NorthPoor site, and the fifth year at the NorthFertile site.

Significant interaction effects between site preparation and species on leading shoot growth were found in many years at the four sites, indicating that the two species' shoot growth responses to the site preparation treatments differed (Table 2). Scots pine performed better at all sites and was less responsive to the site preparation treatments than Norway spruce. The RH treatment induced less leading shoot growth of Norway spruce seedlings than the DSC treatment at all sites, and less than the control treatment at the southern sites (Figures 2 and 3). In contrast, for Scots pine, the control treatment induced a comparably low leading shoot growth at three out of four sites.

Leading shoot growth of both species started slowly at all sites, and a growth check of Norway spruce seedlings was detected in the second growing season following all three treatments at all sites. The growth check was strongest at the northern sites where the average growth was less than 2 cm during the second growing season in all treatments. Leading shoot growth was particularly slow following the DSC treatment at the NorthPoor site where leading shoot growth of Norway spruce and Scots pine was higher in the control or RH plots than in the DSC plots during the first three years after planting. However, during the last 2–3 years of the study, the pattern was reversed and leading shoot growth was higher in the DSC plots than in the C and RH plots (Figure 2). For example, the leading shoot growth was 33.1 and 48.5 cm during the last growing season for Scots pine in the DSC plots in the NorthPoor and NortFertile sites respectively, compared to 3.1 and 12.7 cm for Norway

Table 2. Results of the analysis of variance, showing *p*-values for effects of the explanatory variables and their interactions during six years on leading shoot growth (LS, the numbers 1–6 indicate the growing seasons), total stem volume at the end of the study (TotVol), mortality (Mort), field vegetation cover during the last growing season (VegCov) and temperature sum for day-degree values of the soil during the first, or first and second growing season. (TsumS). NP = NorthPoor, NF = NorthFertile, SP = SouthPoor, SF = SouthFertile. Trt = site preparation treatment, Spec = species. 2352 seedlings were used in the analysis of LS, TotVol and Mort, while 384 assessment plots were used for VegCov, and 152064 temperature observations for the TsumS. Each site and year was analyzed separately. Statistical significant effects ($p < 0.05$) are highlighted in bold.

		p-value									
Site	Effect	LS1	LS2	LS3	LS4	LS5	LS6	TotVol	Mort	VegCov	TsumS[a]
NP	Trt	0.6994	**0.0002**	**<0.0001**	–	**<0.0001**	**<0.0001**	**0.0020**	**0.0002**	**0.0294**	**0.0015**
	Spec	0.5646	**<0.0001**	**<0.0001**	–	**<0.0001**	**<0.0001**	**<0.0001**	0.9681	–	–
	Trt × Spec	0.1134	**0.0026**	**0.0752**	–	0.1253	0.9834	0.7259	0.8546	–	–
NF	Trt	0.2508	0.7971	0.2112	–	**<0.0001**	**0.0196**	0.0502	0.2474	0.0731	**0.0045**
	Spec	0.6871	**<0.0001**	**<0.0001**	–	**<0.0001**	**<0.0001**	**<0.0001**	**0.0396**	–	–
	Trt × Spec	0.9107	0.5443	0.9566	–	0.2283	**0.0006**	**0.0231**	**0.0122**	–	–
SP	Trt	0.1089	0.5949	**0.0072**	**0.0002**	**0.0009**	–	**0.0033**	**0.0001**	**0.0021**	0.0956/ **0.0209**
	Spec	**<0.0001**	**0.0013**	**<0.0001**	**<0.0001**	**<0.0001**	–	**<0.0001**	0.6518	–	–
	Trt × Spec	0.0879	**0.0346**	**0.0476**	**0.0023**	**0.0024**	–	0.2498	0.2753	–	–
SF	Trt	0.2918	0.6596	**0.0052**	**0.0011**	**<0.0001**	–	**0.0105**	**0.0128**	0.0521	0.4973/ **0.0145**
	Spec	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	–	**<0.0001**	**0.0364**	–	–
	Trt × Spec	0.3146	0.7930	**0.0111**	**0.0002**	**<0.0001**	–	**<0.0001**	0.0861	–	–

[a]For the southern sites, *p*-values corresponds to the first and second growing season, respectively.

spruce in the RH plots. In the SouthPoor and SouthFertile sites, leading shoot growth was 55.9 and 54.2 cm during the last growing season for Scots pine in the DSC plots, and 5.2 and 19.2 cm for Norway spruce in the RH plots. Furthermore, for Scots pine, there were significant differences in leading shoot growth between the DSC and RH plots at the poor sites in each region at the last measurement (NorthPoor $p < 0.0001$, SouthPoor $p = 0.0370$), but not at the fertile sites (Figures 2 and 3).

Total stem volume

Total stem volume at the end of the study was significantly or nearly-significantly affected by site preparation and species at all sites (Table 2). Significant interactions were found at both the fertile sites (NorthPoor and SouthFertile), indicating that the species' responses to the three treatments differed at these sites (Table 2 and Figure 4).

Total stem volume of both species was generally highest following the DSC treatment, but the difference between

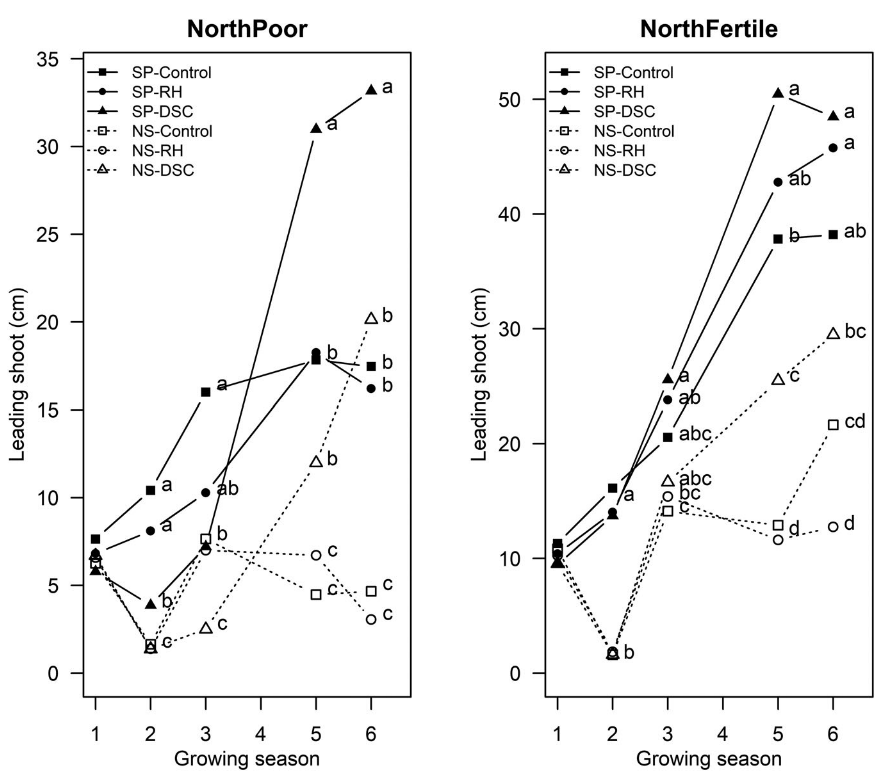

Figure 2. Observed leading shoot growth (cm) following the three site preparation treatments at the two experimental sites of Scots pine and Norway spruce seedlings in the north during the first six growing seasons. Site preparation treatments: Control (no site preparation), Removed Humus (RH) and Deep Soil Cultivation (DSC). Different letters next to an observed mean indicate significant differences within sites and years according to the Tukey multiple comparison difference test. Each data point is represented by 28–43 seedlings.

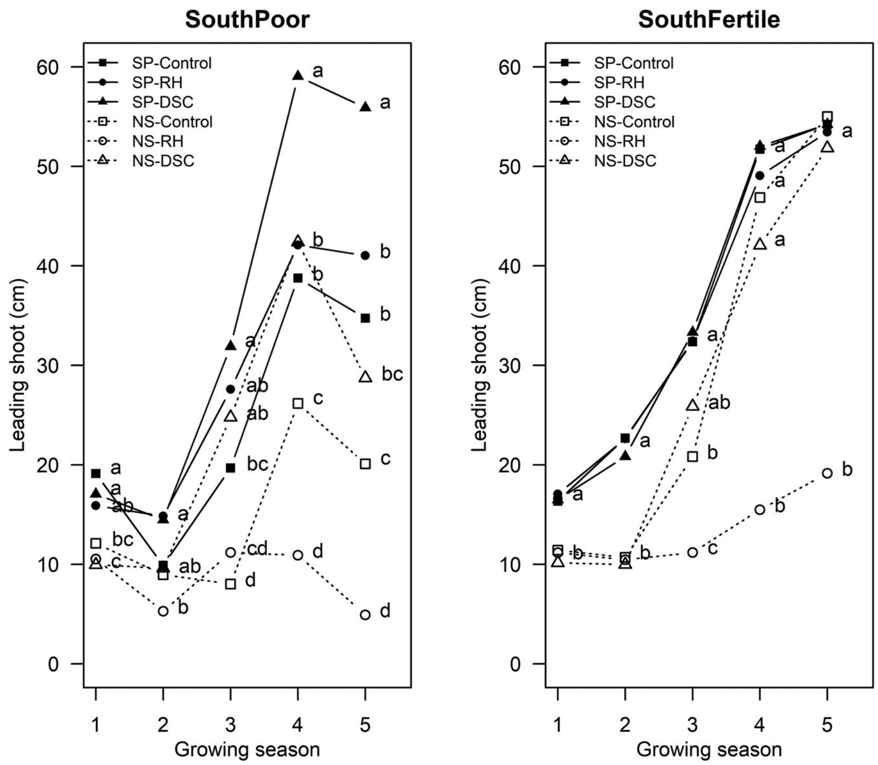

Figure 3. Observed leading shoot growth (cm) following the three site preparation treatments at the two experimental sites of Scots pine and Norway spruce seedlings in the south during the first five growing seasons. Site preparation treatments: Control (no site preparation), Removed Humus (RH) and Deep Soil Cultivation (DSC). Different letters next to an observed mean indicate significant differences within sites and years according to the Tukey multiple comparison difference test. Each data point is represented by 42–93 seedlings.

the DSC treatment and both other treatments were only significant in the NorthPoor site (Figure 4). However, at the SouthFertile site both species showed a different pattern as the total stem volume was highest in the control treatment for both species, and Norway spruce in the RH treatment had significantly lower volume than all other combinations of treatments and species (Figures 2 and 4).

The total stem volume of both species at the end of the study was lowest at the NorthPoor site, followed by the NorthFertile, SouthPoor, and SouthFertile sites (Figure 4). The differences in total stem volume between the NorthPoor site and SouthFertile sites were very strong (more than ten-fold after 5 years, for both species, following all three treatments). For example, Scots pine in the SouthFertile site had a volume of 248.5 cm^3 after five years in the control treatment, compared to 5.9 cm^3 after six years in the NorthPoor site, which equals to 2.4% of the southern site volume. Furthermore, despite high similarity in leading shoot growth (Figures 2 and 3) of Scots pine seedlings at the NorthFertile and SouthPoor site, their total stem volume was around twice as high at the SouthPoor site after five years (Figure 4), where their diameters were larger (data not shown). For Scots pine, the only significant difference found between treatments was between the DSC treatment and the RH treatment in total stem volume at the NorthPoor site ($p < 0.0001$) (Figure 4).

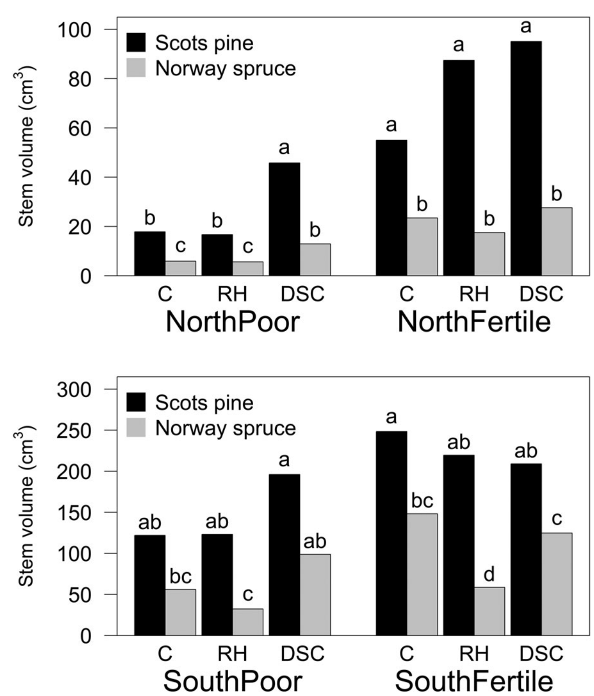

Figure 4. Total stem volume (cm^3) at all sites following each treatment at the final measurement (six and five years after planting at the northern and southern sites, respectively). Site preparation treatments: Control (no site preparation), Removed Humus (RH) and Deep Soil Cultivation (DSC). Different letters over bars indicate significant differences within sites according to the Tukey multiple comparison difference test. Each bar is represented by 28–93 seedlings.

Mortality and damage

Mortality and damage rates varied strongly among sites and site preparation treatments, and slightly among species

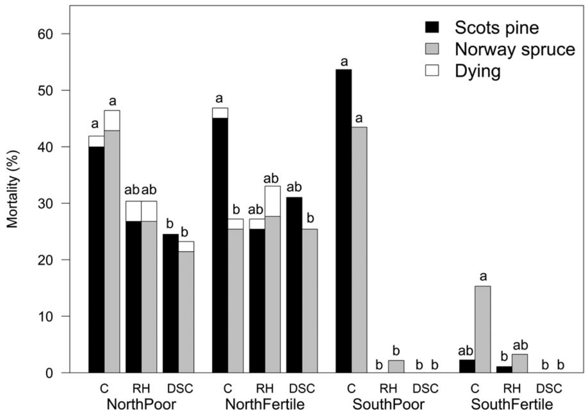

Figure 5. Mortality rates: percentages of dead and dying seedlings at the final measurement (six and five years after planting at the northern and southern sites, respectively). Site preparation treatments: Control (no site preparation), Removed Humus (RH) and Deep Soil Cultivation (DSC). Different letters over bars indicate significant differences within sites according to the Tukey multiple comparison difference test. Each bar is represented by 80 and 116 seedlings at the northern and southern sites, respectively.

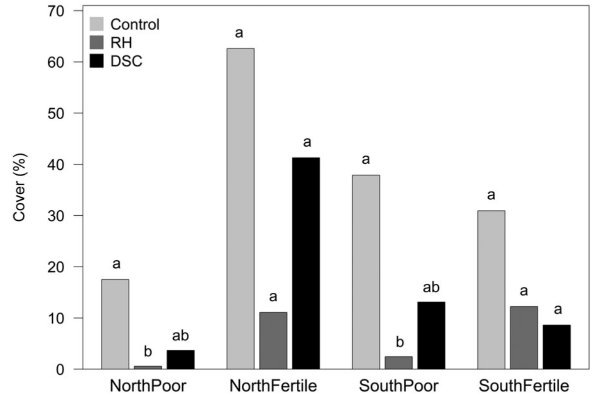

Figure 6. Field vegetation cover at each site during the last growing season (2016). Site preparation treatments: Control (no site preparation), Removed Humus (RH) and Deep Soil Cultivation (DSC). Different letters over bars indicate significant between-treatment differences within sites according to the Tukey multiple comparison difference test. Each bar is represented by 32 field vegetation 1 m^2 squares.

(Figure 5). Within-sites, mortality was often highest in the control plots. At the southern sites, mortality was consistently low, except following the control treatment at the SouthPoor site. Mortality was highest after the second growing season, and mostly caused by pine weevils (which accounted for 75% and 68% of mortality at the SouthFertile site and SouthPoor sites, respectively), followed by unknown causes (25% and 28% at the SouthFertile and SouthPoor sites, respectively). Furthermore, 30% of all seedlings were attacked by pine weevils at the SouthPoor site, while 57% were attacked at the SouthFertile site. In the north, 93% and 90% of the mortality was due to unknown causes at the NorthPoor and NorthFertile sites, respectively (a major reason for the large uncertainty was that specific damage data from the first two years were lost). The following years in the north, the remaining few percent of mortality were due (in declining order) to rodents, frost-heaving and pine weevils.

Other variables

Field vegetation cover

Field vegetation cover consisted of herbaceous, ericaceous, woody and grass species. Field vegetation cover was significantly affected by the treatments in 2016 (after four growing seasons in the south and five in the north) ($p \leq 0.05$) at the poor sites in both regions, but not at the SouthFertile site ($p = 0.0525$) or NorthFertile site ($p = 0.0731$). At the NorthPoor and SouthPoor sites, control plots had a significantly higher cover of field vegetation than RH plots. The variation among sites, species and treatments was relatively high. Highest field vegetation cover was found in the control treatment in the NorthFertile site (62.6%), and lowest in the RH treatment in the NorthPoor site (0.6%) (Figure 6).

Soil temperature sum

Soil temperature sum was significantly affected by the treatments during the first year at the northern sites ($p = 0.0015$ and 0.0045 at the NorthPoor and NorthFertile sites, respectively), and the second year at the southern sites ($p = 0.0209$ and 0.0150 at the SouthPoor and SouthFertile sites, respectively). Lowest soil temperature sum was found in the control treatment in the NorthFertile site (631.6) and highest (962.4) in the DSC treatment in the SouthPoor site in 2013. Soil temperature sums were significantly lower in the control plots than in the other plots every year except the first year at the southern sites (Figure 7). More specifically, soil temperatures tended to be lower in control plots in spring and summer, but slightly higher in the autumn, at most sites except the SouthFertile site, where between-treatment differences in soil temperature were generally small (data not shown).

Discussion

The hypothesis that Scots pine has higher early growth than Norway spruce, especially at low fertility sites, was supported

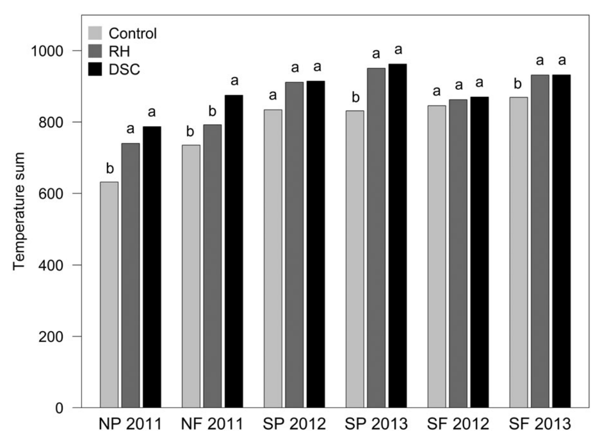

Figure 7. Temperature sum for day-degree values (temperature exceeding 5°C) of the soil at each site during the first growing season (7th July – 3rd October) at the northern sites in Sweden, and two first growing seasons at the southern sites. *NP* = NorthPoor, NF = NorthFertile, *SP* = SouthPoor, SF = SouthFertile. Site preparation treatments: Control (no site preparation), Removed Humus (RH) and Deep Soil Cultivation (DSC). Different letters over bars indicate significant between-treatment differences within sites according to the Tukey multiple comparison difference test. Each bar is represented by four total temperature sums.

by data from this study. Scots pine grew more rapidly at every site, following each site preparation treatment. Norway spruce most closely matched the growth in leading shoot and total stem volume of Scots pine at the very fertile SouthFertile site, located in one of the most fertile forested areas in Sweden. The difference between the two species was generally most pronounced, across sites, following the RH treatment, in which the humus layer and hence large proportions of available nutrients were removed.

A more rapid early growth of Scots pine than of Norway spruce has been reported previously (Johansson et al. 2015; Luoranen 2018). Previous studies of material in later rotation stages have also shown that Scots pine has a bigger growth advantage on less fertile sites (Leijon 1979; Öyen and Tveite 1998; Ekö et al. 2008). In addition, more recent studies have shown that Scots pine can outperform Norway spruce on intermediate sites (Nilsson et al. 2012; Holmström et al. 2018) and grow comparably well on fertile sites (Drössler et al. 2018). However, Scots pine growing on sites that are more fertile will in general have wider annual rings, higher juvenile content and thicker branches that will stay longer on the stem (Liziniewicz 2014).

The second hypothesis, that Norway spruce is more affected by site preparation that alters the soil profile, was supported by observations at the southern sites but not at the northern sites. This may simply be because both growth and processes in the soil are slower at the northern sites, so it takes a longer time for site preparation treatments to have an effect. There were no significant differences in growth responses of Scots pine seedlings at the SouthFertile site to the three treatments, indicating that (unlike Norway spruce seedlings) they acquire enough nutrients to maximize stem volume growth, even when the humus layer is removed. Scots pine had higher total stem volume in the RH treatment compared to the control at the NorthFertile site in this study, which is in line with findings from Kardell (2010). In a somewhat similar study with humus-removal for Scots pine across Sweden, Kardell found that the species could grow better in a removed humus treatment than in the control at some sites. Furthermore, the earlier planting date at the SouthFertile site (April, compared to June for the other three sites) might have been slightly beneficial for the growth at this site, but probably only during the first years.

In addition, no significant differences in growth responses of either species to site preparation treatments during the first year were detected. This is consistent with previous studies on boreal species (Löf 2000; Johansson et al. 2005), in which significant differences in growth were first detected after two or three years (Örlander et al. 1996). It is also consistent with our expectations, as the performance of planted seedlings in the field is predominantly determined by the growth conditions during the previous year, where in this case the seedlings were grown in the nursery.

Growth of both Norway spruce and Scots pine seedlings was highest following DSC site preparation at most sites. In DSC plots, seedlings' early growth was relatively poor in the north, but they subsequently outperformed seedlings in the other plots, possibly due to associated increases in mineralization and nutrient availability, which have been previously observed after soil scarification (Örlander et al. 1990; Schmidt et al. 1996; Lebel et al. 2008). The time-lag recorded in the north could have been due to the slower responses associated with cold temperatures of environmental processes linked to nutrient availability. In addition, growth check of Norway spruce, which is a common phenomenon (Grossnickle 2000), was detected following every treatment in the second growing season, and throughout the study period following the RH treatment.

Norway spruce displayed low growth rates following RH site preparation at all sites. This may have been due to the removal of nutrients, especially nitrogen, in the organic layer, as found in other studies (Simard et al. 2003; Powers et al. 2005). In contrast, Scots pine can apparently acquire nitrogen rather well even following this type of site preparation. These observations are consistent with recommendations to plant Norway spruce in fertile sites and Scots pine in poor sites in Sweden (Albrektson et al. 2012). Similarly, 11 years after planting, lodgepole pine (*Pinus contorta* Dougl. ex Laws. Var. *contorta*) seedlings reportedly had 12 times higher biomass, nine times higher nitrogen content, higher nitrogen acquisition rates and higher retranslocation efficiency than Sitka spruce (*Picea sitchensis* (Bong) Carriére) seedlings at a poor site in North America (Bothwell et al. 2001). Species adapted to low-fertility soils often have high growth rates per unit nutrient, i.e. high nutrient efficiency (Bothwell et al. 2001). Interestingly in this study, differences in leading shoot growth and total stem volume of Scots pine seedlings between DSC and RH treatment were found at the poor but not the fertile sites. This indicates that improvements in nutrient availability following the DSC treatment at poor sites may have contributed strongly to their response to this site preparation.

Low soil temperature often limits growth but can be increased by soil scarification (Örlander et al. 1990; Grossnickle 2000, 2005; Thiffault et al. 2013). Soil temperature sum was generally significantly lower in the control plots than in the RH and DSC plots. However, it should be noted that the soil temperature measurements for all sites used in the analyses only covered the periods from 7th July to 3rd October. The relatively late start of the temperature sum measurements (7th July) may explain why there were no significant between-treatment differences in this variable at the southern sites in 2012. In addition, although between-treatment differences were significant during the second year, they were minor in absolute terms at the SouthFertile site. Furthermore, the DSC and RH treatments resulted in less cover of competing field vegetation, which is beneficial for newly established seedlings due to the accompanying reduction in competition for nutrients (Örlander et al. 1990), than the control treatment. Cumulatively, the increases in soil temperature and reduction in competing field vegetation associated with the RH treatment probably at least partially compensated for the accompanying removal of nutrients.

As expected, and in line with findings by Wallertz et al. (2018), site preparation treatments that exposed bare mineral soil (DSC and RH) resulted in lower rates of mortality and damage by pine weevils than the control treatment at all sites (assuming that pine weevils were the main damage agent also at the northern sites). These treatments were especially beneficial for seedlings in the south. In addition, mortality was low (even in control plots) at the SouthFertile site, probably due to a combination of effective insecticide treatment (two retreatments at both southern sites), planting on a fresh clear-cut and fast early growth. All these factors reportedly reduce seedlings' susceptibility to damage by pine weevils (Nordlander et al. 2011). The higher overall mortality rates in northern Sweden compared to southern Sweden contradicts findings of Wallertz et al. (2016), as well as findings from experiments in similar locations as this study (Nordlander et al. 2011; Wallertz et al. 2014; Johansson et al. 2015). This might be explained by the additional second insecticide retreatment at the southern sites, in combination with a peak in the vole population during the establishment year (2011) in the north. However, observed rates of mortality and damage by pine weevils were often similar for Norway spruce and Scots pine seedlings, in accordance with results presented by Wallertz et al. (2014).

When regenerating a forest stand in Sweden, irrespective of species, scarification generally increases survival and growth (Nilsson et al. 2010). The SouthFertile site seems to be so fertile that it might not be necessary nor possible to increase growth for either of the two species considered on a fresh clear-cut. However, scarification may often be beneficial for other reasons, for example, to control competing field vegetation at older clear-cuts, or prevent pine weevil-mediated damage and mortality. It should be noted that the treatments applied in this study were designed to create extreme scarified and non-scarified environments for comparison, rather than to mimic practical site preparation techniques. The results show that Scots pine seedlings had high early growth rates in diverse environments, and outperformed Norway spruce seedlings at all sites following all treatments. They also show that both species can perform well, even without site preparation at a very fertile site, if the seedlings are sufficiently protected against pine weevils. Both species grew best following the DSC treatment, but only after five years' time-lag at the northern sites. Furthermore, Scots pine seemed to grow relatively well following the RH treatment, but it caused a sustained growth check of Norway spruce throughout the whole trial period. Due to the lack of long- and short-term studies of the two species at the same sites with a statistically sound design, there is high potential for enhancing our knowledge regarding optimal species and site-preparation choices. Hence, the factors influencing species' growth and survival rates in different sites (such as nutrient uptake, nutrient efficiency and retranslocation), and associated variations in growth and damage rates, warrant further attention in future research.

In conclusion, this study confirms earlier results and supports practical recommendations that site preparation should be done before planting as it increases survival and can increase the growth of seedlings of both species. However, using a site preparation technique that removes large amounts of organic material is not suitable when planting Norway spruce.

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Data availability

The data this study is based upon are available from the corresponding author, upon reasonable request.

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