## Effects of mechanical site preparation and slash removal on long-term productivity of conifer plantations in Sweden

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Effects of mechanical site preparation and slash removal on long-term productivity of conifer plantations in Sweden

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Abstract

Mechanical site preparation is commonly used to increase survival and early growth of newly planted seedlings. Ideally, any early positive effects of site preparation should persist for a long time, but concerns have been raised as to whether intensive site preparation might have a negative effect on the long-term productivity of a stand. The present study was therefore designed to investigate the long-term effects of different site preparation methods on productivity and determine any possible interactions with tree species and site fertility. In the 1980s, a randomized block experiment was established at sites throughout Sweden. Four site preparation methods of various intensities were performed on different sites: 1) an untreated control; 2) disc trenching; 3) mounding; and 4) ploughing. As a complementary treatment, slash was either retained or removed from some plots. Depending on soil moisture class, geographical position and site index, Norway spruce, Scots pine, or lodgepole pine were planted in pure stands. Growth variables such as height and diameter were measured during the first years after establishment. After about 30 years they were re-measured at the level of individual trees. Overall, an increased production of the planted trees after site preparation was found. Neither intensive site preparation (such as ploughing) nor slash removal had any negative effect on the long-term productivity of these experimental stands.

Key words: disc trenching, establishment, mounding, ploughing, regeneration, seedling

Introduction

The silvicultural system of clear-felling with subsequent replanting is commonly used across the world. Although this system has given good stand establishment results for decades, it is
not bullet-proof. Harvesting a forest stand alters environmental conditions such as microclimate, soil hydrology and soil fertility. As a consequence, a clear-cut with its changing dynamics is not always a friendly environment for newly planted seedlings (Margolis and Brand 1990; Grossnickle 2000). Seedling stress is common and both biotic and abiotic factors may reduce the regeneration success. One way to improve site conditions and so increase the survival and growth of planted seedlings at an early stage is by site preparation. This increases the availability of resources at a site by reducing competition from other species colonizing the regeneration area (Thiffault and Jobidon 2006; Wiensczyk et al. 2011; Johansson et al. 2013a). Depending on the method used, site preparation may also affect certain soil properties and so improve factors such as microclimate, the mineralization of nutrients, soil temperature and soil water availability (Schmidt et al. 1996; Smolander and Heiskanen 2007). Another important effect of site preparation, especially in conifer plantations in northern Europe, is the reduction of damage from the pine weevil (*Hylobius abietis* L.). By planting in bare mineral soil, the amount of pine weevil damage is significantly decreased (Petersson et al. 2005; Nordlander et al. 2011). Two of the most commonly used site preparation methods in Sweden are disc trenching and mounding. The regeneration results of these methods may vary depending on the specific site conditions and its limiting factors (Örlander et al. 1990). Disc trenching can be performed at most site types, while mounding is used on mesic to moist sites where elevated planting spots is preferred. Ploughing is a more intense method in which continuous mounds are formed (Löf et al. 2012); this is often performed on sites with thick humus layers in cold climatic regions. Ploughing was prohibited under the Swedish Forestry Act of 1994 due to concerns over negative environmental effects. However, the effects, especially the long-term effects of this method on forest productivity, are not fully understood and have not yet been comprehensively surveyed (Örlander et al. 2002). Ploughing has been
shown to increase production in many forest regions, for example in southeastern USA (Carlson et al. 2006) and Finland (Ahtikoski et al. 2010).

Ideally, any positive effects of site preparation on the establishment of seedlings should persist for a long time and preferably, it should even continue to increase production throughout a whole rotation. Several types of long-term responses have been identified depending on the silvicultural treatments applied during stand establishment. Different methods may give rise to different results: diverging growth-curves throughout the rotation; parallel growth-curves where the early growth gains are preserved; or even negative responses in which growth rates decline (Snowdon 2002). These responses have been studied in areas where tree species with short to medium rotations are grown (e.g. *Pinus taeda* and *Pinus radiata*) (Mason 2013). For example, methods that reduce the amount of competing herbaceous vegetation resulted in a positive establishment effect, while a reduction of competing woody species caused a response that was sustained over a longer period for *Pinus taeda* (Nilsson and Allen 2003). For species with longer rotations (*Norway spruce* (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and lodgepole pine (*Pinus contorta* Douglas ex Loudon)), the long-term responses to different regeneration methods have not been fully explored, but positive effects of site preparation that last longer than just the establishment phase have been found for some conifer species (Hébert et al. 2014; Nordborg et al. 2006). There have even been concerns that intensive site preparation might cause nutrient leaching, which would have a negative effect on the long-term production capacity of a site due to the consequent reduction in nutrient supply (Lundmark-Thelin and Johansson 1997). So far, no such effects have been demonstrated; rather the opposite has been found (Örlander et al. 1996; Johansson et al. 2013b), but it still remains that responses can differ between sites due to variation in conditions, methods and tree species.
For many years the usual harvesting practice in Sweden was to leave the slash (i.e. tops, branches and needles) on the regeneration area. Lately, it has become more common to remove the slash for use as biofuel. This could have both positive and negative effects on seedling establishment and growth. The removal of slash has been shown to facilitate both scarification and the practical process of planting (Saarinen 2006). It could also lead to positive effects on seedling establishment, at least in the short term. On the other hand, the retention of slash could improve early seedling growth by reducing the amount of competing vegetation and thus increasing the availability of soil resources (Harrington et al. 2013). The long-term effects of slash removal have been investigated to a far lesser extent, but there is evidence of reduced pools of N and C in the soil (Egnell et al. 2015; Kaarakka et al. 2014). Depleting a site of nutrients through slash removal may decrease its productivity in the long-term.

In the 1980s, a field experiment with Norway spruce, Scots pine and lodgepole pine was established to study the short- and long-term effects of site preparation intensity and slash removal on the performance both of planted seedlings and of soil chemistry (Mattsson and Bergsten 2003; Mjöfers et al. 2017). The main hypothesis at the time the experiment was set up was that scarification and slash removal would have negative impacts on long-term volume production. However, early results from the experiment showed increased survival and more height growth after site preparation (Hunt 1987; Sugg 1990; Jansson and Näslund 1993). After 17 years, site preparation had resulted in a significant increase in stem volume production of lodgepole pine compared to no scarification (Mattsson and Bergsten 2003). In the present paper, our aim was to investigate the effects of the site preparation treatments and
slash removal on the long-term productivity of these same stands, approximately 30 years after they were established. We tested the following hypotheses:

1) That long-term productivity decreases with increasing site preparation intensity.
2) That the removal of slash affects long-term volume production negatively.

Materials and Methods

Experimental design

The experiment originally comprised 13 sites: six in northern Sweden and seven in southern Sweden on sites of varying fertility, soil moisture and field-layer vegetation type (Table 1). Seven of those experimental sites were used in the present study: three in the northern regions of Sweden (Böle (1801), Rätan övre (1803), and Nastelsildret (1806)), and four in the southern regions (Lyttersta (1807), Fläda (1808 and 1809) and Hagfallet (1813)) (Figure 1). All sites were relatively flat except for Rätan that was sloping. These sites are hereafter referred to by their site number. Due to several reasons (Table 1), six sites were excluded from this study. Böle (1802) was one block at the site Böle (1801) and was therefore seen as the same site. Rätan nedre (1804) lacked a control treatment, and treatments at Östbodarna (1805) and Hälla (1812) were not randomized. Fläda (1810) was planted with a sparse spacing of only 1250 seedlings per hectare Lindalen (1811) was accidently clear-felled.

The sites were clear-felled during the winter/spring of 1981 and 1983 in northern and southern Sweden respectively. In the following summer, slash (tops and branches) was removed from some of the plots in southern Sweden. During the fall 1981 (northern Sweden) and 1984 (southern Sweden), four site preparation treatments were performed on 900 m² (30
m x 30 m) plots: 1) untreated control (Control), 2) disc trenching (Disc T), 3) mounding (Mound) and 4) ploughing (Plough). According to expected establishment results, the control was considered to be the least intense method, followed by disc trenching, mounding and ploughing. Disc trenching was performed in continuous rows, mounding was carried out to create elevated planting spots with an inverted humus layer, and the ploughing treatment comprised the creation of furrows 0.3 m - 0.5 m deep (Figure 2). All treatments were replicated twice on each site except for sites 1801 and 1806 where they were replicated three times (Table 2). The experiment was laid out as a randomized-block design where one replicate of each treatment was considered to be a block (Hunt 1987; Sugg 1990). All treatment plots were surrounded by a buffer zone, but the size of this zone varied between sites. On all sites, treatments were performed on plots where the slash had been retained. At the sites in southern Sweden (1807, 1808, 1809 and 1813), some of the treatments were also performed on plots where the slash had been removed. Due to the imbalance in the experimental design, only the disc trenching treatments with and without slash were included in this specific study.

In the spring following site preparation, the sites in southern Sweden were planted. The rows within each treatment plot were numbered and each seedling position was marked with a plastic stick. Depending on the method, the following planting positions were chosen: control – as high a planting position as possible, disc trenching – the highest positions in the hinge of the furrow, mounding – the highest position on the mound, ploughing – on top of the furrow (Figure 2). The seedlings were planted to a depth of 2 cm below the stem base. To protect seedlings from pine weevil damage, the seedlings planted in southern Sweden were treated with an insecticide (synthetic pyrethroid) and provided with a mechanical barrier constructed of nylon and cotton netting (Eidmann and von Sydow 1989) at the time of planting. In
southern Sweden, 2-year-old containerized seedlings of Norway spruce and Scots pine of local provenances were used. All treatment plots were planted to achieve a seedling density of 2,500 seedlings per hectare. Scots pine were planted on the poor and dry site 1807 and on the medium fertility site 1808. Norway spruce were planted on the medium fertile site 1809 and the mesic and fertile site 1813 (Table 2). In northern Sweden, 1-year-old containerized lodgepole pine seedlings were planted on all sites. The control plots in northern Sweden were planted one year earlier than the scarified plots to mimic practical forestry where scarified areas usually sit over a winter before planting. This decreases the risk of air pockets in the berms since they are compressed by precipitation and ground frost during this period. In the control plots, seedlings were planted at a slightly higher density due to an expected higher mortality. They were also wrapped in a plastic cover to protect from pine weevil damage. At site 1801, the initial planting density was 2,347 seedlings per hectare for the control plots and 2,000 seedlings per hectare for plots with site preparation (Mattsson and Bergsten 2003). At site 1803 and 1806, the initial planting densities were 2,327 and 2,388 seedlings per hectare for the control plots, respectively, and 2,222 seedlings per hectare for plots with site preparation. The same planting positions as for southern Sweden were used. Dead and dying seedlings at the southern sites were replaced in supplementary plantings on three occasions. The northern sites underwent supplementary planting between 1982-1984 in the control plots on three occasions and in the treatment plots on two occasions. The same seedling types as in the original planting were used. A more detailed description of the experimental layout and early results from the northern Sweden plots can be found in Hunt (1987), Jansson and Näslund (1993) and Mattsson and Bergsten (2003), and for southern Sweden in Sugg (1990). Measurements
After 27-32 years, trees in the experimental sites were remeasured. On these occasions, diameter at breast height (DBH, measured in two orthogonal directions) was measured on all planted trees. Data were also gathered from the five dominant trees and 15 other sample trees systematically selected in each treatment plot. For Scots pine height (H), height to the first living branch (HL) and thickness of the bark (BT) were measured. For Norway spruce H and HL were registered and only H for lodgepole pine. Additionally, the number and species of naturally regenerated trees with a height > 1.3 m was also recorded in DBH classes of 10 mm.

Stem-volumes of sample trees were calculated with functions developed by Brandel (1990) using DBH, H and HL for Norway spruce and DBH, H, HL and BT for Scots pine as independent variables. For lodgepole pine, DBH and H were used in a function developed by Eriksson (1973). Thereafter, volume of all trees was estimated in 2 cm diameter-classes using the DBH²-weighted volume of sample trees in each diameter-class (Nilsson et al. 2010). Top height (TH) for each plot by measurement occasion was estimated by the height-curve developed by Näslund (1936):

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

where H = tree height (m); DBH = diameter at breast height (cm); a and b are coefficients, and x = 2 for Scots pine and lodgepole pine, and x = 3 for Norway spruce (Pettersson 1955). Top height (TH) was estimated as the average of heights calculated with the above function [1] for the 100 trees with greatest DBH per hectare. For each growth parameter, the value for the dominant trees (i.e. the 100 largest trees by DBH per hectare) in each treatment was calculated by selecting the 10 largest trees by DBH in each treatment plot.
The final measurements in the plots with slash removal were made two years after those in the plots with retained slash at experimental sites 1808 and 1809. Estimated volumes and heights on plots with slash removal were therefore adjusted in order to render the data as if from samples of comparable ages. Annual volume and height increments per hectare for each period were calculated as the average annual volume and height increment between the two last measurements. Thereafter, two years’ worth of increment was subtracted from the height and volume values per hectare.

Statistical analyses

Data were analyzed in order to examine effects of mechanical site preparation on long-term growth and volume production over all sites. Since the experimental design was unbalanced with respect to tree species, the analyses were made regardless of the planted trees species. Any variation due to differences in tree species and site conditions was assumed to have been captured within the sites. For these analyses, measurements registered at each site were used, i.e. standing volume for planted trees (VOL, m$^3$ ha$^{-1}$), DBH (mm), top height (m), basal area (BA, m$^2$ ha$^{-1}$) and stem number per hectare. The total volume, including naturally regenerated trees, (VOL$_{tot}$, m$^3$ ha$^{-1}$) was also analyzed. The following model was used for the analyses:

$$Y_{ijk} = \mu + \alpha_i + b_{ij} + \gamma_k + (\alpha\gamma)_{ik} + \epsilon_{ijk}$$  \[2\]

where $\mu$ is the overall mean, $\alpha_i$ the fixed combined effects of site and tree species ($i = 1-7$), $b_{ij}$ is the random effect of block within site, $\gamma_k$ is the fixed treatment effect ($k = 1-4$), and $\epsilon_{ijk}$ is the experimental error. The interaction between site and site preparation treatments was also
included in the model. The denominator degrees of freedom within the model was adjusted according to the Satterthwaite approximation. The same model was used to study the effects on single trees, i.e. VOL (dm$^3$), H (m) and DBH (cm). In this case, the plot means were calculated before the analyses were made. To analyze effects of slash removal, the same model was used but site preparation treatment was replaced by slash treatment ($k = 1-2$). All statistical analyses were performed by PROC MIXED in SAS 9.4 (SAS Institute, Cary, NC, USA). A significance level of 0.05 was used for all analyses. When significant differences occurred, the least square means were compared pairwise and adjusted according to Tukey-Kramer.

The diameter distribution data were analyzed by fitting two-parameter Weibull distributions in R (version 1.0.136). Shape and scale parameters were estimated for each treatment and site. Statistically significant differences between treatments in the scale-parameter were calculated in the same way as described above for growth-variables.

### Results

**Effects of mechanical site preparation**

Site preparation had a significant positive effect on the standing volume both with and without the inclusion of naturally regenerated trees (Figure 3). The standing volume increased with increasing site preparation intensity ($p = 0.0001$ for both volume of the planted trees and for the total volume). The volume was lowest in the control treatment and highest in the ploughing treatment (Figure 3). To reach the volume achieved in the ploughing treatment after 32 years, it requires 39 years in mounding, 41 years in disc trenching and 53 years in the control, respectively, with the current mean annual growth. Within sites, the same pattern was
found but the magnitude of response differed between sites (Figure 4). Although no statistical analyses could be made at tree species level, the response to site preparation appeared to be highest in Norway spruce and lodgepole pine and lowest in Scots pine. For Norway spruce, ploughing almost doubled the volume compared with the control, while these drastic effects were not seen for the two pine species.

A similar ranking of site preparation treatments as for volume was also found for basal area and DBH (Table 3). Stem density was significantly higher in scarified plots compared with the control, but there were no differences between site preparation methods. More stems after site preparation indicates a higher survival rate. All the measured variables differed significantly between sites (p = 0.0001 for all variables). No interactions between site and site preparation were found, except for the number of stems at stand level, indicating that the positive effects of site preparation on wood production occurred across a range of different sites.

The DBH distributions, described with the shape-parameter of Weibull distributions, differed significantly between treatments (p = 0.0008). In the control treatment, the shape parameter was significantly lower than in scarified treatments indicating that distributions were more skewed towards trees in the lower diameter classes (Figure 5). The shape parameter did not differ significantly among scarified plots. Significant differences between sites were present (p = 0.0001) for the shape-parameter, but no significant interactions between site and treatment were found (p = 0.1324).
Slash removal

Slash removal in the disc trenching treatment on the sites in southern Sweden had no effect on standing volume about 30 years after planting (p = 0.7109). Within sites, slash removal and slash retention gave similar values for both Scots pine and Norway spruce (Figure 6).

Discussion

When the experiment was initially set up, it was hypothesized that site preparation and slash removal would negatively influence long-term volume production. However, this study of long-term productivity about 30 years after planting failed to confirm this hypothesis. Instead, site preparation both increased survival and early growth of the planted seedlings, as well as increase production in terms of standing volume about 30 years after establishment. Other studies also support these observations of the long-term benefits of site preparation. For example, Prévost and Dumais (2018) showed that both height and DBH of planted black spruce seedlings were significantly higher after 25 years in scarified treatments compared to a control. Similar results have been found for Norway spruce after 18 years (Johansson et al. 2013b), and for white spruce after 20 years (Boateng et al. 2006). However, one should bear in mind that 30 years is still only less than half of a rotation period in this area, and the results can change until final felling.

Although not always significantly different, there was a tendency in this experiment towards higher production with increasing site preparation intensity, with disc trenching seen as the least intensive method and ploughing as the most intensive method regarding soil disturbance. This increase in production was seen both for single trees within stands, and for the total
This indicated that the effect of site preparation was not only a matter of increased survival and more stems in the scarified plots; it also positively affected individual trees. The diameter distributions of the site preparation treatments were normally distributed and the shapes were rather similar, with a shift towards greater DBH for the site preparation treatments, in particular after ploughing. In the control treatment, more trees were found in the smallest diameter class. Similar results from mounding and chemical treatments in comparison with control were found for white spruce after 20 years, but in that case the curves were more skewed and with even more trees remaining in the smaller diameter classes (Boateng et al. 2006). In the study by Boateng et al. (2006), differences in survival rates were found in site preparation and control treatments, resulting in large differences in basal area per hectare. In our study, site preparation effects on survival were difficult to evaluate. Even though site preparation increased survival and number of stems per hectare, the fact that the control treatment was initially planted with more seedlings and that the experimental sites were supplementarily planted in the first years after establishment, especially in the control treatments, may underestimate the differences in stand production between control and site preparation. Other studies have shown that site preparation significantly increases survival, and that higher mortality occurs in the first years following planting (Johansson et al. 2013b; Wallertz et al. 2018). On the other hand, if not done immediately, supplementary planting may not contribute to an increase in production. At one of the sites, 1809, a very high proportion of the trees in the control treatment were found in the lowest diameter class. That site, planted with spruce, suffered from frost injuries and pine weevil damage at establishment, and even though supplementarily planted, the volume production was still very low. An earlier study has shown that supplementary planting can be problematic with low survival rates and suppressed growth among the supplementarily planted seedlings leading to
an insignificant decrease in the production of the stand (Nilsson and Gemmel 2007). This was
probably the case for site 1809, and maybe also for site 1801.

The greatest and most significant site preparation treatment effect on standing volume was
found with ploughing. Other studies have also found positive long-term effects of this
intensive treatment (Örlander et al. 1998; Mäkitalo et al. 2010). In addition, at some of the
sites reported in this study, carbon (C) stocks were measured after 25 years (Mjöfors et al.
2017). Results showed that the standing tree carbon stock was highest after ploughing and
with no negative effect on soil C stocks. However, the authors recommended mounding or
disc trenching to promote C sequestration prior to ploughing due to the possible negative
effects of ploughing on aesthetic properties and ecological values. Despite the positive effects
of intense site preparation, ploughing should still be questioned as a method and its use is
currently restricted in many areas. Intense site preparation may result in negative effects
(Örlander et al. 1990; Worrell and Hampson 1997), and it is important to find an acceptable
method that can give a disturbance level sufficient enough for adequate growth (Prévost and
Dumais 2018). Results from the present study show that disc trenching and mounding can
result in acceptable levels of seedling establishment and growth of the remaining stand, and as
Mjöfors et al. (2017) has concluded, also promote C sequestration. Both clear-cutting and site
preparation may increase CO₂ emissions and reduce soil C stocks in the initial phase
compared to undisturbed forests (Pumpanen et al. 2004, Piiranen et al 2015). After some
years, the young forest changes from a carbon source to a carbon sink, and intensive forest
management may shorten this period and increase the soil C pool in the long run. Due to the
complexity of the processes involved in a forest ecosystem, no conclusions about the effects
of forest operations on C-budgets and CO₂ emissions can be made from this study.
The study also confirms that the initial positive effects of site preparation endure over time, indicating that an investment in site preparation may lead to stands with a higher economic value and result in a higher likelihood of fulfilling the goals of the forest stand (Hawkins et al. 2006; Ahtikoski et al. 2010). Even though site preparation is associated with an extra cost in the regeneration phase, it may render higher incomes at the end of the rotation due to shorter rotations and increased biomass. Interest rates and choice of management programs are factors influencing the economical outcome of a chosen regeneration chain (i.e. choice of site preparation method, regeneration method, pre-commercial thinning etc.) and should thus be considered in the establishment phase (Hyytiäinen et al. 2006, Uotila et al. 2010).

Contrary to the second hypothesis in the present study, the removal of slash had no significant negative effects on the long-term productivity. Similar results were found after 15 years in a jack pine stand where no differences were found after stem-only and whole-tree harvest (WTH) (Fleming et al. 2014). Similarly, WTH had no negative effect on the productivity of Norway spruce and Scots pine seedlings within the first 10 years after harvesting in southern Finland (Tamminen and Saarsalmi 2013). By contrast, however, Egnell (2011) found a reduction in stand growth after 31 years in Norway spruce following WTH and increased nitrogen loss was suggested as the primary explanation. As discussed by the authors of the above references, differences in response may depend on harvesting operations. Even when WTH is performed, substantial amounts of logging residues may still be left on the site. These amounts may vary between operations and therefore also between experiments. In practice, when slash is removed it is not usually done until the needles have fallen off the branches, leaving a substantial amount of nitrogen on the site. Other factors that can affect the results
are site fertility, age of stand, and the site preparation methods used in combination with slash removal. If the biomass from harvest residues is increasingly used in the future, more research will be needed to understand the long-term effects of slash removal and WTH on site productivity.

Due to having few replicates on each site and the fact that no site was planted with all three tree species, the comparison of responses among the different species and the presence of possible interactions between tree species and site preparation treatment could not be analyzed. The only strong conclusion to be drawn was that site preparation seems to have a more or less positive effect on the growth of all conifer species planted in the experiment: a finding which is supported by several other long-term experiments planted with one or more conifer species (Örlander et al. 1996; Thiffault et al. 2010; Johansson et al. 2013; Prévost and Dumais 2018). As Thiffault et al. (2010) have shown, there could be interaction effects between species and site preparation due to differences in the species’ nutritional requirements. For the species used in this experiment, the growth of Norway spruce, compared with Scots pine, seems to be more dependent on nutrient availability. On less fertile soils and in harsher climates, Norway spruce growth can be checked and its productivity reduced (Bergh et al. 2010; Nilsson et al. 2012).

Further long-term experiments are essential in order to increase our knowledge of how forest operations affect long-term production. Such long-term trials may have wider applications than their original design and purpose intended, in that they may also be used to raise and address new research questions to advance our knowledge about forest ecosystems (Prescott 2014). In the present experiment, there were some largely unavoidable problems inherent in
the experimental design. Species differed among sites; replication was limited and slash was not removed from all site preparation treatments. As a consequence, it was not possible to evaluate treatment effects on individual tree species, and for some of the parameters tested, tendencies of positive treatment effects could be seen but not statistically proven. Despite these problems, results generated from this experiment are valuable since the existence of such long-term studies are few. The results indicate how site preparation treatments affect production over a forest rotation and are confirmed by other long-term studies. When establishing new long-term experiments, the design is of great importance. Large areas are needed, and it is hard to find large enough homogeneous sites, even on a block-level. To be able to draw general conclusions applicable in practical forestry, many sites are therefore needed to capture all this variation. Other important aspects are the time-consuming and rather expensive measurements that need to be made, as well as management and data handling. It is therefore, as Prescott (2014) states, important that research institutions, universities and forest companies understand the value of these types of experiments and are willing to invest in their establishment and maintenance.

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### Table 1. Description of the experimental sites.

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<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
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<th>Soil texture</th>
<th>Soil moisture</th>
<th>Field layer vegetation</th>
<th>SI*</th>
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<td>1801 Böle</td>
<td>62° 27'</td>
<td>14° 20'</td>
<td>410</td>
<td>Stoney</td>
<td>Dry</td>
<td>Lichen</td>
<td>27.6</td>
</tr>
<tr>
<td>1802 Böle</td>
<td>As above</td>
<td>site merged with 1801 Böle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1803 Räutan övre</td>
<td>62° 31'</td>
<td>14° 32'</td>
<td>420</td>
<td>Sandy till</td>
<td>Mesic</td>
<td>Vaccinium</td>
<td>33.3</td>
</tr>
<tr>
<td>1804 Rätan nedre</td>
<td>Excluded</td>
<td>no control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1805 Östbodarna</td>
<td>Excluded</td>
<td>not randomized</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1806 Nästelsildret</td>
<td>62° 31'</td>
<td>14° 22'</td>
<td>370</td>
<td>Silty</td>
<td>Wet</td>
<td>Sedge</td>
<td>32.8</td>
</tr>
<tr>
<td>1807 Lyttersta</td>
<td>58° 59'</td>
<td>15° 54'</td>
<td>80</td>
<td>Coarse sand</td>
<td>Dry</td>
<td>Lichen</td>
<td>27.2</td>
</tr>
<tr>
<td>1808 Fläda</td>
<td>58° 41'</td>
<td>15° 02'</td>
<td>140</td>
<td>Sand</td>
<td>Mesic</td>
<td>Ericaceous</td>
<td>30.9</td>
</tr>
<tr>
<td>1809 Fläda</td>
<td>58° 41'</td>
<td>15° 02'</td>
<td>140</td>
<td>Sand</td>
<td>Mesic</td>
<td>Ericaceous</td>
<td>32.6</td>
</tr>
<tr>
<td>1810 Fläda</td>
<td>Excluded</td>
<td>sparse spacing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1811 Lindalen</td>
<td>Excluded</td>
<td>commercially thinned</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1812 Hålla</td>
<td>Excluded</td>
<td>not randomized</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1813 Hagfallet</td>
<td>58° 42'</td>
<td>15° 07'</td>
<td>125</td>
<td>Silty sand</td>
<td>Moist</td>
<td>Grass</td>
<td>35.9</td>
</tr>
</tbody>
</table>

* SI is the site index (mean top height (m) at 100 years) according to Elfving (1997) for Scots pine, Elfving (2010) for Norway spruce, and Liziniewicz et al. (2016) for lodgepole pine. Site index is given as an average from disc-trenched plots.
Table 2. Description of the experimental set-up and the treatments performed at each site.

<table>
<thead>
<tr>
<th>Site preparation</th>
<th>Tree species*</th>
<th>Slash removed</th>
<th>Number of replicates per site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1801</td>
</tr>
<tr>
<td>Control</td>
<td>S pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Disc T</td>
<td>S pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Mound</td>
<td>S pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Plough</td>
<td>S pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Control</td>
<td>N spruce</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Disc T</td>
<td>N spruce</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Mound</td>
<td>N spruce</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Plough</td>
<td>N spruce</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Control</td>
<td>L pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Disc T</td>
<td>L pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Mound</td>
<td>L pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Plough</td>
<td>L pine</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>Disc T</td>
<td>S pine</td>
<td>Yes</td>
<td>2</td>
</tr>
<tr>
<td>Disc T</td>
<td>N spruce</td>
<td>Yes</td>
<td>2</td>
</tr>
</tbody>
</table>

*S pine = Scots pine, N spruce = Norway spruce, L pine = lodgepole pine
Table 3. Mean values (least square means) of the measured variables per site preparation treatment at the stand level (ha\(^{-1}\)). Values followed by different letters are significantly different column wise. DBH is the quadratic mean breast height diameter (cm), TH is the mean top height (m), BA is the basal area (m\(^2\)) and Stems is the number of stems per hectare.

A statistical summary of the effects of site, site preparation and their interaction shown as p-values of least square means of different growth variables at the stand level is presented below the mean values.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>DBH</th>
<th>TH</th>
<th>BA</th>
<th>Stems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>10.7 a</td>
<td>11.7 a</td>
<td>18.7 a</td>
<td>1830 a</td>
</tr>
<tr>
<td>Disc T</td>
<td>11.6 b</td>
<td>12.7 b</td>
<td>22.8 b</td>
<td>2016 b</td>
</tr>
<tr>
<td>Mound</td>
<td>11.6 b</td>
<td>12.8 b</td>
<td>24.0 b</td>
<td>2088 b</td>
</tr>
<tr>
<td>Plough</td>
<td>12.5 c</td>
<td>13.5 b</td>
<td>26.9 c</td>
<td>2054 b</td>
</tr>
</tbody>
</table>

Effect, p-values

<table>
<thead>
<tr>
<th>Site</th>
<th>DBH</th>
<th>TH</th>
<th>BA</th>
<th>Stems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site preparation</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Site × Site preparation</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

p-values of least square means of different growth variables at the stand level are presented below the mean values.
**Figure captions**

**Figure 1.** Geographic location of the experimental sites in northern (sites 1801, 1803 and 1806) and southern Sweden (sites 1807, 1808, 1809 and 1813).

**Figure 2.** The mechanical site preparation methods used in the experiment; control i.e. no site preparation (a), disc trenching in continuous rows (b), mounding with elevated planting spots (c) and ploughing with relatively deep furrows in rows (d). The seedling in each treatment figure show the planting position used in the study.

**Figure 3.** Mean values (least square means) of standing volume per hectare ($\text{m}^3 \text{ha}^{-1}$) in different site preparation treatments on all sites about 30 years after planting. $\text{VOL} =$ the volume of planted trees and $\text{VOL}_{\text{tot}} =$ the volume of all trees, including naturally regenerated trees. Different letters show significant differences between the treatments.

**Figure 4.** Volume ($\text{m}^3 \text{ha}^{-1}$, least square means) per site and tree species for the different site preparation treatments. $\text{Lp} =$ lodgepole pine, $\text{Sp} =$ Scots pine and $\text{Ns} =$ Norway spruce.

**Figure 5.** Diameter distributions based on Weibull distributions for each site and treatment. Sites 1801, 1803 and 1806 were planted with lodgepole pine, site 1807 and 1808 with Scots pine and 1809 and 1813 with Norway spruce.

**Figure 6.** Effects of slash removal or retention on standing volume per hectare ($\text{m}^3 \text{ha}^{-1}$) in the disc trenching treatment on the sites in southern Sweden about 30 years after planting. $\text{Sp} =$ Scots pine and $\text{Ns} =$ Norway spruce.
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6