Forestry An International Journal of Forest Research

Institute of Chartered Foresters

Forestry 2013; **86**, 91–98, doi:10.1093/forestry/cps062
Advance Access publication 10 September 2012

A comparison of long-term effects of scarification methods on the establishment of Norway spruce

Karin Johansson[1,2]*, Urban Nilsson[1] and Göran Örlander[3]

[1]*Southern Swedish Forest Research Centre, SLU, Box 49, SE-230 53 Alnarp, Sweden;* [2]*Skogforsk, Ekebo 2250, SE-268 90, Svalöv, Sweden;* [3]*Södra Forest Owner Association, Skogsudden, SE-351 89 Växjö, Sweden*

*Corresponding author Telephone: +46(418)471307; karin.johansson@skogforsk.se

Received 30 January 2012

Scarification is the most common measure to improve the planting environment in Sweden. However, different scarification methods give varying results. During the early 1990s, a nation-wide experiment with 10 field installations was established in order to test the effect of several scarification methods, including two intensities of soil inversion and mounding, on growth of planted Norway spruce seedlings and in comparison with no scarification (i.e. control). Eighteen growing seasons after planting, a higher seedling survival was found following soil inversion (77 per cent for normal and 76 per cent for intensive) compared with mounding (67 per cent) and control (57 per cent). The mean height of the planted trees across all sites 18 years after planting was 413 and 430 cm following normal and intensive soil inversion, respectively, 424 cm after mounding and 346 cm in the control. The difference in height between the scarification treatments and the control corresponded to a time gain of ~4 years of growth after 18 years. However, the length of the leading shoot was not affected by scarification after 14–18 years, indicating that scarification did not affect growth beyond the establishment phase. Scarification reduced variation in height of the planted trees. On scarified plots, the number of naturally regenerated trees increased with more than 100 per cent to reach a mean value of 2300 stems per hectare.

Introduction

Seedling establishment on a reforestation site is restricted by a number of factors. The access to water and nutrients is often limited, and this is partly caused by competition from surrounding vegetation, but also due to climatic factors, seedling characteristics and soil properties.[1] In Sweden, scarification is the most common silvicultural practice to alter the planting environment and to increase the success of seedling establishment, irrespective of species. Today, 92 per cent of the planted area in Sweden is scarified mechanically.[2] The two dominant methods are disc trenching and mounding. Disc trenching can be applied on most sites, even on stony soils, while mounding is more common on mesic to moist sites with moderate stoniness. However, the quality of the planting spots varies between these two methods depending on the specific site and its limiting factors.[3] After disc trenching, planting is often made in the trench where the humus is removed, which can result in a poor nutrient supply and a surplus of water. Mounding, on the other hand, where seedlings are planted on elevated spots, can increase the risk of drought stress in the newly planted seedlings,[4] especially if the buried humus layer becomes too thick and therefore acts as a barrier for the capillary water to reach the seedling root system. Also, the degree of soil disturbance for the two methods is rather high, and there have been concerns regarding possible negative effects on both the short-term and the long-term productivity after scarification due to increased levels of nutrient losses.[5] Another negative aspect is from a recreational and environmental point of view, where scarification can be a disadvantage if damages are caused to cultural and natural values.

Soil inversion can reduce some of these issues by creating a planting spot at the same level as the surrounding ground.[6] The planting spot consists of an inverted humus layer covered by loosened mineral soil, which is returned to the original hole. Soil inversion was introduced as a scarification method in the early 1990s, and for a long time it has been recognized as a treatment that improves early establishment of planted seedlings in Sweden.[6–8] Another important aspect affected by scarification treatments is damage caused by pine weevil (*Hylobius abietis*). If the seedlings are surrounded by pure mineral soil, the damages related to pine weevils will decrease substantially.[9] In comparison with other scarification methods, planting spots created by soil inversion have shown to have a higher content of pure mineral soil.[10] Despite this fact, soil inversion has not been used operationally due to the lack of technical equipment. Recently, new technical improvements have made it possible and again raised the interest for the method.[11]

The current knowledge about the effects of different scarification methods on tree growth beyond the establishment phase is

Table 1 Experimental site distribution in Sweden. Site index is the height in m for Norway spruce after 100 years

Site no	Local	Latitude	Altitude	Soil texture	Soil humidity	Site index
1	Anderstjärn	65°25′	335	Sandy silt	Mesic-moist	16
2	Näverliden	65°20′	365	Sandy silt	Mesic-moist	16
3	Vojmsjön	64°90′	580	Silty	Mesic-moist	17
4	Vojmsjön	64°90′	550	Silty	Mesic	17
5	Knaften	64°30′	350	Sandy silt	Mesic	19
6	Nyby	64°20′	375	Sandy silt	Mesic	17
7	Vimmarvattnet	63°37′	375	Silty sand	Mesic-moist	21
8	Lövliden	63°11′	360	Sandy silt	Mesic	21
11	Lokevägen	57°10′	180	Sandy silt	Mesic	28
12	Hultåsen	57°11′	250	Silty sand	Mesic	32

limited. Rotation periods in Sweden are long, from 60 to over 100 years, and many studies on early seedling establishment were not designed as long-term studies. Although a few studies have been established and have shown that production increases with more intense scarification,[12,13] the effects may differ between sites and tree species. In operational forestry, knowledge about long-term effects of scarification is especially important in order to determine whether scarification is profitable. There is also a need to evaluate the long-term effects on different scarification methods on the production and species composition of naturally regenerated trees as well as the variability within a stand. The scarification method could, for example, affect the emergence of *Betula* ssp.[14] This could lead to a higher cost for pre-commercial thinning, but on the other hand it could also increase the number of merchantable trees in the stand. Vegetation management is crucial for the development of a forest plantation, and herbicides are a common measure to reduce both herbaceous and woody vegetation. In Sweden, the use of herbicides is restricted, and concerns about the use of herbicides is raised in other countries like Canada,[15] where scarification followed by pre-commercial thinning could be one solution.

During the early 1990s a nation-wide experiment was established in order to test the effects of different scarification methods, including soil inversion of varying intensity and mounding, on the establishment of planted Norway spruce in comparison with no scarification (control). In 2007 and 2011, the experiment was measured again. The objectives of this study were:

(1) to evaluate the effects of different scarification methods on survival and growth of the planted trees the first 18 years after planting;
(2) to investigate possible negative effects on the long-term productivity following scarification;
(3) to study the effects of scarification on the amount of naturally regenerated trees.

Materials and Methods

Experimental design

The study consisted in 10 field experiments installed on clear-cuts distributed from 57°N to 65°N on podzolic soils in Sweden, with an emphasis towards the northern parts of this range (Table 1). The sites had a site index that was around the average or slightly above the average site index relative to each region, and most of them were on mesic to moist soils where the soil texture was sandy silts. The original study established in 1993 included 12 study sites, but two of these sites, located in the central parts of Sweden, had to be excluded due to severe damages by pine weevils (*Hylobius abietis*) since up to 90 per cent of the planted seedlings died (site number 9 and 10). For more details about the original design, early results and measurements, see Hallsby and Örlander.[16]

During the winter of 1992/1993, the stands were clear felled and in the fall of 1993, scarification was carried out using excavators. Each site was considered as a block and four scarification treatments were randomly applied to 0.5 ha plots (50 × 100 m) at each site: (1) control (no scarification), (2) mounding (2 500 spots per ha), (3) soil inversion (2 500 spots per ha) and (4) intensive inversion (3500 spots per ha). The mounding and soil inversion both consisted of 0.5 m^2 spots with a buried humus layer covered with a 0.1–0.2 m deep layer of mineral soil (Figure 1). The difference between the regular soil inversion and the more intensive inversion was the number of planting spots. By creating more planting spots per hectare, a higher proportion of the area was disturbed and there were more planting spots to choose from. The same number of seedlings was planted on all treatments.

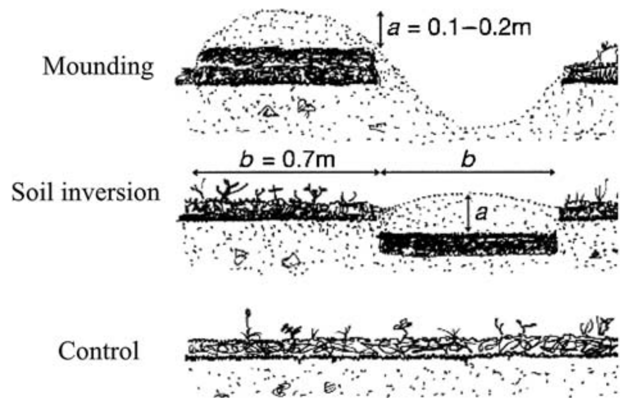

Figure 1 Scarification treatments used in the study. Mounding = an elevated spot with an inverted humus layer covered by 10–20 cm of mineral soil. Soil inversion = an inverted humus layer covered by 10–20 cm mineral soil, which is in level with the surrounding ground. Control = the ground was left untreated.

In May–July 1994, starting with the southernmost sites, Norway spruce seedlings were planted at 2 × 2 m spacing, which gave a total of 2500 seedlings per ha. Containerized 1-year-old seedlings (grown in Hiko V50) were used on all sites except for the two southernmost ones where 3-year-old bare-rooted seedlings (1.5/1.5) were used. Since the experiments ranged from 57°N to 65°N, large environmental and climatic differences occurred between sites. Therefore, suitable provenances were chosen for each site to reduce the negative effects on growth and increased risk of damages due to poor climatic adaptation, see Hallsby and Örlander[16] for details about the provenances. Larger seedlings where used in the south to avoid severe damages by pine weevils, but on all sites the seedlings were treated with permethrin (0.5 per cent active ingredient) to protect them against pine weevils. The different seedlings types and provenances were accounted for in the block effect.

Measurements

At the time of planting, eight permanent circular sample plots were installed in each treatment. Each sample plot was 100 m^2 and contained ~25 seedlings. After the first, third and fifth growing season, average height and vigor of the seedlings were measured. A total of 200 seedlings were measured per treatment and site. In 2007, 14 years after planting, the sites were measured again. Five circular sample plots with a radius of 5.64 m were laid out along the diagonal of each scarification treatment plot. Total height, length of the leading shoot and diameter at breast height (DBH) were measured on the trees and the vigor of each tree was registered by using the following classes: 1 = healthy (increased growth since last measurement), 3 = poor (reduced or no growth due to damages or stress) and 5 = dead. The naturally regenerated trees within each sample plot were counted. If any naturally regenerated trees were present, both height and DBH of up to five of the largest trees were measured. If there were more than five naturally regenerated trees in the sample plot, species and average height of these additional trees were estimated and registered. In the fall of 2011, 18 years after planting, the same measurements as those made14 years after planting were done, but this time on the eight permanent sample plots used in the first three measurements. On the two southernmost sites, height was only measured on every fifth tree, but DBH was measured on all trees. On the other eight sites, heights of all the planted trees within the sample plots were measured.

Calculations and statistical analysis

Mortality was calculated as the difference between the number of seedlings planted, 2500 seedlings per ha, and the average value of standing trees per hectare and treatment after 14 and 18 years, respectively. On one site, Lokevägen, the stand had been pre-commercially thinned and not only naturally regenerated trees but also planted trees had been removed. These trees were accounted for by measuring the diameter of the stumps. On every fifth remaining planted tree, diameter at both stump and breast height were measured. Thereafter, a regression function was fitted and used for estimating DBH for pre-commercially thinned trees from the diameter of the stumps. On the two southernmost sites, height of all trees was estimated by fitting a height curve for each treatment. In this calculation, height of pre-commercially thinned trees was also estimated. The pre-commercially thinned trees were considered as living trees in the mortality data. Since an unknown amount of the naturally regenerated trees had been removed in pre-commercial thinning between year 14 and 18, data on natural regeneration after year 14 were not used in any analysis.

An estimate of time gain was calculated as the number of years it would take for the control treatment to reach the same height as the respective scarification treatment. Time gain was defined as the ratio between the difference in height between each scarification treatment and the control and average annual height increment of the control. Time gain was calculated with the following formula:

$$T_{\text{gain}} = \frac{\text{H18}_{\text{scarification}} - \text{H18}_{\text{control}}}{(\text{H18}_{\text{control}} - \text{H14}_{\text{control}})/5}$$

where H18 is the height at 18 years and H14 is the height at 14 years.

When analysing the data, scarification treatment was set as the explanatory variable and each site was considered as a block. Mean values for the different response variables for each block and treatment were calculated before the analyses were made. Thereafter, an ANOVA was made using PROC GLM in SAS (SAS Institute, Cary, NC, USA) and the following model was applied:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$$

where μ is the overall mean, α_i the block effect ($I = 1$–10), β_j is the scarification treatment effect ($j = 1$–4) and ε_{ij} is the experimental error. Block was set as a random factor. When analysing seedling survival, the data were transformed using arc sine transformations ($\acute{Y} = \arcsin\sqrt{Y}$) to reduce non-normality and unequal variances. Differences with a P-value of <0.05 were considered to be significant. When significant differences appeared, Tukey's test was used to separate individual factors.

Results

Tree mortality

The first 5 years after planting, the control treatment showed a significantly greater mortality rate in comparison with soil inversion and mounding.[16] The early effects of scarification on seedling mortality were consistent over time and significant effects of scarification treatments on mortality were found both 14 and 18 years after planting ($P < 0.0001$ and $P = 0.0048$, respectively). Fourteen years after planting, mortality was significantly higher in the control treatment compared with the mounding and soil inversion (Table 2). Comparing mounding and soil inversion, the mortality was 10–15 per cent higher after mounding, but the difference was statistically significant only when compared with the intensive inversion. After 18 years, the differences between the control and the scarified treatments remained. The mortality in the control treatment after 18 years was slightly lower than after 14 years and this was probably due to the fact that different sampling plots were used in the two measurements. However, the data indicate that an increase in mortality between year 14 and 18 was not significant.

Table 2 Mortality (per cent) for the different treatments during the first eighteen years after planting. Significant differences are indicated by different letters within lines

Years after planting	Control	Mounding	Soil inversion	Intensive inversion
5	34a	27a	15b	15b
14	47a	34b	24bc	19c
18	43a	33ab	23b	24b

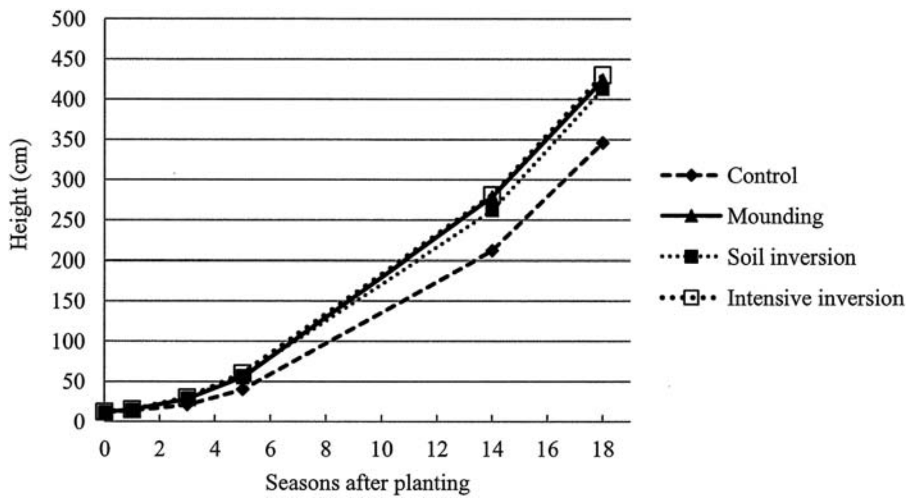

Figure 2 Mean height (cm) of Norway spruce grown at 10 different sites in Sweden during 18 years.

Table 3 Time gain in year of growth between the scarification treatments in relation to the control (control = 0) 18 years after planting

Site no	Local	Mounding	Soil inversion	Intensive inversion
1	Anderstjärn	3.41	8.85	11.55
2	Näverliden	7.90	6.24	9.11
3	Vojmsjön	4.28	−0.13	−0.09
4	Vojmsjön	3.54	2.75	2.56
5	Knaften	4.88	9.74	7.26
6	Nyby	2.08	0.77	4.80
7	Vimmarvattnet	6.95	11.04	9.56
8	Lövliden	3.78	4.21	4.40
11	Lokevägen	−1.43	0.51	−0.62
12	Hultåsen	0.55	−0.30	0.28
Treatment Mean		3.59	4.37	4.88

Production effects

Fourteen years after planting, the mean height of the planted trees across all sites was 262 and 281 cm following regular and intensive soil inversion, 279 cm after mounding and 212 cm for control plots. The height of the trees in the control treatment was significantly lower compared with the three scarification treatments ($P < 0.001$) (Figure 2). Hence, the difference in growth between plots with or without scarification was more than 50 cm, which corresponds to a time gain of ~4 years of growth after 14 years. Until this period, the difference in growth between scarification and control had increased over time, but after 14 years this difference remained constant and did not change over time ($P = 0.690$). Eighteen years after planting, the trees had reached a mean height of 413 and 430 cm in the regular and intensive soil inversion, 424 cm in the mounding and 346 cm in the control. The difference between control and scarification was statistically significant ($P = 0.002$). When the height difference between the treatments was translated into time gain compared with the control, the trees in the scarified treatments were 3.6–4.9 years ahead the trees grown in the control treatment (Table 3). Significant treatment effects ($P = 0.001$) showed that the mean values for the scarification methods differed significantly from the control treatment, but not from each other. Time gain differences seemed to occur between the sites, with higher time gain on less fertile sites in the north compared to the more fertile sites in the south. However, due to the experimental design of this study, it was not possible to statistically test this hypothesis.

Height of the 1000 trees with the largest diameter per hectare was significantly lower ($P < 0.001$) for the control treatment both 14 and 18 years after planting (Figure 3). For the same trees, the length of the leading shoot was not statistically different between treatments, neither 14 nor 18 years after planting. The difference in height after 18 years between the 1000 largest DBH trees per hectare and all the measured trees (2500 per hectare minus the mortality) was small, only 4 cm for both the control and the mounding and 8 cm for the soil inversion.

The mean basal area (m^2 per ha) 18 years after planting was significantly higher on the scarified plots compared with the control plots ($P = 0.001$) (Table 4). There were also significant differences between the sites ($P < 0.001$), showing the gradient from north to south and also reflecting the site index. Statistical analyses to test for site by treatment interactions were not possible to conduct, but comparing the results from each site, the control treatment seemed to be consistently lower when compared with the scarifications, except for Vojmsjön (site 3) where it was lowest after mounding, at Nyby where it was similar to mounding and at Lokevägen where it was similar to soil inversion.

Scarification also reduced the variation in height of the planted trees, creating a more homogeneous stand. The coefficient of variation for height, CV, was 41 per cent for the control treatment, 32 per cent for the soil inversion, 30 per cent for the intensive inversion and 31 per cent for the mounding.

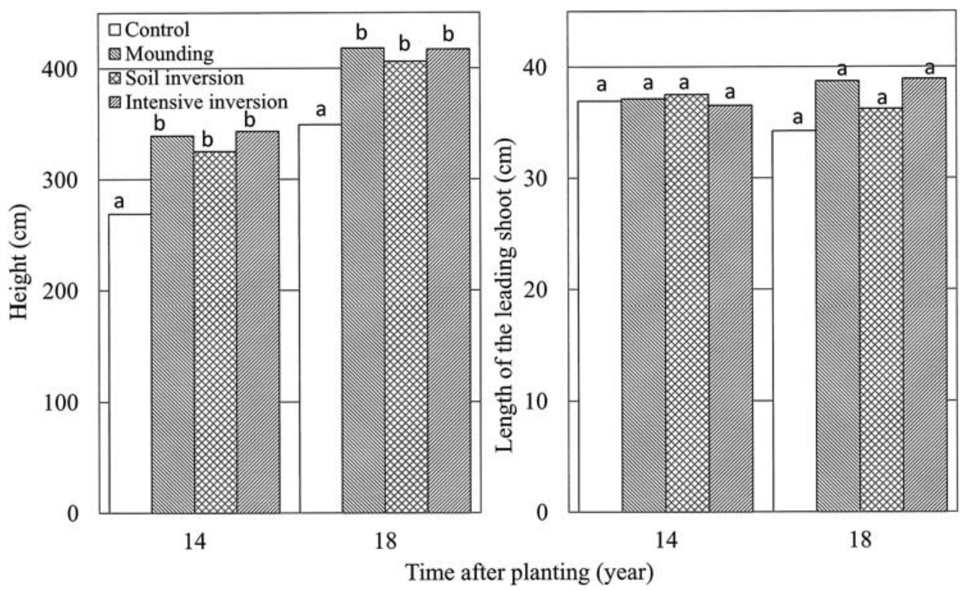

Figure 3 Height (left) and length of the leading shoot (right) for the 1000 trees with the largest diameter per hectare 14 and 18 years after planting. Values are mean values in cm for all 10 sites. Significant differences are indicated by different letters above columns.

Table 4 Basal area (m^2 per ha) for the different treatments on each site 18 years after planting. Significant differences for the mean values are indicated by different letters

Site no	Local	Control	Mounding	Soil inversion	Intensive inversion	Site mean
1	Anderstjärn	0.55	1.95	0.97	2.02	1.38 a
2	Näverliden	0.35	1.03	1.68	1.77	1.21a
3	Vojmsjön	0.74	0.55	2.17	0.85	1.08a
4	Vojmsjön	0.82	1.70	2.05	1.84	1.60a
5	Knaften	0.42	2.42	1.61	2.33	1.69a
6	Nyby	0.74	0.72	1.63	2.45	1.38a
7	Vimmarvattnet	0.79	4.72	2.70	3.73	2.98ab
8	Lövliden	3.11	4.45	6.18	6.90	5.16b
11	Lokevägen	8.10	12.75	7.96	8.92	9.43c
12	Hultåsen	10.07	13.06	13.32	14.19	12.66d
Treatment mean		2.57a	4.33b	4.03b	4.50b	

Treatment effects on CV were statistically significant ($P < 0.001$), the CV for the control treatment was significantly higher compared with the scarification treatments.

Natural regeneration

Scarification affected the number of naturally regenerated trees ($P = 0.002$). On plots treated with soil inversion or mounding, the number of naturally regenerated species, mainly broadleaved species such as birch (*Betula pubescens* and *Betula pendula*) and alder (*Populus tremula*) but also pine (*Pinus sylvatica*) and spruce (*Picea abies*), increased more than 100 per cent 14 years after planting (Table 5). The highest number of naturally regenerated trees was found in the intensive inversion treatment, and this was statistically different from the control treatment. However, scarification did not increase the mean height of the naturally regenerated trees ($P = 0.242$). Comparing the mean heights of the planted trees and the naturally regenerated trees 14 years after planting, the planted trees in the mounding and in the intensive soil inversion were significantly higher when compared with the naturally regenerated trees ($P = 0.046$ and $P = 0.033$, respectively). This difference was not found in the control treatment or after the regular soil inversion.

Discussion

The positive effects of scarification on early seedling establishment were still evident 18 years after planting. During the establishment phase, scarification led to an improved survival rate. The first 5 years following planting were the most critical for seedling survival, hereafter the risk leveled out and between 14 and 18 years after planting, no substantial mortality occurred. The higher survival in the scarified plots may be caused by different

Table 5 Number of naturally regenerated trees per hectare and their mean height 14 years after planting. Significant differences are indicated by different letters within columns

Treatment	Trees per hectare	Mean height (cm)
Control	921a	226a
Mounding	2151ab	231a
Soil inversion	2136ab	216a
Intensive inversion	2653b	213a

factors. Most obviously, competition from ground vegetation was reduced, which has been shown to improve the availability of water and nutrients during the critical establishment phase.[17] Additionally, favourable environmental conditions such as greater soil water availability, higher soil temperature and increased nitrogen mineralization could lead to increased growth.[18] A high initial seedling growth is probably important in order to reduce the critical establishment phase. Although not significantly different, the mortality rate in the soil inversion treatments were about 10 per cent lower than in the mounding. Supported by results from other studies,[6,19] this indicates that the site conditions were improved and that the characteristics of the planting spot increased the ability of the seedling to establish fast, reducing the risk of several stresses such as drought and pine weevil damages.

One of the most important pests causing seedling mortality in Swedish plantations is the pine weevil.[20] The use of insecticides has been the most common measure to reduce the level of damages. In many cases, the use of insecticides is not enough due to high population levels, and the treatment has to be combined with another factor to get satisfying results, and one of these factors is planting spots with pure mineral soil.[9,21] Planting in pure mineral soil was probably an important factor in this study for the higher survival in the scarified plots when compared with the control plots not scarified. It could also be one explanation for the higher survival rate in the soil inversion compared with the mounding treatment in this experiment. In a recent study where several scarification methods were compared, including soil inversion, mounding and disc trenching, soil inversion had a significantly higher percentage of planting spots with pure mineral soil in comparison with the other methods, and also the highest survival rate.[10] It also seems to be easier to plant the seedlings deep enough so that it reaches the buried humus layer in the soil inversion, which reduces the risk of drought, compared with planting in mounding or control. According to this, an improved survival could be a result of the fact that it is easier for the planter to find a favourable planting spot in the soil inversion. To be able to identify and select suitable planting spots for seedling, survival and growth is very important for the outcome of the operational plantations.[22] When comparing the two different soil inversion intensities, no difference in mortality was found. The quality of the planting spots were high enough with the regular intensity of 2500 spots per hectare, and no positive selection effects on mortality were found when the intensity was increased to 3500 spots per hectare. However, there was a trend towards a higher growth in the more intensive inversion, so in terms of production the selection possibility might have had an impact.

Long-term effects on resource availability were evident since the height growth and basal area of the planted trees was positively affected by scarification. After 14 years, the difference in height was still diverging when comparing the scarification treatments with the control. However, between 14 and 18 years of age, the difference was constant and the curves did not continue to diverge (Figure 2). At this point, the time gain after scarification was ∼4 years when compared with the control, but on some sites it was considerably higher. At the northernmost sites, the time gain could be up to 11 years, and if this time gain is preserved it will have a great effect on the economical outcome of the stand. In terms of the type of response describing long-term effects, this treatment results in a type B response where the initial difference is maintained and do not continue to increase over time, which is a typical scarification response.[23] The fact that scarification resulted in a type B response was also indicated by the growth of the 1000 trees with the largest diameter per hectare. For these trees, there was no difference in the length of the leading shoot between treatments during year 14 and 18. This suggests that the growth difference between the scarification and the control was limited to the initial advance of growth at the time of stand establishment. However, due to the lower mortality, the tree density was higher for the scarified plots and this might have a positive effect on future basal-area and volume growth.[24] The difference in growth of all the standing trees compared with the 1000 trees per hectare with the largest DBH was between 4 and 8 cm depending on the treatment. The largest trees provide a measure of the production potential of the specific treatment, but in this case all surviving trees will probably contribute to future production of the stands. When this study was initiated in the early 1990s, there were concerns about potential negative effects of intensive scarification on site productivity. So far, no negative effects on long-term productivity have been found with an increased area of soil disturbance, neither with regular soil inversion or mounding, nor with intensive soil inversion. The results are in accordance with other studies where no negative growth effects were found 10 years after soil disturbance such as scarification or stump removal.[25,26] Regardless, soil properties are changing after soil disturbance and interactions between climate factors, tree species and climate occurs[26,27] that might change over a rotation. Therefore, the long-term effects on site productivity need to be further investigated in the future to be able to draw final conclusions about possible negative or positive effects.

The layout of this experiment did not allow for statistical analysis of interaction effects between sites and treatments, only tests for main effects were possible to perform. By looking at the mean values for each site, the plots that were scarified held a consistently greater basal area when compared with the control plots and there was a substantial time gain. There was also an effect of geographical position and site index, where there was a significant increase in basal area the further south the site was located and the higher the site index was. In relative terms, there also seemed to be a greater difference between control and scarification on the less fertile sites, comparing for example Anderstjärn, the northernmost site with site index 16, and Hultåsen, the southernmost site with site index 32 (Tables 3 and 4).

As concluded above, the growth of the planted trees increased after scarification, but so was also the abundance of woody species (i.e. birch, aspen and willow). Thus, the initial advantage of reduced competition from ground vegetation was counter-balanced by increased competition from woody vegetation a couple of years after scarification.[28] The number of naturally regenerated trees per hectare was significantly higher in the intensive soil inversion compared with the control treatment. The soil disturbance was higher and more mineral soil was exposed after intensive soil inversion, which created a greater area suitable for naturally dispersed seeds to establish. Competition from woody vegetation will reduce the growth of the crop trees.[29,30] For the growth gain to be maintained and to be able to maximize future production of the planted trees, the removal of the woody vegetation in a pre-commercial thinning is necessary on many of the studied sites. On the other hand, mixed stands can sometimes be desirable and if they are managed properly, the naturally regenerated trees can increase the quality of the planted Norway spruce trees by reducing wood defects,[29,30] and the naturally regenerated trees can be harvested in early thinning for bioenergy or pulpwood.

In conclusion, improved plantation establishment and stand development following scarification can be expected on a majority of the traditional planting sites of Norway spruce in Sweden. The positive effects of scarification in the establishment phase and the reduction of the variation in height are of great value for the development of future stands. A higher survival after scarification also leads to a greater number of crop trees on the site, which increases the possibility of selective cleaning and thinning in the future stands. Thus, the forest owner may use different management strategies to grow trees either for high production or for high-quality timber. However, the possible increase of woody species later on needs to be taken into account. To secure further positive development of the stand, pre-commercial thinning of deciduous species might be necessary, either to continue to grow the stand as a monoculture or as a mixed stand. Although vegetation management is crucial to stand development and growth, results from this study shows that vegetation management can be made without the use of herbicides under similar conditions.

Funding

This work was supported by Formas (Skogsföryngringsprogrammet 2006–2009) and Vinnova (Trees and Crops for the Future).

Acknowledgements

We would like to thank the staff at Vindeln Experimental Forest Research Station, SLU, at Asa Experimental Forest Research Station, SLU and at Skogforsk, for all the help with the field measurements.

Conflict of interest statement

None declared.

References

1 Grossnickle S.C. 2000 *Ecophysiology of Northern Spruce Species: The Performance of Planted Seedlings*. NRC Research Press, Ottawa, Ontario, Canada. 409 pp., ISBN 0-660-17959-8.

2 Anon. 2011 *Swedish Statistical Yearbook of Forestry 2011*. Swedish Forest Agency, Jönköping. 386 pp., ISBN 978-91-88462-95-4.

3 Örlander G., Gemmel P. and Hunt J. 1990 Site Preparation – a Swedish Overview. FRDA Report 105, p. 61, ISSN 0835-0752.

4 Nilsson U. and Örlander G. 1999 Water uptake by planted *Picea abies* in relation to competing field vegetation and seedling rooting depth on two grass-dominated sites in southern Sweden. *Scand. J. For. Res.* **14**, 312–319.

5 Johansson M.-B. 1994 The influence of soil scarification on the turn-over rate of slash needles and nutrient release. *Scand. J. For. Res.* **9**, 170–179.

6 Örlander G., Hallsby G., Gemmel P. and Wilhelmsson C. 1998 Inverting improves establishment of *Pinus contorta* and *Picea abies* – 10-year results from a site preparation trial in northern Sweden. *Scand. J. For. Res.* **13**, 160–168.

7 Nordborg F., Nilsson U. and Örlander G. 2003 Effects of different soil treatments on growth and net nitrogen uptake of newly planted *Picea abies* (L.) Karst. Seedlings. *For. Ecol. Manage.* **180**, 571–582.

8 Johansson K., Nilsson U. and Allen H.L. 2007 Interactions between soil scarification and Norway spruce seedling types. *New For.* **33**, 13–27.

9 Petersson M., Örlander G. and Nordlander G. 2005 Soil features affecting damage to conifer seedlings by the pine weevil *Hylobius abietis*. *Forestry.* **78**, 83–92.

10 Petersson M. 2011 Markberedningsmetoders effekt på snytbaggeskador – the effect of scarification on Pine weevil damages. SLU, Asa försökspark, Rapport nr 1 2011. 13 pp.

11 Sundblad L.-G. 2009 Grävmaskinburet aggregat klarar både inversmarkberedning och högläggning – an excavator based equipment for both soil inversion and mounding. Skogforsk, Resultat nr 11 2009. ISSN: 1103-4173.

12 Mattsson S. and Bergsten U. 2003 Pinus contorta growth in northern Sweden as affected by soil scarification. *New For.* **26**, 217–231.

13 Nordborg F., Nilsson U., Gemmel P. and Örlander G. 2006 Carbon and nitrogen stocks in soil, trees and field vegetation in conifer plantations 10 years after deep soil cultivation and patch scarification. *Scand. J. For. Res.* **21**, 356–363.

14 Lehtosalo M., Mäkelä A. and Valkonen S. 2010 Regeneration and tree growth dynamics of *Picea abies*, *Betula pendula* and *Betula pubescens* in regeneration areas treated with spot mounding in southern Finland. *Scand. J. For. Res.* **25**, 213–223.

15 Thiffault N. and Roy V. 2011 Living without herbicides in Quebec (Canada): historical context, current strategy, research and challenges in forest vegetation management. *Eur. J. For. Res.* **130**, 117–133.

16 Hallsby G. and Örlander G. 2004 A comparison of mounding and inverting to establish Norway spruce on podzolic soils in Sweden. *Forestry.* **77**, 107–117.

17 Parker W.C., Pitt D.G. and Morneault A.E. 2010 Influence of woody and herbaceous vegetation control on leaf gas exchange, water status, and nutrient relations of eastern white pine (*Pinus strobus* L.) seedlings planted in a central Ontario clearcut. *For. Ecol. Manage.* **260**, 2012–2022.

18 Johansson K., Langvall O. and Bergh J. 2012 Optimization of environmental factors affecting initial growth of Norway spruce seedlings. *Silva Fennica.* **46**, 27–38.

19 Nordborg F. and Nilsson U. 2003 Growth, damage and net nitrogen uptake in *Picea abies* (L.) Karst. seedlings, effects of site preparation and fertilization. *Ann. For. Sci.* **60**, 657–666.

20 Nilsson U., Luoranen J., Kolström T., Örlander G. and Puttonen P. 2010 Reforestation with planting in northern Europe. *Scand. J. For. Res.* **25**, 283–294.

21 Nordlander G., Hellqvist C., Johansson K. and Nordenhem H. 2011 Regeneration of European boreal forests: effectiveness of measures against seedling mortality caused by the pine weevil *Hylobius abietis*. *For. Ecol. Manage.* **262**, 2354–2363.

22 Johansson K. 2010 *Plantera rätt – en handledning från Skogforsk*. Skogforsk förlag, Uppsala, Sweden, 38 pp., ISBN: 978-91-977649-3-3.

23 Nilsson U. and Allen H.L. 2003 Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *For. Ecol. Manage.* **175**, 367–377.

24 Gizachew B. and Brunner A. 2011 Density–growth relationships in thinned and unthinned Norway spruce and Scots pine stands in Norway. *Scand. J. For. Res.* **26**, 543–554.

25 Périé C. and Munson A.D. 2000 Ten year responses of soil quality and conifer growth to silvicultural treatments. *Soil Sci. Soc. Am. J.* **64**, 1815–1826.

26 Hope G. 2007 Changes in soil properties, tree growth, and nutrition over a period of 10 years after stump removal and scarification on moderately coarse soils in interior British Columbia. *For. Ecol. Manage.* **242**, 625–635.

27 Burgess D., Baldock J.A., Wetzell S. and Brand D.G. 1995 Scarification, fertilization and herbicide treatment effects on planted conifers and soil fertility. *Plant Soil.* **168–169**, 513–522.

28 Karlsson M., Nilsson U. and Örlander G. 2002 Natural regeneration in clear-cuts: effects of scarification, slash removal and clear-cut age. *Scand. J. For. Res.* **17**, 131–138.

29 Klang F. and Ekö P-M. 1999 Tree properties and yield of *Picea abies* planted in shelterwoods. *Scand. J. For. Res.* **14**, 262–269.

30 Fahlvik N., Agestam E., Nilsson U. and Nyström K. 2005 Simulating the influence of initial stand structure on the development of young mixtures of Norway spruce and birch. *For. Ecol. Manage.* **213**, 297–311.