Fifteen-Year Response of Weed Control Intensity and Seedling Type on Norway Spruce Survival and Growth on Arable Land

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The effects of seedling type (2-year-old container seedlings vs. 4-year-old bare-rooted seedlings) and post-planting vegetation control intensity on the growth and survival of Norway spruce (*Picea abies* (L.) Karst.) seedlings were compared based on 15-year data from a field experiment established on arable land. Vegetation control treatments with terbuthylazine and glyphosate were carried out 1–3 times on successive years, either as overall or spot applications. The highest stand volumes were obtained with the combination of large bare-rooted seedlings and effective vegetation control. Volume of bare-rooted seedlings was greater than that of container seedlings in all treatments (e.g. on the control plots 9.5 m^3/ha vs. 4.1 m^3/ha). The best results were obtained with the most intensive weed control treatments (spot treatment repeated twice and overall application repeated three times). These treatments increased both bare-rooted and containerised seedlings' survival by 33–40% units and their height, breast height diameter, and volume by 45–49%, 17–47%, and 249–279%, respectively. In terms of survival, the container seedlings, in due part to their smaller size, benefited from vegetation control more than the bare-rooted seedlings. Successive early summer frosts damaged the seedlings and significantly retarded their growth. The frequency of frost damage was not affected by vegetation control nor was it attributed to seedling type.

Keywords afforestation, frost damage, Norway spruce, seedling size, seedling type, vegetation control
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1 Introduction

Norway spruce (*Picea abies* (L.) Karst.) is the most widely planted tree species in Finland. The number of Norway spruce seedlings planted has increased from 34 million in 1980 to over 100 million seedlings in 2005 (Finnish … 2006, Fig. 1). In 1980, bare-rooted seedlings (typically 2-2 stock) represented more than 94% of the spruce seedlings produced in Finland (Fig. 1). Thereafter, the nurseries have almost completely turned over to production of container seedlings. In 2005, 98% of the Norway spruce seedlings produced were containerised. The use of container stock has been promoted by the development of nursery technology, and soil preparation methods as well as adoption of new types of nursery stocks. Nowadays two-year-old Norway spruce container seedlings of different sizes are produced (Luoranen and Kiljunen 2006).

Larger seedlings are usually recommended for fertile growing sites and sites with intensive competition from ground vegetation (Parviainen 1990). Tall grass vegetation pressed down by a thick snow layer can seriously damage tree seedlings, and smaller seedlings in particular are probably more susceptible to this kind of damage. Larger seedlings are also more resistant to *Hylobius* weevil attacks (Selander et al. 1990, Örlander and Nilsson 1999, Thorsén et al. 2001). On the other hand, smaller seedlings are less expensive, and their planting can more easily be mechanised.

Since 1969, more than 240 000 ha of agricultural fields have been afforested in Finland (Finnish … 2006). Norway spruce is currently recommended for the afforestation of most of the abandoned fields (Hynönen and Hytönen 1998). Former agricultural land is usually more fertile than conventional forest sites because of changes in soil properties caused by agricultural practices (Hytönen and Wall 1997, Wall and Hytönen 2005). Consequently, vegetation on abandoned fields is more vigorous, and competes with tree seedlings for water, nutrients and light. Norway spruce, as a shade tolerant species, is in terms of survival considered to be more resistant to competition of weeds than the other tree species planted in Finland. Spruce is also less susceptible to vole and moose damage than Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth) (Rossi et al. 1993, Hynönen and Saksa 1997, Hytönen 1999). Norway spruce is, however, susceptible to early summer frost damage especially when planted on open arable fields (Jylhä and

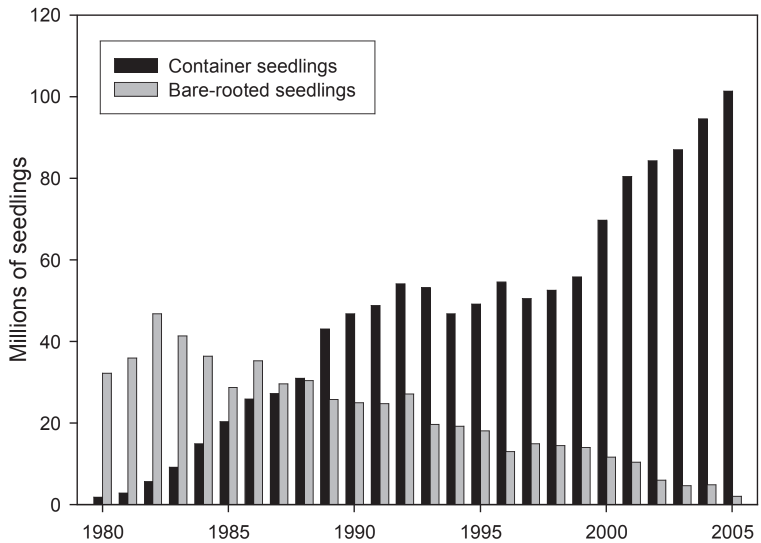

Fig. 1. Number of domestic container and bare-rooted Norway spruce seedlings delivered for planting in 1980–2005 (Finnish … 2006).

Hytönen 2006, Hynönen and Hytönen 1998) and in reforestation areas, too (Kinnunen 1989, Saksa et al. 1990, Kolström 1991).

Most studies dealing with the effects of competing vegetation and vegetation control on the survival and growth of Norway spruce cover the few first post-planting years only (e.g. Bärring 1967, Leikola 1976, Siipilehto 2001, Nilsson and Örlander 1999a, 1999b, 2003, Nordborg and Nilsson 2003). Results on the long-term effects of weed control on growth, especially stand growth, are still lacking. Such data are needed for economic calculations on profitability of vegetation management.

The aim of this research was to investigate the long-term effects of Norway spruce seedling type and the intensity of post-planting weed control methods in terms of seedling growth, damage, and mortality. The follow-up period covered 15 post-planting growing seasons.

2 Material and Methods

2.1 Field Experiment

The field experiment was established in spring 1990 at Toholampi (63º45'N, 24º18'E), Finland. Until establishment, the field had been in agricultural use. The mineral soil was classified as silt, based on particle-size distribution determined by dry-sieving and sedimentation method (Elonen 1971). Four soil samples taken from the tilling layer (0–10 cm) were analyzed for pH (water) and organic matter content (ashing at 550ºC for 8 h). The pH was 5.1–5.4 and the share of organic matter 10–13%. Complete soil preparation by rotavation and harrowing was done in the spring before planting. Container and bare-rooted seedlings of Norway spruce were planted on 10 m × 10 m plots on 11–20th June 1990 to a density of 3000 seedlings ha^{-1}. The container seedlings were two years old and had been grown in Ecopot PS608 containers (diameter 6 cm, height 8 cm) – the first growing season in a greenhouse and the second growing season outdoors. The bare-rooted seedlings were four years old and they had been transplanted after two growing seasons (2A+2A). After planting, four different levels of weed control intensity were tested, using soil-active terbuthylazine and foliar-active glyphosate (Table 1). The herbicides were applied with a knapsack sprayer, and the seedlings were protected from drift by cone shaped shields. The experiment was established as randomised block design with 4 replications. Due to missing data from one sample plot, however, there were only 31 experimental units in the analyses of variance.

Table 1. Weed control treatments

Date of application	Intensity of weed control treatment Control	Low	Medium	High
19.–25.6.1990	No treatment	Terbuthylazine, overall application	Terbuthylazine, spot application	Terbuthylazine, overall application
10.–17.6.1991	No treatment	No treatment	Terbuthylazine + glyphosate, spot application	Terbuthylazine + glyphosate, overall application
23.–26.6.1992	No treatment	No treatment	No treatment	Terbuthylazine, overall application

Application rates: Terbuthylazine (Gardoprim) 6–7 l per treated ha, glyphosate (Roundup) 3 l per treated ha

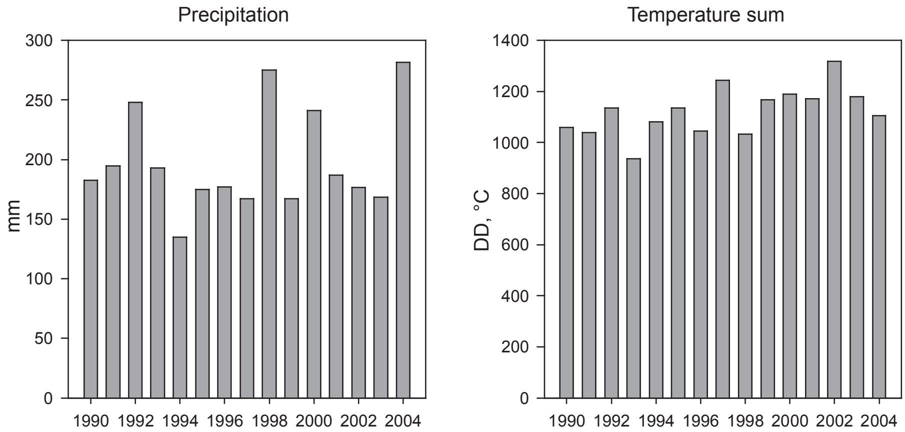

Fig. 2. Precipitation and effective temperature sum during June–August at the experimental field.

2.2 Measurements

The height (h, measured with an accuracy of 1 cm) and vitality (alive or dead) of the seedlings were recorded, and two main causal agents of damage were assessed within a circular 50 m^2 sample plot set up in the middle of each plot after the 2nd, 3rd, 4th, 5th, 7th, and 15th growing seasons. After the third and fourth growing seasons, also the base diameters ($d_{0.1}$) of the seedlings were measured (accuracy of 0.1 mm). Breast height diameter ($d_{1.3}$) was recorded (accuracy of 1 mm) as an additional variable after the 15th growing season.

The vegetation was examined for species composition and cover percentage two, three and four growing seasons after planting (August 1991, July 1992, and July 1993). The vegetation cover percentage was estimated using three to five 1 m^2 sub-sample plots. In addition, the dominant height of the weeds was estimated on these plots.

The annual temperature sum (threshold for temperature sum 5ºC) during the follow-up period in the experimental field varied from 936 to 1318 dd ºC (Fig. 2.) and the mean temperature from 2.4ºC to 4.5ºC. The precipitation during the summer months (June–August) varied from 167 to 275 mm and it was 28–42% of the annual precipitation. Climatic variables were calculated using the method described by Ojansuu and Henttonen (1983).

2.3 Data Analysis

The stem volumes of the trees were computed applying the models of Laasasenaho (1982). For trees taller than 3 m, the models included height and diameter at breast height. For shorter trees, models with diameter at breast height only were applied. In the case of the seedlings shorter than 1.3 m, a stem volume of 0.1 dm^3 was assumed. Analysis of variance was used to test the statistical significance of the seedling type, the weed control treatment and their interaction on weed coverage, seedling mortality, height, basal diameter, volume, and the occurrence of frost damage. Prior to analysis, assumptions of homogeneity of variances were tested. Transformations were used to homogenise variances where necessary. The arcsin transformation was applied to variables with percentage values. Tukey's honestly significant difference test ($p < 0.05$) was used to separate the means of the treatments. The effect of weed control intensity on the vegetation cover percentage was only tested on plots with overall treatment, since the measurements on the spot-treated plots were not made around the seedlings and would thus have lead to biased results. Pearson's correlation coefficients between percent vegetation cover and seedling mortalities were calculated, as well as between seedling height and the percentage of frost damaged seedlings.

Table 2. The effect of weed control intensity on mean vegetation cover percentages 2–4 growing seasons after the first application (n = 23 for all seasons). Means followed by the same letter did not differ from each other at 0.05 significance level according to Tukey's test.

Season		Intensity of weed control Control	Low	High	Test statistics F	Sign.level
2nd	Grasses	73% a	62% a	2% b	93.466	p < 0.001
	Forbs	22% a	25% a	6% b	9.987	p = 0.001
	Total	96% a	87% b	8% c	157.433	p < 0.001
3rd	Grasses	83% a	80% a	12% b	73.079	p < 0.001
	Forbs	15% a	16% a	25% a	1.298	p = 0.299
	Total	98% a	96% a	37% b	89.677	p < 0.001
4th	Grasses	62% a	58% a	19% b	52.955	p < 0.001
	Forbs	14% a	15% a	39% b	9.644	p = 0.002
	Total	76% a	74% a	58% a	3.335	p = 0.060
2nd–4th	Grasses	73% a	67% a	11% b	126.886	p < 0.001
	Forbs	17 a	19 a	23 a	0.822	p = 0.456
	Total	90 a	86 a	34 b	142.173	p < 0.001

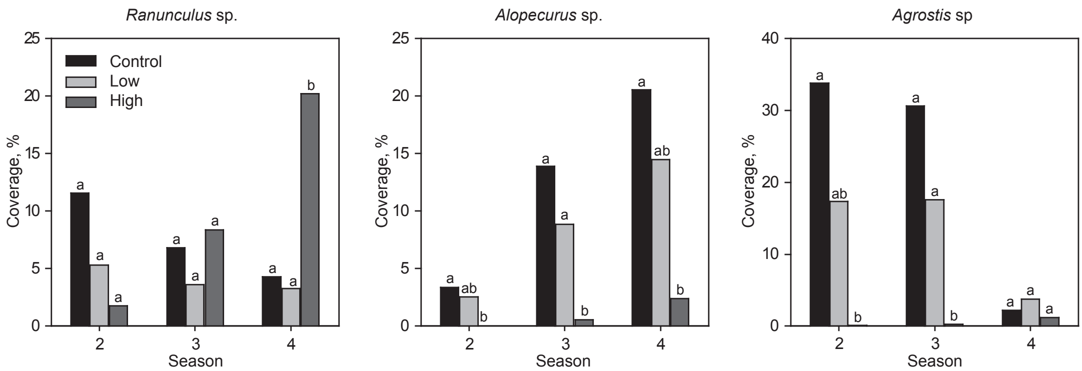

Fig. 3. Mean coverage of the dominant species 2–4 seasons after the first herbicide application by weed control intensity. Mean coverage of each growing season marked with the same letter did not differ from each other at a 5% significance level.

3 Results

3.1 Vegetation Dynamics

When planting the seedlings, there was no vegetation on the experimental area because of complete soil preparation. Two years after the low and high intensity treatments, the weed coverage on the study plots were 12 and 88 percentage units lower than that on the control plots, respectively (Table 2). The high intensity treatment reduced the weed coverage significantly for at least four growing seasons. Weed control initially decreased the coverage of both grasses and forbs. However, even though the high intensity treatment continued to strongly decrease the coverage of grasses, the coverage of forbs increased. In the control plots, the most common weed species were *Agrostis* spp., *Phleum pratense* (L.), *Descahmpsia flexuosa* (L.), *Alopecurus pratensis* (L.) and *Ranunculus repens* (L.). On the untreated plots, the coverage of *Alopecurus pratensis* increased considerably during the three-year follow-up (Fig. 3). The most intensive treatment, three times repeated overall application resulted in a significant increase in the coverage of *Ranunculus repens* (Fig. 3).

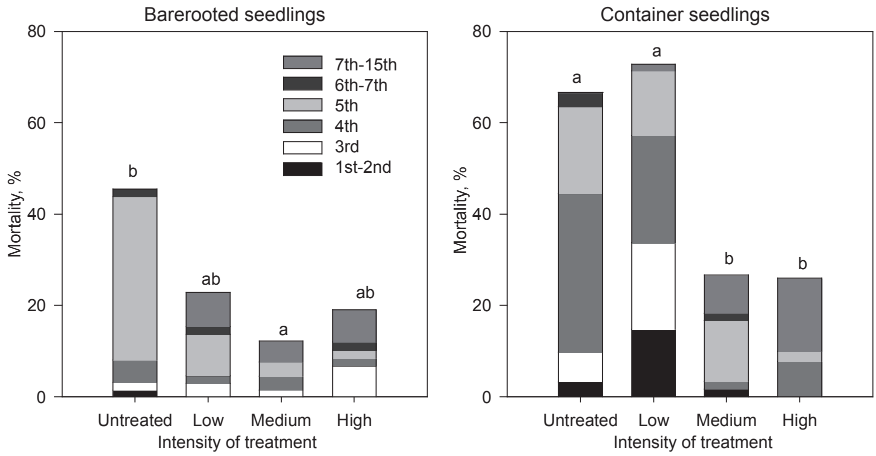

Fig. 4. The effect of vegetation control intensity on the mortality of bare-rooted and container seedlings. Mortalities taken place between the measurements are shown within the bars. Mean cumulative mortalities after the 15th growing season followed by the same letter above the bars did not differ from each other at 0.05 significance level according to Tukey's test.

Table 3. F-values for the analysis of variance for cumulative seedling mortality. Significance levels: *p < 0.05, **p < 0.01, ***p < 0.001.

Season	Intensity of weed control	Seedling type	Intensity × seedling type
2nd	1.713	4.094	1.974
3rd	5.538**	4.315	5.628**
4th	5.494**	11.897**	3.936*
5th	10.453***	12.275**	2.909
7th	11.789***	13.766**	2.885
15th	7.965**	16.658**	1.615

3.2 Seedling Mortality

Mortality of the bare-rooted seedlings was lower than that of the container seedlings throughout the 15-year study period (Fig. 4). Vegetation control intensity affected mortality from the second growing season on, whereas seedling type had an effect from the third growing season onwards (Table 3). The interaction term was significant only for the 3rd and 4th growing season (Table 3). This was due to the lower survival of container seedlings on untreated plots and plots with low weed control intensity.

The mortality of bare-rooted seedlings remained low during the first four years, and treatment did not affect it. Their cumulative mortality after the fourth growing season was 5–8%. After the fifth growing season, however, the mortality of the bare-rooted seedlings on the control plots increased sharply. Thereafter, it increased only slightly. At the end of the 15-year follow-up period, the mortality of the bare-rooted seedlings on the control plots was 46%, whereas it was 12–23% on the plots with herbicide treatment. The lowest mortality was observed on the plots with medium weed control intensity (double spot treatment). The mortality of the seedlings on the untreated control plots differed significantly from that of the plots with medium weed control intensity (Fig. 4).

The mortality of the container seedlings started to increase after the third growing season – two years earlier than on the plots planted with bare-rooted seedlings. It was highest on the control plots and on the plots with low intensity treatment (single overall treatment). After five growing seasons, mortality on these plots was 63–71%, respectively. Lower mortalities were found on the plots with medium and high weed control intensity, 17% and 10%, respectively. By the end of the 15th growing season, mortality had increased only slightly on the control plots and on the plots with low intensity weed control. The final mortality on these plots was 67–73%, respectively.

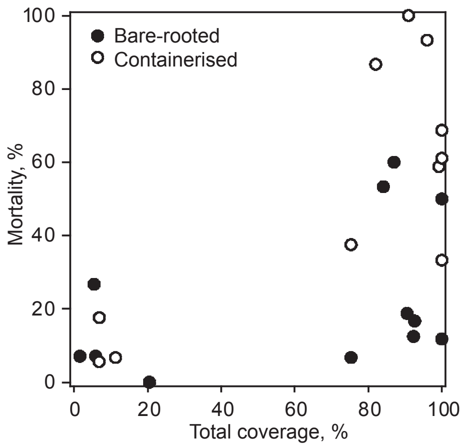

Fig. 5. The effect of the second growing season vegetation coverage on the cumulative mortality of the seedlings after the fifth growing season.

Table 4. Correlation coefficients between grasses, herbs, and total vegetation coverages with the cumulative seedling mortalities after the 4th, 5th, 7th and 15th growing seasons.

Vegetation coverage	Cumulative seedling mortality 4th season	5th season	7th season	15th season
2nd season				
Grasses	0.367*	0.491**	0.472**	0.404*
Herbs	–0.087	0.105	0.140	0.105
Total	0.277	0.453*	0.450*	0.380*
3rd season				
Grasses	0.297	0.405*	0.400*	0.333
Herbs	–0.194	–0.157	–0.127	–0.158
Total	0.244	0.387*	0.397*	0.303
4th season				
Grasses	0.190	0.366*	0.375*	0.323
Herbs	–0.291	–0.367*	–0.356	–0.334
Total	–0.061	0.097	0.123	0.076
2nd–4th seasons				
Grasses	0.309	0.444*	0.437*	0.371*
Herbs	–0.267	–0.207	–0.173	–0.191
Total	0.223	0.399*	0.406*	0.325

Significantly lower mortalities were observed on the plots with medium and high weed control intensity, 27–34%, respectively.

The second growing season grass coverage correlated significantly with the cumulative mortalities of the 4th, 5th, 7th, and 15th growing seasons, but the coverage of the herbs did not (Table 4). The 2nd season total vegetation coverage correlated with cumulative mortality from the fifth growing season on. The grass coverages during the third and fourth growing seasons did not correlate with the cumulative mortality of the 15th year any more. The herb coverage of the fourth growing season correlated negatively with mortality. Seedling mortality started to increase considerably once the vegetation coverage had exceeded the level of 70% (Fig. 5).

3.3 Height and Diameter Growth

Bare-rooted seedlings were taller than container seedlings throughout the 15-year follow-up period (Tables 5 and 6). At the age of 15 years, the bare-rooted and container seedlings growing on the control plots were 325 cm and 234 cm tall, respectively. Base diameter ($d_{0.1}$) of the bare-rooted seedlings measured after the third and fourth growing seasons was greater than that of the container seedlings. After the fourth growing season, the mean base diameter of the bare-rooted seedlings (12.9 mm) was almost double that of the container seedlings (6.8 mm). Also after 15 growing seasons the breast height diameter of the bare-rooted seedlings (45 mm) was higher than that of the container seedlings (39 mm). The interaction term was not significant for seedling height (Table 5).

Weed control intensity had a significant effect on seedling height after the 3rd, 7th and 15th growing seasons. The tallest seedlings at the end of the follow-up period were found on the plots with medium intensity weed control (double spot treatment). On these plots, bare-rooted and container seedlings were 145 cm and 115 cm taller than the seedlings on the untreated plots. The most intensive weed control treatment did not increase seedling height growth compared to the plots with medium intensity.

Weed control intensity had a significant effect on the base diameter of the seedlings measured after the third and fourth growing seasons (Table 5). The effect of weed control intensity was much stronger on the base diameter than on height during these years.

3.4 Stand Volume

In 15 years, the bare-rooted seedlings gave more than double stand volume compared to the container seedlings on the control plots (9.5 m^3/ha vs. 4.1 m^3/ha) (Fig. 6). The seedling types differed significantly from each other ($p < 0.001$), but interaction of treatment and seedling type was non-significant ($p = 0.077$).

Weed control intensity had a significant effect ($p < 0.001$) on stand volume. In the case of bare-rooted seedlings, the greatest stand volume at the end of the experiment was observed on the plots with medium intensity weed control (double spot treatment). Mean volume on these plots was 3.8-fold as compared to that of the control plots (36.0 m^3ha^{-1} vs. 9.5 m^3ha^{-1}). The most intensive treatment did not increase volume compared to medium intensity treatment. Low intensity treatment (single overall application) gave 2.3-fold volume compared to control. With containerised seedlings, high intensity weed control gave 3.8-fold volume as compared to untreated plots (15.4 m^3ha^{-1} vs. 4.1 m^3ha^{-1}). Medium intensity treatment resulted in an almost equal volume increment. Low intensity weed control did not affect the volume of container seedlings.

Table 5. F-values for analysis of variance for seedling height and base diameter. Significance levels: * = p < 0.05, ** = p < 0.01, *** = p < 0.001.

	F Statistic		
	Intensity	Seedling type	Intensity × seedling type
Height			
2nd	2.530	53.904***	1.802
3rd	3.282*	102.303***	0.295
4th	1.470	68.415***	0.717
5th	2.283	49.082***	0.745
7th	7.273**	45.429***	1.289
15th	20.916***	84.600***	0.946
Base diameter			
3rd	14.787***	213.686***	2.849
4th	26.010***	121.508***	4.016*

3.5 Frost Damage

Recurrent early summer frost was virtually the only causal agent of seedling damage. Only minor damage was observed in the second and third growing season, when 2% of the seedlings were damaged. In the springs of the 4th, 5th, and 7th growing seasons, on average 92% (60–100%), 62% (0–100%), and 42% (0–100%) of the seedlings on the sample plots were damaged by frosts, respectively. Even in the 15th growing season, frost had still caused damage to 21% (0–83%) of the seedlings. This damage, however, was limited to lateral branches, as the mean height of the seedlings was already 230–470 cm. Throughout

Table 6. Mean heights (h, cm) and base diameters ($d_{0.1}$, mm) of the seedlings by seedling type and weed control intensity. Means followed by the same letter do not differ from each other at 0.05 significance level according to Tukey's test. Significance levels of the F test: * = p < 0.05, ** = p < 0.01, *** = p < 0.001.

	Growing season							
	2nd	3rd		4th		5th	7th	15th
	h	h	$d_{0.1}$	h	$d_{0.1}$	h	h	h
Bare-rooted								
Control	41a	52	9.3a	57	10.1a	57	80a	325a
Low	40a	51	9.5a	56	10.9ab	63	98ab	386b
Medium	47b	58	13.2b	64	16.2c	74	124b	469c
High	39a	50	12.4b	57	14.6bc	67	128b	460c
F	7.569**	3.031	10.605***	2.822	10.336**	3.061	8.637**	35.612***
Container								
Control	33	37	5.4ab	41	6.3	41	56	234
Low	33	36	4.5a	41	5.7	44	62	289
Medium	33	40	6.6b	42	7.3	46	78	349
High	32	35	6.4b	39	7.7	42	74	338
F	0.016	0.983	5.833*	0.213	2.965	0.620	2.190	4.415*

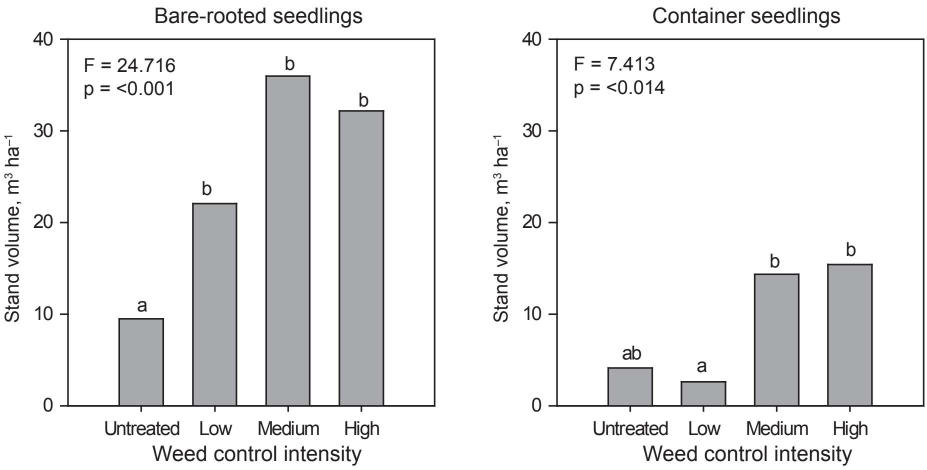

Fig. 6. Effect of vegetation control intensity on the stand volume of bare-rooted and containerised Norway spruce seedlings after 15 growing seasons. Mean volumes followed by the same letter above the bars do not differ from each other at 0.05 significance level according to Tukey's test.

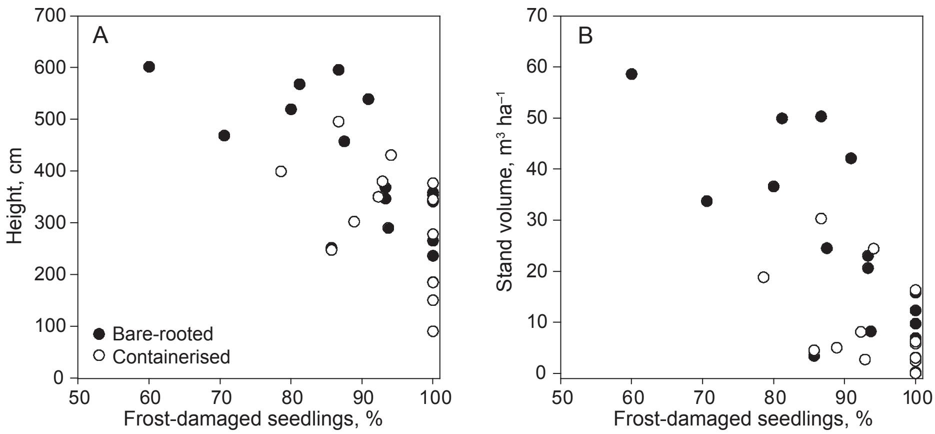

Fig. 7. Relations between the percentage of seedlings on the experimental plots damaged by frost in the fourth growing season and mean seedling height (A) and mean stand volume (B) after the 15th growing season by seedling types.

the whole follow-up period, occurrence of frost damage was independent of seedling type, intensity of weed control and their interaction.

The percentage of the seedlings damaged by frost on the experimental plots correlated negatively with the mean height of the seedlings, especially after the most severe frost in the beginning of the 4th growing season (Fig. 7). Correlation coefficients between the percentage of frost-damaged seedlings in the 4th growing season and mean seedling height after the 4th, 5th, 7th, and 15th growing seasons were –0.377 ($p = 0.036$), –0.476 ($p = 0.008$), –0.598 ($p < 0.001$), –0.658 ($p < 0.001$), respectively. The frost damage of the 4th season correlated significantly with stand volume at the end of the 15-year study period ($r = -0.708$, $p < 0.001$).

4 Discussion

In this study, both seedling type and vegetation control intensity had a significant effect on the survival and growth of the seedlings planted on former agricultural land. Bare-rooted seedlings were taller and had lower mortality than containerised ones throughout the 15-year follow-up period. In the case of the best treatments in terms of growth, bare-rooted seedlings gave 1.5-fold breast height diameter, 1.3-fold height, and 2.3-fold volume as compared to container seedlings of corresponding weed control intensity. Proportionally higher volume growth can partly be explained by the lower mortality of the bare-rooted seedlings. In agreement with this study, Haugberg (1971) reported large 4-year-old transplanted seedlings of having higher survival rate and height growth than smaller seedlings, both on former agricultural soil and on forest soil in Norway. Also in Finnish reforestation experiments larger and older Norway spruce seedlings have had lower mortality than smaller and younger ones (Kinnunen 1989).

In this study, the absolute mean height difference between bare-rooted and container seedlings increased from 9 cm (2nd growing season) to 109 cm. Nilsson and Örlander (1999a) reported that the initial relative height and diameter difference between 3-year-old bare-rooted and 2-year-old container Norway spruce seedlings remained almost constant during their 5-year study. In addition to Norway spruce, reforestation with a large planting stock, in order to reduce competition from ground vegetation, has been shown to have a positive response, especially on growth, but often also on survival of many tree species, such as *Picea sitchensis* (South and Mason 1993), *Picea mariana* (Jobidon et al. 1998), *Pinus taeda* (South et al. 1995, 2001b,), *Pinus radiata* (South et al. 2001b), *Pinus elliottii* (Engelm.) (South and Mitchell 1999), *Pseudotsuga menziesii* (van den Driessche 1992, Rose and Ketchum 2003, Rosner and Rose 2006), *Abies grandis* (Rosner and Rose 2006), *Thuja plicata* (Rosner and Rose 2006), and *Tsuga heterophylla* (Rosner and Rose 2006).

The size of the seedlings could be an even better indicator of the afforestation success, rather than seedling type only. Taller seedlings are considered more competitive against ground vegetation than smaller seedlings (Jobidon et al. 2003). Container seedlings can even have a higher initial growth than bare-rooted seedlings (Nilsson and Örlander 1999a). Bare-rooted seedlings have to establish new root-soil contacts in order to sustain water and nutrient uptake. In the case of dry planting season, they can suffer from water stress for a longer time than container seedlings (Nilsson and Örlander 1999a). Thus, in some cases, the survival of containerised Norway spruce seedlings can be higher than that of bare-rooted seedlings (Nilsson and Örlander 1995).

Weed control reduced the vegetation coverage to such an extent that the seedlings clearly benefited from it. When establishing the experiment, the soil was free from vegetation because of complete soil preparation. After two growing seasons, vegetation coverage on the control plots had reached 96%. On the plots with low and high intensity treatments, the coverages were 12 and 88 percentage units lower. The single overall application of soil active terbuthylazine (low intensity weed control) controlled vegetation for two growing seasons. In some cases even 3-year response has been detected (Hytönen and Jylhä 2005, Jylhä and Hytönen 2006). In this study, high intensity treatment controlled grasses at least for four growing season. At the same time, however, it allowed vegetative re-colonization of *Ranunculus repens*. Earlier Siipilehto (2001) has observed the same phenomenon when using terbuthylazine. As a low-lying forb species, *Ranunculus repens* could be an ideal cover, but no studies on its competitiveness exist.

Competition from ground vegetation affected the mortality of Norway spruce. However, during the first two growing seasons, no vegetation-induced mortality was detected. Mortality started to increase only when competition was severe, with the mean vegetation cover exceeding 70%. Similar results have been obtained earlier from Scots pine (Jylhä and Hytönen 2006) and silver birch (Hytönen and Jylhä 2005). However, Jylhä and Hytönen (2006) did not find any effect of vegetation cover on Norway spruce mortality.

In the present study, container seedlings started to die earlier than bare-rooted seedlings, indicating that smaller seedlings are more susceptible to competition from vegetation. Vegetation cover percentage of the second growing season correlated significantly with the mortality after 15 growing seasons. Therefore, eliminating competing vegetation during the first few years after planting seems to be of great importance. Lund-Høie (1984) and Jylhä and Hytönen (2006) concluded that in order to get a good response to vegetation control, competition should be reduced for two or three post-planting growing seasons. As in Jylhä and Hytönen (2006), however, correlations between spruce height growth and vegetation coverage were non-significant. This may be due to the severe early season frosts in both of these studies. This is emphasised by the fact that weed control intensity had a significant effect on seedling base diameter after third and fourth growing seasons.

The growth of Norway spruce seedlings during the first few years has been reported to benefit from weed control (Lund-Høie 1984, Kolström 1991, Siipilehto 2001, Nilsson and Örlander 1993a,b, 2003). In this study, however, weed control treatment had only a slight effect on the seedling height at the initial phase. After the 4th growing season, for example, the tallest bare-rooted seedlings were only 7 cm and container seedlings 1 cm taller than the seedlings grown on the untreated plots. Initial effect of weed control was seen in the base diameter of the seedlings after the third and fourth growing seasons. The divergence of height growth took place only later. At the age of 7 years, these height responses were 44 cm and 22 cm, and after 15 years, 144 cm and 114 cm, respectively. Delayed response of height growth of the seedling was probably due to frequent summer frosts damaging the annual shoots. Despite the frosts, the early response to vegetation control was seen in the seedling base diameter as reported earlier by Jylhä and Hytönen (2006).

In the present study, effective weed control decreased mortality of both bare-rooted and container seedlings, and the effect was stronger in the case of container seedlings. However, usually survival of large 4-year-old Norway spruce seedlings has been reported of being rather high. According to several studies, their mortality on abandoned fields (Leikola 1976, Jylhä and Hytönen 2006) and on reforestation areas (Brække et al. 1986, Kolström 1991) has been independent of weed control. In this study repeated frosts decreased height growth of the seedlings and made them susceptible to competition by vegetation for many post-planting years. The mortality of bare-rooted seedlings started to increase later than the mortality of container seedlings indicating that larger Norway spruce seedlings are able to stand longer intensive weed competition than smaller seedlings. Smaller 2-year-old spruce seedlings have been reported to benefit from weed control more than older seedlings and this has manifested in the form of decreased mortality (Kolström 1991).

Higher height and diameter growth with lower mortality resulted in higher stand volumes on the treated plots. Effective weed control (high and medium intensive treatments) yielded 3.8-fold stand volume as compared to untreated plots by the end of the 15th growing season in the case of both seedling types. Container seedlings, however, did not benefit from low weed control intensity treatment in terms of volume.

Medium intensity treatment (double spot treatment) and the high intensity treatment (three times repeated overall treatment) gave the best results in terms of growth and survival. The low intensity treatment (single application of terbuthylazine) more than doubled stand volume on the plots planted with bare-rooted seedlings, but did not have any effect on the volume of the container seedlings. Repeated herbicide applications are not recommended in Finland, even though no studies on the effects of repeated application have been published. However, the results of this study show that in afforestation of agricultural land considerable growth increases could be achieved with another application. Second application is probably even more important when foliar active herbicides are used. Applying herbicides on three consecutive years did not give any additional growth increase.

Interactions between seedling type and vegetation control intensity did not have significant effect on seedling height and volume. This is in accordance with results from earlier studies on various tree species, such as *Pinus taeda* L. (South et al. 1995, 2001a), *Pinus radiata* (South et al. 2001b) and *Pseudotsuga menziesii* (Mirb.) (Rose and Ketchum 2003). In these studies, growth increased along with increasing seedling size and weed control intensity, while no interaction between stock size and weed control intensity was observed. However, even with non-significant effect of interaction between seedling size and weed control method/intensity on seedling height and diameter, Rosner and Rose (2006) found that stand volume increased with increasing seedling size. Thus, volume return from weed control was greatest for larger seedlings. In this study, growth gains were greatest when intensive vegetation control and larger seedlings were combined.

Norway spruce seedlings are very sensitive to frost under active growth. The apical meristems, the elongating zone, and the needles are damaged at about –3ºC (Christersson and Fircks 1988). Early summer frosts have been considered as one of the most important factors retarding spruce growth when establishing plantations on open areas with no shelter trees (Leikola and Rikala 1983, Kinnunen 1989, Saksa et al. 1990, Jylhä and Hytönen 2006). Therefore, frost damage is typical for abandoned agricultural lands and clear-cut areas (Kolström 1991, Hytönen 1995, Hynönen and Hytönen 1988, Jylhä and Hytönen 2006). Effective weed control can increase the risk of frost damage to spruce seedlings by reducing high vegetation that could provide shelter for small seedlings (Leikola 1976).

In this study and in the study of Langvall et al. (2001), vegetation control did not affect frequency of frost damage. On the other hand, competing vegetation can increase the risk of frost damage by retarding the hardening (lignification) process of the seedlings (Brække et al. 1986). Kolström (1991) found that seedlings raised in a greenhouse were more sensitive to frost damage in a reforestation area than seedlings grown on an open ground. Langvall et al. (2001) reported bare-rooted Norway spruce seedlings as having considerably lower frequency of frost injury compared with containerized ones. In this study frost damage was not attributed to seedling type. The frosts significantly affected the height growth of the seedlings. For example, the proportion of frost-damaged seedlings on the sample plots correlated with the stand volume at the age of 15 years.

Achieving optimal results in field afforestation in terms of success in plantation establishment, economy and ecological considerations calls for integrated vegetation management. The need for effective vegetation control increases as seedling size decreases, because of lower competitiveness of small seedlings. By 2005, the proportion of bare-rooted spruce seedlings produced has declined to 2% from the 94% of 1980 (Finnish … 2006). At the same time, the use of forestry herbicides has been drastically reduced (Markkula et al. 1990, Torjunta-aineet 2007). The soil-effective herbicide, terbuthylazine, used in this study is not in the market any more. At present, there are only two herbicides (glyphosate and cycloxydim) available for conifers in Finland (Poteri 2007). Research and application of integrated and alternative means of vegetation control are thus of great importance.

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