Early Establishment of *Pinus sylvestris* and *Picea abies* Sown on Soil Freshly Prepared and After Stabilisation

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The aim of this study is to investigate the early establishment of *Pinus sylvestris* L. (Scots pine) and *Picea abies* (L.) Karst. (Norway spruce) seedlings on soil freshly prepared and soil left to stabilise for one year after preparation. Three site preparation treatments were studied: exposed C horizon, mound (broken O/E/B horizon piled upside down over undisturbed forest floor), and exposed E/B horizon. The years investigated were different in terms of weather, one being rainy and the other one dry. As such, emergence was very low in the dry year. Content of fine silt particles, bulk density, water retention, air-filled porosity, loss-on-ignition, and near saturated hydraulic conductivity did not differ statistically between fresh and stabilised soil. Nevertheless, early establishment of *P. sylvestris* seedlings was improved on exposed C and E/B horizon after one year of soil stabilisation. In contrast, early establishment of *P. sylvestris* on mounds, and that of *P. abies* on all types of site preparation treatments were not improved by soil stabilisation. In addition, mortality due to frost heaving did not differ significantly between freshly prepared and stabilised soil. Considering the fact that growing season climate had a great influence on the sowing outcome, and that early establishment is also affected by other factors that vary yearly, such as predation, seedbed receptivity, and competition from vegetation, it may not be advantageous to wait for soil to stabilise before regenerating from seeds.

Keywords direct seeding, Norway spruce, Scots pine, site preparation, soil properties
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1 Introduction

The Finnish Forest Act requires a forest site to be adequately regenerated as soon as possible after tree harvest (Ministry of Agriculture and Forestry 1997). In Finland, half of forest cuttings are regenerated from seeds: 20% using direct seeding and 30% through natural regeneration (Finnish Statistical Yearbook… 2001). However, direct seeding of *Picea abies* (L.) Karst. (Norway spruce) represents only a few percentage points compared to the share of *Pinus sylvestris* L. (Scots pine). Site preparation is commonly used at the regeneration stage in order to improve seedbed and environmental conditions for seedling growth. Delaying seeding after the site preparation treatment can have both favourable and unfavourable effects on seedling emergence and establishment.

Freshly prepared soil is susceptible to frost heaving, especially after wet summers, which increases seedling mortality (de Chantal et al. 2003). In order to diminish the risk of losses due to frost heaving, site preparation should be allowed to stabilise for up to two years before sowing seeds (Pohtila 1977). However, a long time period between site preparation and sowing can be detrimental to regeneration success (Pohtila and Pohjola 1985, Solbraa and Andersen 1997) as seedbed receptivity diminishes with time after site preparation (Arlidge 1967, Fleming and Mossa 1995, Karlsson and Örlander 2000). Vegetation may gradually overtake the sowing areas, thus decreasing seedbed receptivity and competing with seedling establishment (Arlidge 1967, Örlander et al. 1990, Fleming and Mossa 1995, Nilsson and Örlander 1999). Litter accumulation may also reduce the area of receptive seedbed (Fleming and Mossa 1995). In addition, the receptivity of seedbeds depends on yearly climate and soil moisture content (Fleming and Mossa 1995, de Chantal et al. 2003).

The beating action of raindrops on exposed soil breaks up soil aggregates, such that percolation water causes fine soil particles to move into macropores, thus sealing pores and forming a surface crust. In addition, settling of soil occurs due to wetting-drying and freeze-thaw cycles, which make the soil shrink and swell in alternance, thus promoting the compaction of soil aggregates (Kozlowski 1999). On mounds, the compaction is further enhanced by the weight of snow (Heineman 1999). As a consequence of soil settling and compaction, soil pore size distribution changes, such that the fraction of small pores increases (Kozlowski 1999). As a result of surface crust formation, soil settling, and compaction, air-filled porosity and water infiltration decrease, and bulk density increases (Kauppila and Lähde 1975, Hillel 1980, Kozlowski 1999). However, mild compaction may be beneficial as it improves capillary movement of soil water (Kozlowski 1999).

Moreover, the increased soil temperature of prepared soil compared to undisturbed ground (Kubin and Kemppainen 1994, Fleming et al. 1998) can affect the availability of soil nutrients positively, as decomposition of organic matter is increased by warm soil temperatures (Salonius 1983). In addition, conditions for bacterial decomposition of organic matter are improved upon mixing humus and mineral soil (Salonius 1983), such that fertility of mounds increases with time elapsed since site preparation.

With particular stress on the risk arising from competing vegetation, today's forestry practices in Finland strive to sow in conjunction with the site preparation treatment. Accordingly, the aim of this study is to compare the early establishment of *P. sylvestris* and *P. abies* seedlings sown on freshly prepared soil and on soil left to stabilise for one year after preparation. In addition, the differences in soil properties between fresh and stabilised site preparation were studied.

2 Material and Methods

2.1 Study Site

The experimental area was set in a 2 ha clearcut located 3 km away from the Hyytiälä Forestry Field Station of the University of Helsinki (61°48'N, 24°19'E, 151–153 m a.s.l.). The site is on a slope (3.4%) with a gradient in soil moisture and fertility resulting from variation in soil texture. On the upper slope, the site is classified as *Vaccinium vitis-idaea* (VT), which is a site dominated by *P. sylvestris* with dry, less fertile, and coarse-textured soil, according to the Finnish classification of forest types (Cajander 1925). The VT site gradually becomes a *Vaccinium myrtillus* (MT) site covered by a mixed *P. sylvestris* and *P. abies* forest at mid-slope. On the lower slope, the site becomes mesic, more fertile, fine-textured, and is dominated by *P. abies*, i.e. an *Oxalis acetosella-Vaccinium myrtillus* (OMT) site. *Betula pendula* Roth was also present in minority. Before clearcutting the stand at 100 years of age, timber productivity followed the moisture-fertility gradient,

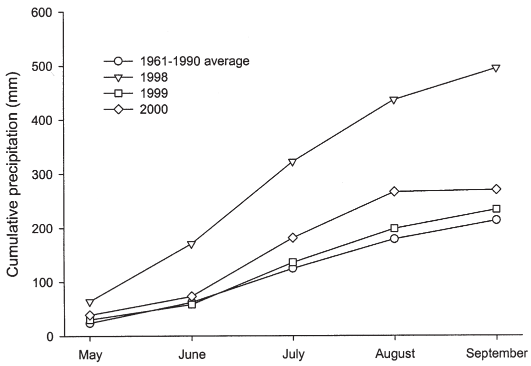

Fig. 1. Monthly precipitation in the study area during the three study years (1998–2000) compared to the 1961–1990 average for the region.

with average aboveground tree biomasses of 13.7, 15.1, and 16.3 kg m^{-2}, for the VT, MT, and OMT sites, respectively (Pietikäinen et al. 1999). Total volume was 240 m^3 h^{-1}. The forest was harvested by machine in winter, and logs were removed from the site at the same time, so the snow cover protected the soil against any disturbance. Mecke and Ilvesniemi (1999) have described the hydrological properties of the site before clearcut. The soil parent material is a glaciofluvial deposit with a texture varying from coarse to fine sand. The 1961–1990 average precipitation during the growing season (May–September) in the region is 214 mm, and mean air temperature is 13.2ºC (Finnish Meteorological Institute 1991). Precipitation during the growing season in the region of the experimental site was 496 mm in 1998, 234 mm in 1999, and 270 mm in 2000 (Hyytiälä Forestry Field Station meteorology data; Fig. 1).

2.2 Experimental Design

In May of 1998 and 1999, series of eight blocks, each 10 × 15 m in size, were delimited perpendicular to the slope and cleared from harvesting debris (Fig. 2). Blocks represent spatial location along the slope and include the variation in soil properties, such as particle size, water availability and water retention. Block 1 is located on the dry upper slope and block 8 on the moist lower slope.

For both *P. sylvestris* and *P. abies*, a split-plot design was used, consisting of three types of site preparation treatments (exposed C horizon, mounding, and exposed E/B horizon; Fig. 2) randomised and replicated three times within each block. To expose the C horizon, the humus layer (O horizon) and mineral soil (E and B horizons) were removed down to the surface of C horizon at 20–25 cm depth. The excavated humus and mineral soil were placed upside down over undisturbed forest floor to form mounds, 20–25 cm high (broken O/E/B horizon). The E/B horizon was exposed by removing the overlaying O horizon. Each site preparation plot was about 1 m^2. Site preparation plots were roughly made using an excavator, and finition was done by shovel to make sure the soil horizons were as intact as possible. There were 24 plots of each site preparation treatment made each year, i.e. 72 site preparation plots in total.

Seeds were sown in mid-May 1998 and 1999 on freshly prepared soil; seeds were also sown in mid-May 1999 on soil that had stabilised for one year (Fig. 3). Each sowing period, two sowing areas of 22 × 18 cm were marked on levelled soil in the centre of each site preparation plot on freshly prepared and stabilised soil. Each sowing area was subdivided into 20 sowing microsites of equal size (4.4 × 4.5 cm), in a 5 × 4 grid pattern. One seed was sown uncovered in a 2-mm depression at the centre of each of the sowing microsites, for a total of 20 seeds per sowing area. Sowing areas were randomly allocated to *P. sylvestris* and *P. abies* in each site preparation plot. Seeds of *P. sylvestris* and *P. abies* were obtained from local seed sources (orchard no. 220 for *P. sylvestris*, Hartola, 61º35'N, 26º16'E, 115 m elevation; orchard no. 109 for *P. abies*, Kangasniemi, 61º55'N, 26º41'E, 100 m elevation). According to the standard germination tests (ISTA 1985), the viability (21-day-test) of *P. sylvestris* and *P. abies* seeds was 99 and 97%, respectively.

2.3 Measurements

Seedling emergence (percentage of seedlings that appeared above the soil surface in relation to sown seeds), mortality (percent reduction in living seedlings between two time points), and

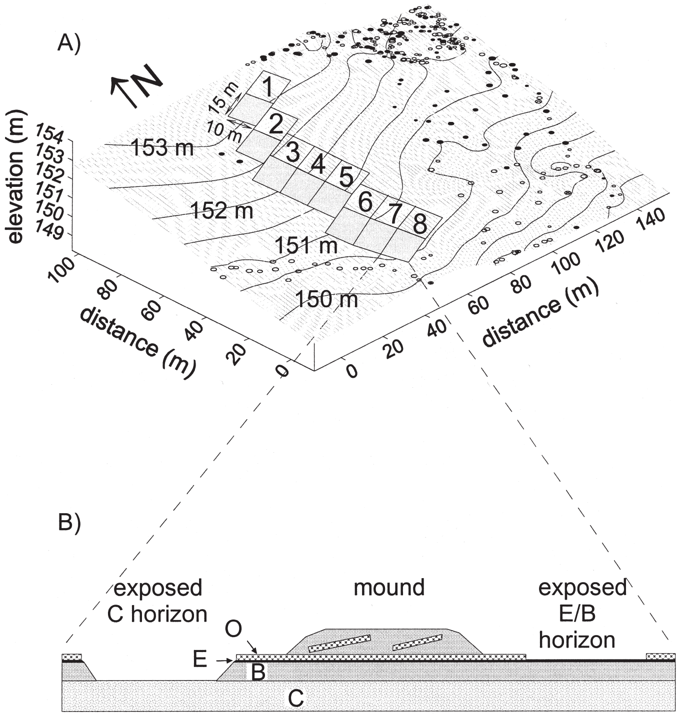

Fig. 2. A) Overview of the experimental site with the block layout along the slope (block 1 is on the upper slope and block 8 on the lower slope; open blocks were soil prepared and sown in 1998, shaded blocks in 1999; full, open, and crossed dots represent the location of pine, spruce, and birch trees, respectively, with dot size proportional to DBH), and B) illustration of exposed C horizon, mound, and exposed E/B horizon.

early establishment (percentage of seedlings that were living after two growing seasons in relation to sown seeds) were inventoried regularly during the growing seasons. Seedling inventories were done every second day during the first month after sowing, weekly later during the first growing season, and every month during the second growing season.

In summer 1998, undisturbed core samples (150 cm^3) were extracted from the top soil layer (6 cm deep) of every fresh site preparation plot (altogether 72 samples). In the summer 1999, the sampling was repeated on one random plot of each stabilised site preparation treatment from the eight blocks (altogether 24 samples). Correspondingly, samples were extracted from plots freshly prepared in 1999 (24 samples).

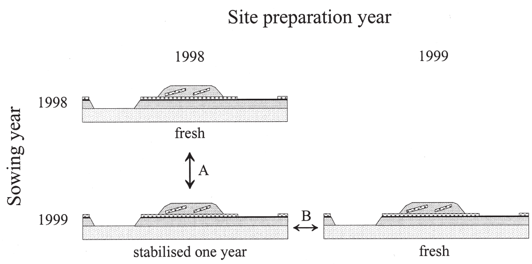

Fig. 3. Soil properties, seedling emergence, and early establishment were compared between freshly prepared soil and soil that had stabilised during one year: (A) same site preparation plots sown in different years; (B) different site preparation plots sown in the same year.

Near saturated soil hydraulic conductivity at –11 cm pressure head (K_{11}, tension infiltrometer, SW-080, 8.75-cm disk diameter, Soil Measurement Systems, Phoenix, AZ) was measured in the field during summer 1999 for those points from which soil cores were extracted (i.e. 48 measurements in total). In the laboratory, soil moisture desorption curves (pressure plate extractor, Soil Moisture Equipment Corporation, CA, USA), particle size distribution (laser diffraction, Coulter Corporation, FL, USA), loss-on-ignition (LOI, weight loss on ignition at 550ºC for 2 h, measured from fraction of soil particles <0.06mm), and bulk density were measured from all soil cores. Water retention at –10 kPa (field capacity) and air-filled porosity at –10 kPa (water retention at saturation minus water retention at –10 kPa) were calculated from the soil moisture desorption curves.

From each site preparation plot, soil water content at 5 cm-depth was monitored weekly during all growing seasons using TDR probes (Heimovaara 1993).

2.4 Statistical Analyses

Soil properties, seedling emergence, mortality, and early establishment were compared in two ways (Fig. 3). First, the same site preparation plots were compared as freshly prepared and after the soil had stabilised for one year (Comparison A). The differences in climate between years is a confounding factor in this comparison. Second, different fresh and stabilised site preparation plots were compared during the same time period (Comparison B). In this case, the climate was the same, but the original soil properties were different.

The effects of block, soil stabilisation, and site preparation on soil properties were tested using analysis of variance for split-plot design (Model 1).

$$X_{ijkl} = \mu + B_i + S_j + Ea_{ij} + P_k + (B \times P)_{ik} + (S \times P)_{jk} + Eb_{ijkl} \quad (1)$$

where X_{ijkl} is the soil property, μ is the overall mean, B_i is the main effect of block, S_j is the main effect of soil stabilisation, Ea_{ij} is the whole-plot error a, P_k is the main effect of site preparation, $(B \times P)_{ik}$ is the interaction between block and site preparation, $(S \times P)_{jk}$ is the interaction between soil stabilisation and site preparation, and Eb_{ijkl} is the sub-plot error b.

The effects of block, soil stabilisation, site preparation, and species on emergence, mortality, and early establishment of *P. sylvestris* and *P. abies* seedlings were tested using an analysis of variance model for split-plot design (Model 2).

$$Y_{ijklm} = \mu + B_i + S_j + Ea_{ij} + P_k + (S \times P)_{jk} + (B \times S \times P)_{ijk} + Eb_{ijkl} + Sp_m + (S \times Sp)_{jm} + (B \times S \times Sp)_{ijm} + (S \times P \times Sp)_{jkm} + Ec_{ijklm} \quad (2)$$

where Y_{ijklm} is seedling emergence, mortality, or early establishment, μ is the overall mean, B_i is the main effect of block, S_j is the main effect of soil stabilisation, Ea_{ij} is the whole-plot error a, P_k is the main effect of site preparation, $(S \times P)_{jk}$ is the interaction between soil stabilisation and site preparation, $(B \times S \times P)_{ijk}$ is the interaction between block, soil stabilisation, and site preparation, Eb_{ijkl} is the sub-plot error b, Sp_m is the main effect of species, $(S \times Sp)_{jm}$ is the interaction between soil stabilisation and species, $(B \times S \times Sp)_{ijm}$ is the interaction between block, soil stabilisation, and species, $(S \times P \times Sp)_{jkm}$ is the interaction between soil stabilisation, site preparation and species, and Ec_{ijklm} is sub-plot error c. The emergence and early establishment percentages were arcsin-transformed (using radians), whereas hydraulic conductivity was log-transformed (base e) for the analysis since the variance is a function of the mean in binomial distribution (Zar 1999, p. 275–280). The analyses of variance were calculated using the GLM procedure of SAS (SAS Institute Inc. 1989). Comparison testing between the different soil stabilisation and site preparation treatments was done using Tukey's Studentised range test at the 0.05 significance level.

Table 1. Average and standard deviation for soil properties of fresh and stabilised soil. n.a.: not available.

	Fresh (1998)		Stabilised (1999)		Fresh (1999)	
	Average	s.d.	Average	s.d.	Average	s.d.
Content of particles 0.02–0.002 mm (%)						
exposed C	3.95	3.04	3.81	3.14	7.79	8.45
mound	4.67	1.57	4.10	2.68	6.43	4.65
exposed E/B	8.21	2.39	6.01	1.92	6.34	4.71
Loss on ignition (%)						
exposed C	n.a.	n.a.	0.84	0.40	0.45	0.13
mound	n.a.	n.a.	1.50	0.32	1.45	0.56
exposed E/B	n.a.	n.a.	2.27	1.03	2.22	0.88
Bulk density (g cm^{-3})						
exposed C	1.44	0.06	1.47	0.09	1.48	0.11
mound	1.26	0.09	1.31	0.13	1.32	0.13
exposed E/B	1.17	0.15	1.23	0.06	1.16	0.06
Soil water retention at –10 kPa (%)						
exposed C	15.7	7.3	17.0	8.1	25.6	13.8
mound	19.9	5.1	19.8	6.2	23.4	14.9
exposed E/B	26.2	4.7	26.5	2.4	28.1	4.7
Soil aeration at –10 kPa (%)						
exposed C	25.2	4.9	24.4	6.1	19.3	10.0
mound	27.5	4.7	25.1	3.3	22.2	7.5
exposed E/B	26.1	5.2	24.1	3.9	25.0	2.8
Hydraulic conductivity, –11 cm pressure (cm h^{-1})						
exposed C	n.a.	n.a.	0.92	0.71	1.51	0.93
mound	n.a.	n.a.	3.36	3.63	6.75	10.30
exposed E/B	n.a.	n.a.	0.22	0.11	0.51	0.47
Volumetric soil moisture content (cm^3 cm^{-3}), 1999						
exposed C	n.a.	n.a.	0.08	0.03	0.12	0.06
mound	n.a.	n.a.	0.09	0.01	0.11	0.02
exposed E/B	n.a.	n.a.	0.12	0.02	0.14	0.02
Volumetric soil moisture content (cm^3 cm^{-3}), 2000						
exposed C	n.a.	n.a.	0.08	0.02	0.13	0.06
mound	n.a.	n.a.	0.06	0.01	0.10	0.02
exposed E/B	n.a.	n.a.	0.10	0.02	0.14	0.02

3 Results

3.1 Soil Properties

There was a difference in content of fine silt particles between site preparation treatments. For soil prepared in 1998, exposed E/B horizon contained more fine silt than exposed C horizon and mounds ($F = 23.31$, $p < 0.001$; Table 1). However, for soil prepared in 1999, the order was reversed and the fine silt content did not differ between types of site preparation (Table 1). This result arises from spatial variation in soil due to an irregular pattern of fine-textured lenses and layers typical of glaciofluvial deposits. In addition, variation in fine silt particles was considerable between blocks. Exposed C horizon on coarse-textured blocks (1–5) contained 8% fine silt particles,

Table 2. ANOVA results for the effect of block (B), soil stabilisation (S), and site preparation (P) on volumetric soil water content ($cm^3\ cm^{-3}$) of freshly prepared (1999) and stabilised soil, measured during the same growing season. Numbers in bold are significant at the 0.05 level.

	Growing season 1999				Growing season 2000			
	df	MS	F	*p*	df	MS	F	*p*
B	7	0.019			7	0.014		
S	1	0.049	12.66	**0.009**	1	0.156	43.86	**<0.003**
error a	7	0.004			7	0.004		
P	2	0.052	24.11	**<0.001**	2	0.043	21.97	**<0.001**
B × P	14	0.006	2.91	**<0.009**	14	0.007	3.79	**<0.001**
S × P	2	0.003	1.24	0.293	2	0.001	0.53	0.587
Error b	110	0.002			110	0.002		
Total	143				143			

whereas mounds contained 12%. On fine-textured blocks (6–8), exposed C horizon contained 20% and mounds 18% fine silt particles. In contrast, exposed E/B horizon contained 19 and 30% fine silt particles on coarse-textured and fine-textured blocks, respectively.

For fresh and stabilised soils prepared in different years, loss-on-ignition increased from exposed C horizon to mounds and to exposed E/B horizon (Table 1), and differed between all types of site preparation treatments ($F = 22.41$, $p < 0.001$). For these same soils, average K_{11} was lowest on exposed E/B horizon and differed from K_{11} of exposed C horizon and K_{11} of mounds, where it was highest ($F = 19.29$, $p < 0.001$; Table 1). For all freshly prepared and stabilised soils, bulk density decreased from exposed C horizon to mounds and to exposed E/B horizon, and differed between all types of site preparation treatments (comparison A: $F = 31.50$, $p < 0.001$; comparison B: $F = 16.57$, $p = 0.002$; Table 1). Air-filled porosity was not affected significantly by soil stabilisation and site preparation.

These results indicate that the water storage capacity would be lowest on soil of exposed C horizon and highest on soil of exposed E/B horizon. Accordingly, soil water retention from sites prepared in 1998 increased from exposed C horizon to mounds and to exposed E/B horizon (Table 1), and differed between all types of site preparation treatments ($F = 30.69$, $p < 0.001$). In contrast, when comparing fresh and stabilised soils prepared in different years, water retention did not differ significantly between site preparation treatments.

Soil stabilisation did not affect any of the studied soil properties at the tested statistical level, except volumetric soil water content (Table 2). During both growing seasons, volumetric soil water content was usually higher on fresh site preparation treatments than on the corresponding stabilised ones (Fig. 4). In addition, soil water content was affected by site preparation and the effect depended on block (Table 2). Both growing seasons, with exposed C horizon, soil water content was higher on fine-textured soil (e.g. blocks 6 and 7) than on coarse-textured soil (e.g. blocks 2 and 5). Soil water content of mounds or exposed E/B horizon did not vary significantly with soil texture (blocks). Exposed E/B horizon had the highest soil water content, and mounds had the lowest (Fig. 4 and Table 1). During growing season 1999, volumetric soil water content was higher on exposed E/B horizon than on exposed C or mounds, whereas in 2000, soil water content differed between all types of site preparation treatments.

3.2 Emergence

3.2.1 *Seeds Sown Different Years on the Same Site Preparation Plots as Fresh and Stabilised*

Emergence was higher in the moist 1998 growing season when seeds were sown on fresh site preparation than in the dry 1999 growing season when sowings were done on stabilised site preparation (Fig. 5, Table 3). Thus, the effect of

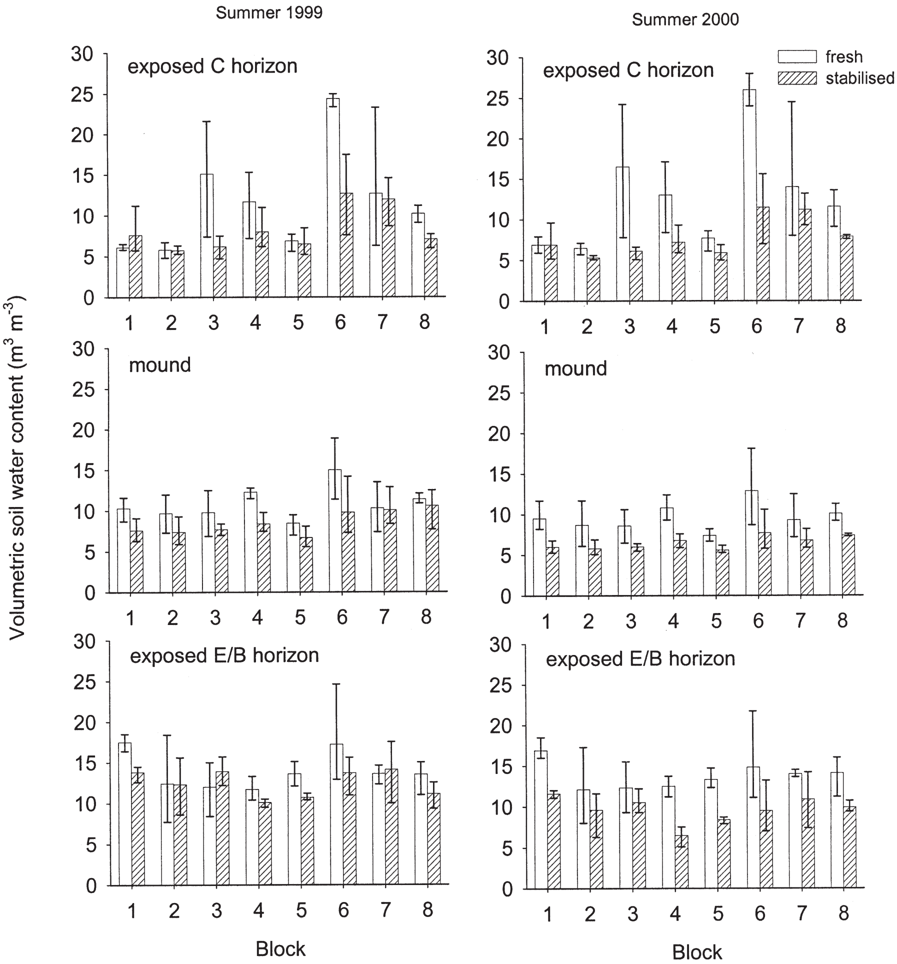

Fig. 4. Average volumetric soil water content (m^3 m^{-3}) during the growing seasons 1999 and 2000. Blocks 1–5 are coarse-textured and blocks 6–8 are fine-textured.

soil stabilisation is confounded with the effect of climate. The effect of soil stabilisation depended on site preparation, as shown by the significant interaction (Table 3). With fresh site preparation in 1998, emergence was higher on mounds than on exposed C and E/B horizon, whereas with stabilised site preparation in 1999, emergence decreased from exposed E/B horizon to exposed C horizon and to mounds (Fig. 5 and Table 4). Seedling emergence was higher for *P. sylvestris* than for *P. abies* (Fig. 5 and Table 3). Emergence of *P. sylvestris* was 81, 90, and 93% on fresh soil, compared to 19, 29, and 6% on stabilised soil, whereas emergence of *P. abies* was 68, 67, and 82% on fresh soil, compared to 5, 14, and 1% on stabilised soil, with exposed C horizon, E/B horizon, and mounds, respectively (Fig. 5).

3.2.2 Seeds Sown the Same Year on Different Freshly Prepared and Stabilised Soil

The effect of soil stabilisation on seedling emergence depended on species and site preparation, as shown by the significant interactions (Table 3). Growing season 1999 being dry, emergence was low for both species, though higher for *P. sylvestris* than for *P. abies* on stabilised exposed

Table 3. Split-plot ANOVA results for the effect of block (B), soil stabilisation (S), site preparation (P), and species (Sp) on emergence, mortality, and early establishment of *P. sylvestris* and *P. abies* seedlings. Numbers in bold are significant at the 0.05 level.

	Seeds sown different years on the same site preparation plots as fresh and stabilised				Seeds sown the same year on different fresh and stabilised site preparation plots			
	df	MS	F	*p*	df	MS	F	*p*
Total emergence								
B	7	0.097			7	0.163		
S	1	60.554	675.60	**<0.001**	1	0.220	3.91	0.089
Error a	7	0.090			7	0.056		
P	2	0.256	3.76	**0.027**	2	1.235	19.30	**<0.001**
S × P	2	1.388	20.40	**<0.001**	2	0.181	2.83	0.064
B × S × P	28	0.068	1.00	0.478	28	0.103	1.61	**0.046**
Error b	96	0.068			96	0.064		
Sp	1	3.525	88.49	**<0.001**	1	1.237	46.24	**<0.001**
S × Sp	1	0.001	0.02	0.890	1	0.544	20.33	**<0.001**
B × S × Sp	14	0.040	1.02	0.442	14	0.030	1.12	0.344
S × P× Sp	4	0.060	1.51	0.204	4	0.074	2.76	**0.031**
Error c	124	0.040			124	0.028		
Total	287				287			
First winter mortality								
B	7	0.542			7	0.133		
S	1	0.009	0.04	0.848	1	0.015	0.06	0.819
Error a	7	0.223			7	0.269		
P	2	0.927	4.04	**0.022**	2	0.426	1.28	0.290
S × P	2	0.457	1.99	0.144	2	0.602	1.81	0.178
B × S × P	25	0.376	1.64	0.055	15	0.218	0.66	0.805
Error b	70	0.229			35	0.332		
Sp	1	0.889	9.25	**0.003**	1	0.449	2.00	0.181
S × Sp	1	0.001	0.02	0.902	1	2E-05	0	0.992
B × S × Sp	13	0.140	1.46	0.156	9	0.090	0.40	0.912
S × P× Sp	4	0.226	2.35	0.062	3	0.197	0.88	0.479
Error c	71	0.096			13	0.225		
Total	204				101			
Early establishment								
B	7	0.222			7	0.088		
S	1	12.006	81.13	**<0.001**	1	0.412	8.01	**0.025**
Error a	7	0.148			7	0.051		
P	2	1.066	13.56	**<0.001**	2	0.466	13.75	**<0.001**
S × P	2	0.015	0.19	0.825	2	0.113	3.32	**0.040**
B × S × P	28	0.144	1.83	**0.016**	28	0.055	1.63	**0.042**
Error b	96	0.079			96	0.034		
Sp	1	3.661	101.52	**<0.001**	1	0.225	14.25	**<0.001**
S × Sp	1	0.924	25.63	**<0.001**	1	0.228	14.42	**<0.001**
B × S × Sp	14	0.035	0.97	0.489	14	0.017	1.09	0.374
S × P× Sp	4	0.051	1.42	0.231	4	0.047	2.99	**0.022**
Error c	124	0.036			124	0.016		
Total	287				287			

C and E/B horizon (Fig. 5, Tables 3 and 5). When compared between soil stabilisation treatments, emergence of *P. sylvestris* was higher on stabilised than on freshly exposed C and E/B horizon, but was equally poor between fresh and stabilised mounds (Fig. 5 and Table 5). When compared between site preparation treaments, emergence of *P. sylvestris* was higher on exposed C (19%)

Table 4. Results of Tukey's Studentised range tests (p-values) for seedling emergence compared between site preparation treatments for the same soil observed over two growing seasons as freshly prepared and after stabilisation. Numbers in bold are significant at the 0.05 level.

	Fresh	Stabilised
Emergence		
exposed C vs mounds	**<0.001**	**0.003**
exposed C vs exposed E/B	0.935	**0.003**
mounds vs exposed E/B	**0.004**	**<0.001**

Table 5. Results of Tukey's Studentised range tests (p-values) for seedling emergence and early establishment compared between soil stabilisation treatments and species, for fresh and stabilised soil prepared in different years. Numbers in bold are significant at the 0.05 level.

	Comparison between soil stabilisation treatments		Comparison between species	
	P. sylvestris	*P. abies*	Fresh	Stabilised
Emergence				
exposed C	**<0.001**	0.932	1.000	**<0.001**
mounds	1.000	0.999	0.091	0.074
exposed E/B	**<0.001**	1.000	1.000	**<0.001**
Early establishment				
exposed C	**<0.001**	1.000	0.750	**0.028**
mounds	1.000	1.000	0.999	0.993
exposed E/B	**<0.001**	0.651	0.990	**0.001**

and E/B horizon (29%) than on mounds (6%) for stabilised soil, but there was no significant difference between site preparation treatments for freshly prepared soil (6, 8, and 13% for exposed C, mounds, and exposed E/B horizon, respectively; Fig. 5 and Table 6). One year of soil stabilisation did not affect significantly the emergence of *P. abies* (Table 5). However, emergence was higher on freshly exposed E/B horizon than on fresh mounds, and on stabilised exposed E/B horizon than on stabilised mounds and exposed C horizon (Table 6). Average emergence of *P. abies* was 2, 9, 13% on fresh mounds, exposed C, and exposed E/B horizon, respectively; the respective values were 1, 5, and 14% for stabilised site preparation (Fig. 5). The effect of soil stabilisation and site preparation also depended on block, as indicated by the significant interaction (Table 3). Both species combined, emergence on freshly exposed C horizon was higher on block 6 compared to blocks 1 and 5; for freshly exposed E/B horizon, emergence was higher on block 1 compared to blocks 3 and 7 (Fig. 5). Similarly, emergence on stabilised E/B horizon was higher on block 2 than on block 5 (Fig. 5). Blocks with high emergence also had high volumetric soil water content (Fig. 4 and 5).

3.3 Winter Mortality

Soil stabilisation did not affect significantly seedling mortality over the winter period, which was mostly due to frost heaving (Table 3). When comparing the first winter mortality of seedlings

Table 6. Results of Tukey's Studentised range tests (p-values) for seedling emergence and early establishment compared between site preparation treatments, for fresh and stabilised soil prepared in different years. Numbers in bold are significant at the 0.05 level.

	P. sylvestris		*P. abies*	
	Fresh	Stabilised	Fresh	Stabilised
Emergence				
exposed C vs mounds	0.993	**0.001**	0.202	0.587
exposed C vs exposed E/B	0.188	0.088	0.932	**0.036**
mounds vs exposed E/B	0.872	**<0.001**	**0.002**	**<0.001**
Early establishment				
exposed C vs mounds	1.000	0.678	**0.002**	0.782
exposed C vs exposed E/B	0.191	1.000	0.072	0.625
mounds vs exposed E/B	0.553	0.842	**<0.001**	**0.007**

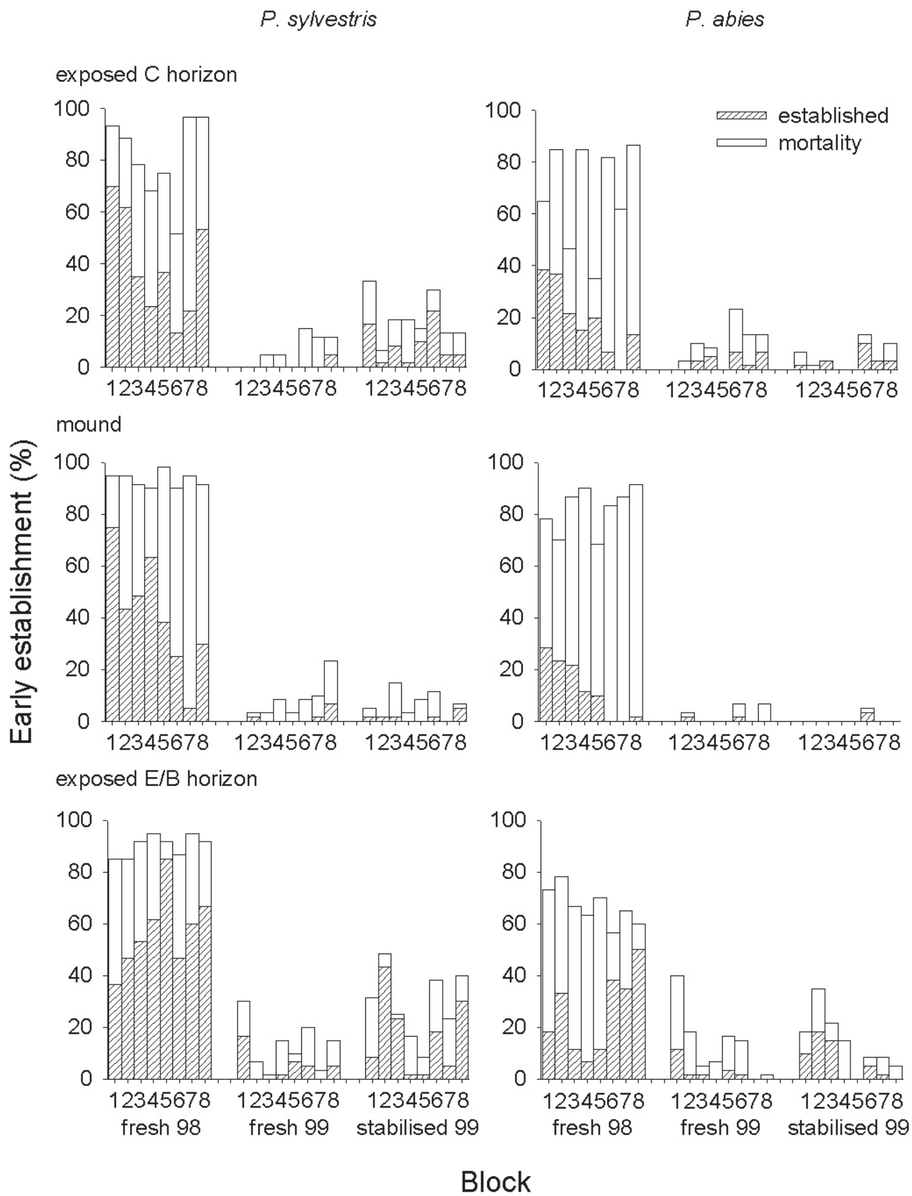

Fig. 5. Early establishment (%) for *P. sylvestris* and *P. abies* sown on freshly prepared and stabilised soil. Seedling emergence is the total of early establishment and mortality. The difference between emerged seedlings and 100% is the proportion of non-germinated seeds.

emerged different years on fresh and stabilised soil, seedling mortality over the winter period was affected by species and site preparation (Table 3). Mortality was higher for *P. abies* than for *P. sylvestris*. In addition, seedling mortality was higher for seedlings growing on mounds than on exposed C and E/B horizon. Mortality of *P. sylvestris* was 4, 18, and 24% on fresh soil, and 16, 11, and 20% on stabilised soil, for exposed E/B, exposed C, and mounds, respectively. In comparison, mortality of *P. abies* was 20, 30, and 54% on fresh soil, and 22, 10, and 50% on stabilised soil, for exposed E/B, exposed C, and mounds, respectively. Seedling mortality was not affected by any of the studied factors when comparing fresh and stabilised soils sown in the same year (Table 3). Mortality of seedlings growing on soil freshly prepared in 1999 was 10, 25, and 50% for *P. sylvestris*, and 28, 39, and 45% for *P. abies* growing on exposed E/B horizon, mounds, and exposed C horizon, respectively.

3.4 Early Establishment

3.4.1 Seeds Sown Different Years on the Same Soil as Freshly Prepared and After Stabilisation

The effect of soil stabilisation depended on species, such that the difference in early establishment between fresh and stabilised site preparation was larger for *P. sylvestris* than for *P. abies* (Table 3). Establishment was higher for *P. sylvestris* than for *P. abies* seedlings, and higher in 1998 (fresh site preparation, moist growing season) than in 1999 (stabilised site preparation, dry growing season; Fig. 5 and Table 3). The difference between the years (effect of soil stabilisation) was also dependent on site preparation and block (Table 3). As for seedling emergence, the effect of soil stabilisation on establishment of seedling is confounded with the effect of climate. Establishment on fresh mounds was higher on coarse-textured soil (blocks 1–4) than on fine-textured soil (blocks 6–8); similarly, establishment on freshly exposed C horizon was better on coarse-textured soil (blocks 1 and 2) than on fine-textured soil (blocks 6 and 7; Fig. 5). For stabilised exposed E/B horizon, establishment was higher on block 2 than on blocks 4, 5, and 7 (Fig. 5). In comparison, establishment on stabilised mounds and exposed C horizon, and on freshly esposed E/B horizon did not show any trend along the slope (Fig. 5).

3.4.2 Seeds Sown the Same Year on Different Freshly Prepared and Stabilised Soil

The effect of soil stabilisation on early establishment depended on species and site preparation, as shown by the significant interactions (Table 3). After two growing seasons, establishment was higher for *P. sylvestris* than for *P. abies* seedlings on stabilised exposed C and E/B horizon (Fig. 5, Tables 3 and 5). Establishment of *P. sylvestris* was higher on stabilised than on fresh site preparation with exposed C and E/B horizon, but was equally low between fresh and stabilised mounds (Fig. 5). However, establishment of *P. sylvestris* did not differ significantly between types of site preparation treatments, either freshly prepared or stabilised (Table 6). Establishment of *P. sylvestris* was 1, 0.6, and 4% on mounds, exposed C, and E/B horizon on fresh site preparation, and 1, 9, and 16% on stabilised site preparation, respectively (Fig. 5). In comparison, establishment of *P. abies* was as low on fresh as on stabilised site preparation treatments (Fig. 5 and Table 5). Establishment of *P. abies* was higher on freshly exposed C and E/B horizon than on fresh mounds; establishment was also higher on stabilised exposed E/B horizon than on stabilised mounds (Table 6). Establishment of *P. abies* was 0.4 and 3% on both fresh and stabilised mounds and exposed C horizon, and 3 and 6% on fresh and stabilised exposed E/B horizon, respectively (Fig. 5). The effects of soil stabilisation and site preparation also depended on block (Table 3). As such, early establishment of both species on stabilised exposed E/B horizon was higher on block 2 compared to blocks 4–8, and on block 3 compared to blocks 4–5; with freshly exposed E/B horizon, early establishment was better on block 1 than on block 7 (Fig. 5). Establishment on mounds and exposed C horizon did not show any trend along the slope (Fig. 5).

4 Discussion

We should keep in mind that the effect of soil stabilisation on soil properties, seedling emergence, mortality, and early establishment is confounded with the effect of climate (Pohtila 1977), especially since 1998 and 1999 were very different in terms of precipitation. Growing season moisture conditions (i.e. precipitation, relative air humidity, air temperature, and soil water) have a strong effect on sowing outcome (Vaartaja 1954, Kinnunen 1982, Oleskog and Sahlén 2000, Oleskog et al. 2000). In addition, seedling emergence, mortality, and early establishment are affected by other factors that vary yearly, such as frost heaving and predation, which also confound the effect of soil stabilisation (Fleming and Mossa 1995). Frost heaving of seedlings is a common cause of over-winter mortality on wet or disturbed soils, especially when the snow cover is thin or inexistant (Pohtila 1977, Örlander et al. 1990, Goulet 1995, Bergsten et al. 2001). Furthermore, seedling predation is related to growing season moisture conditions, substrate, stand disturbance, and distance from the forest edge (Heikkilä 1977, Nystrand and Granström 1997a,b, 2000). Therefore, the experiment should be replicated over several years and sites to obtain results that can be generalised. However, such replication would be very laborious and time-consuming. Accordingly, the effect of yearly variation in climate on early establishment was assessed through literature.

Settling and compaction of soil were minimal after a time lapse of one year. Consequently, soil stabilisation did not affect any of the studied soil properties, except volumetric soil water content. This could be due to the fact that harvesting debris were removed before site preparation was done, such that mounds, where most re-arrangement in soil matrix is expected, rested against the ground, limiting the amount of settling. In addition, sample sizes (150 cm^3) were small compared to the actual mound sizes. However, for the water retention measurements, sample size was relatively large, such that the changes due to soil stabilisation that occurred at the soil surface (e.g. crust formation) were not reflected on the whole sample. Because we measured the difference in soil properties (for the comparison on the same soil as freshly prepared and stabilised) between the end of the first growing season and a variable time point during the second growing season, the full extent of soil settling is not known. Contrary to the results obtained, loss-on-ignition should be highest for mound soil, as they contained the most humus. However, because a good mound should be covered by at least 5 cm of mineral soil, little humus material from the broken O horizon was incorporated into the core soil sample taken from the top 6 cm layer of soil.

When emergence and early establishment of seedlings growing on the same site preparation plots but sown during different growing seasons are compared, the outcome of sowing was higher on fresh than on stabilised soil. However, these results are most likely due to moister climatic conditions during the first growing season (Kinnunen 1982, Oleskog and Sahlén 2000, Oleskog et al. 2000) when soil was freshly prepared than the following year when soil had stabilised. On the opposite, when comparing sowings done during the same growing season but on different fresh and stabilised site preparation plots, emergence and early establishment of *P. sylvestris* were higher (though very poor by any standards) on stabilised exposed C and E/B horizon compared to freshly exposed ones. Soil stabilisation did not affect significantly the emergence and early establishment of *P. abies*. The very low seedling establishment obtained after two growing seasons may result from a lack of precipitation just after sowing (Vaartaja 1954, Oleskog and Sahlén 2000, Oleskog et al. 2000). Accordingly, it may not be advantageous to wait for soil to stabilise before regenerating *P. abies* from seeds, though *P. sylvestris* could benefit from soil stabilisation, except when regenerating using mounds. However, the benefit of soil stabilisation has to be weighed against the risks of decreased seedbed receptivity and competition from vegetation. It is noteworthy that soil stabilisation did not affect significantly winter mortality.

The seedling emergence and early establishment results on the different types of site preparation treatments can be partly explained by the differences in near saturated soil hydraulic conductivity (K_{11}). Water moves slowly through the soil profile when K_{11} is low, e.g. on exposed E/B horizon, such that seeds can get enough water to imbibe and germinate, and seedlings to survive. Accordingly, water retention was highest on exposed E/B horizon. This is due to the accumulation of Al, Fe, and organic compounds between mineral particles in the B horizon, which changes pore size distribution to smaller pores, and thus increases water-holding capacity (Mecke et al. 2002). Likewise, variation in the content of Al, Fe, and organic compounds in soil of exposed E/B horizon could explain the variation in early establishment of seedlings between blocks. On the opposite, soil water quickly percolates down into the soil when K_{11} is high. A high humus (O horizon) content in soil increases water infiltration (Ritari and Lähde 1978), as observed with the high hydraulic conductivity on mounds. Therefore, soil moisture conditions may not meet the requirements for seed germination and seedling survival when K_{11} is high, even though volumetric soil water content at 5 cm-depth may be high. Although not measured, it is obvious that the soil surface of coarse-textured soil was very dry in the dry 1999 growing season. Accordingly, emergence of seeds sown on exposed C horizon was higher on fine-textured soil, where K_{11} was lower and water retention was higher. Consequently, K_{11} may be as important as volumetric soil water content for emergence and early establishment of seedlings. Because the measurement process of K_{11} is very laborious, measurements were conducted over an extended period of time during growing season 1999, and each replicate was measured only once during the study period. However, because soil properties changed as soil stabilised, the measurements may include biases due to temporal variation (Messing and Jarvis 1993, van Es et al. 1999). In fact, temporal variability within a growing season may affect water infiltration more significantly than soil properties and spatial variability (van Es et al. 1999).

5 Conclusion

We did not observe significant differences in soil properties between fresh and stabilised site preparation treatments, indicating that a period of one year may be too short to observe the effects of soil stabilisation. Nevertheless, emergence and early establishment of *P. sylvestris* seedlings were improved using exposed C and E/B horizon site preparation treatments on stabilised soil. In contrast, early establishment of *P. sylvestris* on mounds, and that of *P. abies* on all types of site preparation treatments were not improved by soil stabilisation. In addition, mortality due to frost heaving did not differ significantly between freshly prepared and stabilised soil. Considering the fact that growing season climate had a great influence on post-sowing outcome, and that early establishment is also affected by other factors that vary yearly, such as predation, seedbed receptivity, and competition from vegetation, it may not be advantageous to wait for soil to stabilise before regenerating from seeds.

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