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Effects of complete deep-soil cultivation on initial forest stand development

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Abstract

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Long-term effects of complete deep-soil cultivation on forest growth and yield were evaluated in an experiment initiated in 1988 on six different sites in Sweden. Complete deep-soil cultivation was compared with less intensive site preparation. Ten years after the start, growth, stand structure, damage and survival were evaluated. Conifer seedling growth and survival on sandy sites, frost-prone sites or both, generally increased following deep-soil cultivation compared to patch scarification. Silty sites exposed to summer frost were also positively affected by deep-soil cultivation, although the risk of frost-heaving increased. For deciduous seedlings the result varied, but survival in birch was improved by deep-soil cultivation. On former farmland, deep cultivation may effectively control competing vegetation. Deep-soil cultivation in strips over half the area appeared to be as efficient as complete treatment. This has financial and environmental implications. Deep cultivation reduced variability in tree size, since it provided a more uniform environment during stand establishment. When long-term effects of complete deep-soil cultivation on forest growth and yield are evaluated, the significant differences in stand establishment demonstrated in the study must be considered. Future revisions of the experiment must address the question of the long-term effects of intensive soil cultivation on forest growth and yield.

Keywords: forest regeneration, intensive soil scarification, seedling damage, seedling establishment, stand structure, *Picea abies*, *Pinus contorta*, *Pinus sylvestris*, *Betula pendula*, *Tilia cordata*, *Quercus robur*, Norway spruce, Lodgepole pine, Scots pine, Silver birch, Small-leaved lime, Pedunculate oak

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Introduction

On many site types, the soil is cultivated before being planted after clearfelling. In Sweden, most clearfelled areas are mechanically scarified, predominantly by disc-trenching (Anon., 1998). Soil scarification generally promotes the rapid establishment of planted seedlings (*e.g.* Nilsson & Örlander, 1999). In many studies, soil scarification or ploughing of forest soil has improved survival and early growth. If a high proportion of the surface is exposed, the risk of night frost decreases (Kohh, 1970; Neckelman, 1998). Owing to the control of competing vegetation, scarification reduces competition for water and nutrients (Ross & Malcolm, 1982; Neckelman, 1998; Nilsson & Örlander, 1999). Scarification methods which result in the exposure of mineral soil around the seedling decrease the risk of damage by the pine weevil (*Hylobius abietis*; Neckelman, 1998; Örlander & Nilsson, 1999). Scarification increases soil temperature (Lähde, 1978; Ross & Malcolm, 1982; Örlander, Hallsby, Gemmel & Wilhelmsson, 1998), a factor which favours root growth and seedling establishment, especially in northern forests (Örlander, Gemmel & Hunt, 1990). Exposure of mineral soil may also be detrimental in some cases, and may lead, *e.g.*, to an increased risk of frost-heaving (Goulet, 1995).

Deep cultivation may result in improved soil aeration (*e.g.* Thompson, 1984). Soil water relations are often improved by cultivation, since the soil's infiltration capacity may increase and moisture is better conserved if the organic material is ploughed into the mineral soil, rather than kept intact on the surface (Buchholz & Neumann, 1964). Deep cultivation decreases soil density (Ross & Malcolm, 1982). The reduced density, and the incorporation of organic matter in the soil profile, increase root penetration and rooting volume (Hochtanner & Seitschek, 1964; Hetch, Kramer & Wessels, 1981; Ross & Malcolm, 1982), and thereby increase the amount of water and nutrients available for tree growth.

Scarification, and especially the ploughing of forest soil, has sometimes improved site productivity (*cf.* Wittich, 1942; Hochtanner & Seitschek, 1964; Wilson & Pyatt, 1984).

However, there has been concern that the early, advantageous effects of intensive soil preparation do not persist throughout the rotation (*e.g.* Thomson & Neustein, 1973; Lundmark, 1977; Wilson & Pyatt, 1984; Johansson, 1987). As early as 1926, Wittich (Rehfuess, 1978) showed that ploughed soils may lose significant amounts of organic material and N, compared to unploughed soils. Several other examples exist of the loss of C and nutrients after ploughing, mixing or disc-trenching (*e.g.* Burschel, Eder, Kantari & Rehfuess, 1977; Rehfuess, 1978; Vitousek, Andariese, Matson, Morris & Sanford, 1992). Johansson (1994) demonstrated that needles decompose and release N and Ca faster on scarified than on untreated areas. Results from long-term Swedish experiments on Scots pine on poor, sandy sediments suggest, however, that site productivity may increase despite a considerable loss of C and N (Örlander, Egnell & Albrektson, 1996). The results of Kardell (1987) also support that finding.

A deep-cultivation experiment in Scotland, followed for 30 years, showed that growth improved during the first ten years after complete deep-cultivation. However, during the following ten years, trees on control plots grew better than trees on deep-cultivated plots (Thomson & Neustein, 1973). A third analysis, conducted ten years later, showed *(a)* that current increment was approximately equal for all treatments, *(b)* that the difference in volume yield after ten years still remained, and *(c)* that benefits from deep-cultivation might still be present (Wilson & Pyatt, 1984). This experiment clearly demonstrates that it is difficult to draw any conclusions about long-term yield when the stand is too young.

As mentioned above, site preparation will often lead to higher survival and initial growth, hence to a higher stocking density. Growth conditions become more uniform following site preparation, which may result in decreased variation in the seedling stand. Moreover, variation in tree size usually increases with stand age until crown closure (Lieffers & Titus, 1989). High variability in tree size may increase the level of self-thinning, thereby negatively affecting forest yield (Nilsson & Allen, 2002). In comparisons of the long-term effects of soil treatment, it is important to consider both stocking density and stand structure, since they may be important to carrying capacity and wood production during the rotation.

In 1988, experiments were established at six localities in Sweden, to study the long-term effects of intensive soil preparation on growth, yield and stand structure. The main aim of the present study was to investigate the establishment phase of those experiments; a second aim was to determine whether they could be used in future growth and yield studies. Three main hypotheses were tested in the present study: *(i)* That deep, complete soil cultivation causes increased seedling growth compared to less intensive site preparation; *(ii)* That damage and mortality are reduced on plots with deep, complete soil cultivation compared to plots with less intensive site preparation; and *(iii)* That variation in tree height is smaller on plots with deep, complete soil cultivation compared to plots with less intensive site preparation.

Materials and methods

From 1988, six experiments in the same series were established in three regions of Sweden (Fig. 1). Trollberget and Degerön are situated in the north, Sandbäcken and Norrekvarn in the southern interior, and Sperlingsholm and Härsängen in the southwestern coastal region. In each region, one experiment was situated on former farmland and one on forest land. Only sites that could be ploughed were selected for the study; hence coarse-textured till soils with boulders were excluded. The soil texture varied from sand to clayey till, and the soil moisture class was dry or mesic. Site details are given in Table 1.

Randomised block experiments with four replications were established on all sites except one, which had only two replications (Table 2). Two treatments were included in the study: deep, complete soil cultivation, and a control. The control plots were also subjected to soil treatment, but this was as limited as possible, to secure early seedling establishment (Table 2). On forest land, stumps were removed from the plots before ploughing. For practical reasons, the stumps were replaced on top of the soil on

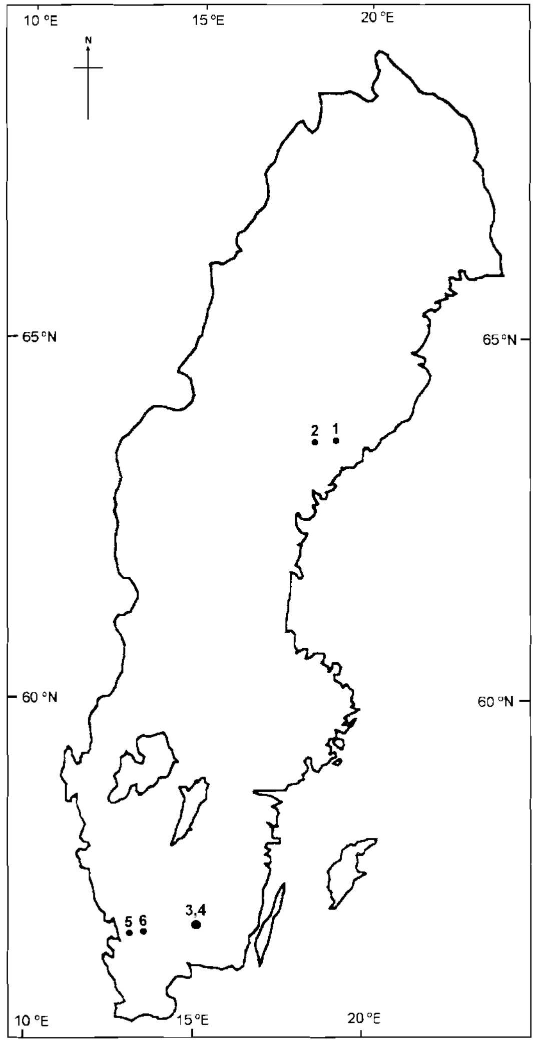

Fig. 1. Geographical location of the experiments. 1 = Trollberget, 2 = Degerön, 3 = Sandbäcken, 4 = Norrekvarn, 5 = Sperlingsholm and 6 = Härsängen.

one site, and removed from the other two sites. The soil was ploughed to a depth of 40–60 cm on all sites. The humus layer was placed deep in the soil below the mineral soil, most of it in the deeper half of the ploughed soil profile (Fig. 2). In three of the experiments, agricultural equipment was used for ploughing. In the remaining three experiments, an excavator was used to turn over the soil in a similar way. The plots were planted with various tree species, and in some cases with mixtures of species. The tree species were selected to fit each site. In some cases, restocking was carried out, to create fully stocked plots (Table 2).

Table 1. *Site description*

	Site					
	Trollberget	Degerön	Sandbäcken	Norrekvarn	Sperlingsholm	Härsängen
Site number	1	2	3	4	5	6
Latitude, °N	64°10′	64°11′	57°10′	57°11′	56°41′	56°42′
Longitude, °E	19°55′	19°40′	14°46′	14°47′	12°55′	13°20′
Altitude (m.a.s.l.)	120	150	180	180	25	170
Previous land use	Farmland	Forest	Farmland	Forest	Farmland	Forest
Soil texture	Silt	Sand	Silty sand	Silt	Clayey till	Sand
Soil moisture	Mesic	Dry	Mesic	Mesic	Mesic	Dry
Vegetation type	Grass	Lichen	Grass	Grass	Grass	Grass

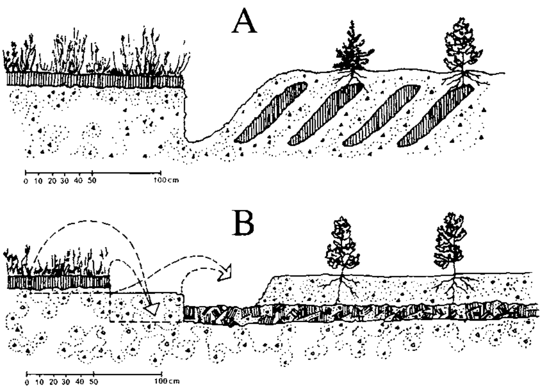

Fig. 2. Principle sketches of the deep soil-cultivation profiles in the experiment. Profile A corresponds to Trollberget and Degerön, while profile B corresponds to Sandbäcken, Norrekvarn, Sperlingsholm and Härsängen.

Experimental areas and treatments

Trollberget

Trollberget is situated *ca.* 50 km NW of Umeå (64°10′N, 19°55′E), on a southwest slope on former farmland (Fig. 1). The land had been used for hay production, and was abandoned several years before the experiment was established. The entire area was covered with grass when the experiment was established. The soil texture was mainly silt, and the organic content in the topsoil was relatively low, since the field had not been intensively cultivated. The bulk density was approx. 1.1 g cm^{-3} in the topsoil and 1.9 g cm^{-3} in the pure mineral soil. The *p*H of the mineral soil was 5.3. The soil had relatively low amounts of N and high amounts of Al, Fe and Mn (Tables 3, 4).

Deep-cultivated plots were ploughed with a large, double-mouldboard farm plough to a depth of *ca.* 40 cm (Fig. 2a). Control plots were tilt-ploughed, the tilts being about 10 cm deep. The plots were divided into two subplots of equal size (20 × 20 m) and planted with silver birch (*Betula pendula* Roth) and Norway spruce (*Picea abies* (L.) Karst.), respectively. The soil treatment was carried out in November 1987, and planting was done in May 1988.

Degerön

Degerön is situated *ca.* 60 km NW of Umeå (64°11′N, 19°40′E) on a level sand deposit close to the river Vindelälven (Fig. 1). The previous stand was a pure pine forest, felled one year before the experiment was established. The soil texture was sand, the soil moisture class was dry, and the vegetation type was lichen. The humus layer was *ca.* 3 cm thick. The bulk density of the mineral soil before treatment was *ca.* 1.7 g cm^{-3}. The *p*H of the mineral soil and humus layer was 6.2 and 5.6, respectively. The sandy soil had small amounts of nutrients, with low values for *e.g.* N and K (Tables 3, 4).

Deep-cultivated plots were ploughed to a depth of *ca.* 50 cm in May 1998, by means of a large, single-mouldboard farm plough (Fig. 2a). Control plots were manually patch-scarified (4 × 4 dm). The plots were planted with lodgepole pine (*Pinus contorta* Douglas) a few days after ploughing.

Sandbäcken

Sandbäcken is situated in Asa Experimental Forest, *ca.* 40 km NW of Växjö (57°10′N, 14°47′E) on a slight, east-facing slope on former farmland (Fig. 1). The land had been used for grazing and hay production, and was abandoned several years before the experiment was established. The area was covered with dense grass when the experiment started. The soil texture was sand with some silt. The cultivated topsoil (down to the previous ploughing depth) was easily distinguished from the mineral soil

Table 2. *Description of treatments*

	Site					
	Trollberget	Degerön	Sandbäcken	Norrekvarn	Sperlingsholm	Härsängen
No. of blocks	4	4	2	4	4	4
Plot size	40 × 20 m	30 × 30 m	20 × 25 m	30 × 30 m	40 × 40 m	40 × 40 m
Tree species (1)	Norway spruce	Lodgepole pine	Silver birch	Norway spruce	Pedunculate oak	Norway spruce
Provenance (1)	Hissjö	SCA[a]	Asarum	Vitebsk, Tolotjin	Gebeit II, NL	Emmaboda
Seedling type, age (1)	Container, 2 yrs	Container, 2 yrs	Bare-rooted, 2 yrs	Bare-rooted, 3 yrs	Bare-rooted, 4 yrs	Bare-rooted, 4 yrs
Tree species (2)	Silver birch			Scots pine	Small-leaved lime	
Provenance (2)	AC Bureå 300			Albjershus	Dalby	
Seedling type, age (2)	Container, 1 yr			Bare-rooted, 2 yrs	Bare-rooted, 2 yrs	
Spacing	2 × 2 m[b]	2 × 2 m	2 × 2 m	2 × 2 m[c]	1.3 × 1.3 m[d]	2 × 2 m
Ploughing, method	Double plough	Single plough	Excavator	Excavator	'Reol' plough	Excavator
Ploughing, depth (cm)	40	50	60	60	60	60
Stump treatment		Returned		Removed		Removed
Reference soil treatment	Shallow-furrow plough	Patch	Herbicide	Patch + herbicide	Herbicide	Patch
Ploughing date	Nov. 1987	May 1988	March 1990	Apr. 1990	Nov. 1989	Apr. 1990
Planting date	May 1988	May 1988	May 1990	May 1990	May 1990	May 1990
Replacement planting			May 1990, 1991	May 1991		May 1994

[a] Lat. 60°10′, long. 128°20′, 800 m.
[b] Planted in separate subplots, 20 × 20 m.
[c] Mixed 2:1, Norway spruce: Scots pine.
[d] Mixed 4:1, Oak: Lime.

Table 3. *Concentration of elements (%) in the topsoil and mineral soil at each location. Soil density in g cm⁻³*

Location	Soil type	Depth, cm	*p*H	C	N	P	K	Ca	Mg	S	Na	B	Al	Cu	Fe	Mn	Mo	Zn	Density
Trollberget	Topsoil	0–25	mv	mv	0.08	0.054	0.20	0.255	0.459	0.014	0.013	0.008	1.51	0.0008	4.45	0.064	0.002	0.005	1.13
	Mineral soil	25–50	5.30	mv	0.03	0.063	0.26	0.325	0.577	0.006	0.016	0.009	1.60	0.0013	5.21	0.093	0.003	0.007	1.93
Degerön	Humus layer	0–3	5.60	mv	0.31	0.038	0.08	0.154	0.106	0.034	0.010	0.002	0.47	0.0004	1.00	0.016	0.001	0.002	0.35
	Mineral soil	3–50	6.20	mv	0.02	0.031	0.07	0.122	0.171	0.007	0.010	0.003	0.87	0.0003	1.79	0.019	0.001	0.003	1.73
Sandbäcken	Topsoil	0–31	6.14	3.57	0.29	0.057	2.12	0.619	0.370	0.012	1.674	0.003	1.05	0.0007	1.46	0.036	0.002	0.005	0.62
	Mineral soil	31–50	5.84	1.33	0.12	0.039	1.84	0.391	0.450	0.012	1.302	0.003	0.82	0.0009	1.57	0.019	0.001	0.005	1.10
Norrekvarn	Humus layer[1]	0–30	3.90	8.11	0.36	0.028	1.88	0.324	0.136	0.014	1.314	0.001	0.90	0.0002	0.57	0.011	0.001	0.002	0.19
	Mineral soil	30–50	4.36	1.75	0.08	0.025	2.22	0.487	0.212	0.003	1.477	0.002	0.94	0.0002	0.94	0.015	0.001	0.002	1.20
Sperlingsholm	Topsoil	0–31	5.98	2.28	0.21	0.054	3.45	0.647	0.431	0.009	1.937	0.004	1.03	0.0006	1.87	0.042	0.002	0.005	0.92
	Mineral soil	31–50	6.01	0.52	0.06	0.028	3.09	0.464	0.421	0.003	2.254	0.007	0.82	0.0013	3.33	0.053	0.002	0.005	1.04
Härsängen	Humus layer[1]	0–37	4.51	7.36	0.35	0.039	1.82	0.309	0.128	0.007	1.290	0.003	0.96	0.0002	1.38	0.018	0.001	0.002	0.37
	Mineral soil	37–50	4.62	1.55	0.09	0.028	6.60	0.453	0.223	0.006	1.629	0.004	0.72	0.0002	1.71	0.025	0.001	0.003	1.51

mv = missing value.
[1]Mineral soil mixed with organic matter (A-horizon) included.

Table 4. *Amount of some elements in the soil profile (0–50 cm), kg ha⁻¹*

Location	N	P	K	Ca	Mg	S	Na	B	Al	Cu	Fe	Mn	Mo	Zn
Trollberget	3423	4548	18175	22867	40782	675	1118	668	119979	85	376744	6310	241	502
Degerön	1796	2568	5887	10116	14044	574	858	279	71210	25	146782	1557	123	239
Sandbäcken	8112	1917	79424	20133	16556	483	59560	141	37348	32	61147	1099	64	183
Norrekvarn	4012	762	64156	13560	5873	153	43052	42	27841	6	25899	415	39	50
Sperlingsholm	7152	2088	159088	27552	20566	315	99582	253	45518	43	119025	2231	81	254
Härsängen	6527	1079	154006	13077	6109	213	49458	119	27187	7	52357	728	45	88

below. The cultivated soil was *ca.* 31 cm deep. The bulk density of the mineral soil was *ca.* 1.1 g cm^{-3}. The *p*H of the mineral soil and topsoil was 5.8 and 6.1, respectively. The soil was relatively rich in nutrients, *e.g.* N (Tables 3, 4).

Plots 20 × 25 m in size were laid out and replicated twice. There was insufficient land suitable for further replications, and plots were relatively small. The soil in deep-cultivated plots was turned over by an excavator. The soil was deep-cultivated in March 1990, to a depth of 50–60 cm (Fig. 2b). The vegetation on control plots was treated with a herbicide (1 l glyphosate ha^{-1}) before planting, and this was repeated the following spring. The plots were planted with silver birch (*Betula pendula* Roth) in May 1990. The plots were protected by an electric fence from browsing by roe deer (*Capreolus capreolus*) and European elk (*Alces alces*). Seedlings that died during the first two years after planting were replaced (Table 2). In total, 7% of the seedlings on deep-cultivated plots, and 22% on control plots, were replanted.

Norrekvarn

Norrekvarn is also situated on forest land in Asa Experimental Forest (Fig. 1). The previous forest was a mixed pine and spruce stand that was clearfelled seven years before the experiment was established. The site was unsuccessfully regenerated in 1987 by disc-trenching and planting. The few remaining seedlings were removed from all plots before the experiment began. The soil texture was silty, with some sand and clay. The humus layer was *ca.* 11 cm thick, but there was a relatively thick horizon (*ca.* 20 cm), in which humus and mineral soil were mixed. The bulk density of the mineral soil was *ca.* 1.2 g cm^{-3}, and *p*H in the mineral soil and topsoil was 4.4 and 3.9, respectively (Tables 3, 4).

In April 1990, the soil in deep-cultivated plots was turned over by means of an excavator to 50–60 cm depth (Fig. 2b). Two of the blocks were completely tilled, and two were tilled in 1-m-wide strips 1 m apart; thus 50% of the plot was untreated. The control plots were manually patch-scarified before planting. The experimental area was fenced against browsing animals. The plots were planted with Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) in May 1990. The spruces were planted at 2 × 2 m spacing, and the Scots pines were planted close (25–30 cm) to every second Norway spruce seedling in the same planting position. The two species were mixed in a ratio of 2 : 1. Immediately after planting, the seedlings were damaged by severe night-frost in May and June 1990 (*cf.* Örlander & Langvall, 1993). Seedlings with severe damage, which had not recovered during 1990, were replaced in May 1991. On the control plots, 69% of the Scots pine was replaced, whereas the percentage in deep-tilled plots was considerably lower (17%). Corresponding figures for Norway spruce were 18% and 1% for control and deep-cultivated plots, respectively. The control plots were patch-scarified before replanting, and the field vegetation was treated with a herbicide (1 l glyphosate ha^{-1}) in 1992. The minimum temperature was recorded on the control and deep-cultivated plots twice weekly during June and July 1990. One minimum thermometer each was placed on the control area, on the completely deep-cultivated area and on both the cultivated and the untreated area of the partly scarified plots. The thermometers were placed 0.25 m and 1.5 m above the soil surface, but the 1.5 m level was omitted from the cultivated area of the partly scarified plots.

Sperlingsholm

Sperlingsholm is situated *ca.* 10 km NE of Halmstad (56°41′N, 12°55′E), on a south-east slope on former farmland (Fig. 1). The land had been used for agriculture until the year before the experiment was established. The area was covered with dense grass at the time. The soil texture was clay. The cultivated topsoil (down to the previous ploughing depth) was easily distinguished from the pure mineral soil below; the cultivated soil was *ca.* 37 cm deep. The bulk density of the mineral soil was *ca.* 1.0 g cm^{-3}. The *p*H of both the mineral soil and the topsoil was 6.0. The soil was rich in most nutrients compared to other sites in the experiment (Tables 3, 4).

Deep-cultivated plots were ploughed in April 1990 by means of a large, double farm plough (Fig. 2b). The ploughing depth was 50–60 cm. The vegetation on control plots was treated with a herbicide (1 kg ha^{-1} glyphosate) before planting, with a repeat treatment in the winters of 1990 (1 kg ha^{-1} terbutylazine and 2 kg ha^{-1} propyzamide) and 1992 (2 kg ha^{-1} propyzamide). The plots were planted with pedunculate oak (*Quercus robur* L.) and small-leaved lime (*Tilia cordata* Mill.) in May 1990. The oaks and limes were planted at a regular spacing of 1.3 × 1.3 m, and mixed in a ratio of 4:1 (oak:lime). The plots were fenced against hare (*Lepus* spp), roedeer and European elk.

Härsängen
Härsängen is situated *ca.* 20 km E of Halmstad (56°42′N, 13°20′E) on level forest land (Fig. 1). The previous forest was of mixed pine and spruce, felled in the winter of 1986–1987. A shelterwood of Scots pine was retained for natural regeneration, and the stand was scarified for the same reason. The shelterwood was wind-thrown in 1987. The site had then unsuccessfully regenerated, and only a few living seedlings remained when the experiment was established. Those seedlings were removed from all plots. The soil texture was sand. The humus layer was *ca.* 10 cm thick, but there was a relatively thick horizon (*ca.* 20 cm) in which the mineral soil had a high organic content. The bulk density of the mineral soil was *ca.* 1.5 g cm^{-3}. The *p*H of the topsoil and pure mineral soil was 4.5 and 4.6, respectively.

The soil in deep-cultivated plots was turned over to 50–60 cm depth by means of an excavator, in April 1990 (Fig. 2b). Two of the blocks were completely tilled, and two were tilled in 1-m-wide strips 2 m apart; thus 50% of the plot was untreated. The control plots were manually patch-scarified before planting. In May 1990, the plots were planted with Norway spruce (*Picea abies*) at 2 × 2 m spacing. Many seedlings were damaged by frost in the years after planting. By 1993, mortality was so high on control plots that additional planting was required. Seedlings of the same provenance were planted at the original spacing in the spring of 1994, but the replanted rows were placed between the original rows. Surviving seedlings were retained. Before replanting, the soil in the planting spots was turned over in 50 × 50 cm patches with a small excavator.

Seedling measurements

Seedling survival, damage and height were assessed after the first, second, third, fifth and tenth growing seasons after planting. Records were kept for individual trees throughout the ten years. Four classes of severity of seedling damage were recognised: undamaged, slightly damaged, severely damaged, and dead. The category severely damaged included seedlings with damage that could be expected substantially to reduce seedling height growth. The following injures were recorded: frost, drought, flood, damage related to competing vegetation, browsing, insects (mainly pine weevil, *Hylobius abietis*), and unknown. During the first five years, all seedlings were measured, except at Sperlingsholm, where every third row was assessed (owing to the large number of seedlings).

Ten years after planting, stem diameter was measured at 1.3 m height and at the root collar for trees shorter than 1.3 m. At Degerön, both height and diameter were measured on every third tree, and at Trollberget, on every tree. At the other sites, the diameter of all trees was measured, and the height of every fifth tree.

At Härsängen, a dense natural regeneration of Scots pine was established, particularly on deep-cultivated plots. The height and number of naturally regenerated trees were recoded for each species in both treatments, on each of four circular plots of area 10 m^2.

Soil sampling and analysis

Soil was sampled at the establishment of the experiments, mainly as a reference for future nutrient analysis. The samples were taken systematically over the entire experimental area, and in some cases on control plots if ploughing had been done. At least ten soil samples were collected from each site, except Trollberget, where only three samples were collected. Each soil sample was separated into two sampling levels (Table 3). The first level was pure organic material or mixed humus and mineral soil. On farmland, the former ploughing depth determined the first level. The next sample was taken in pure mineral soil down to 50 cm depth. Soil samples from each level were mixed into one composite sample for each level and site. Sample weights varied between 0.5 and 7.0 kg. Each soil sample was analysed in respect of its texture according to standard procedures, including dry-sieving and sedimentation analysis for fine particles.

The chemical analyses included the total content of N, P, K, Ca, Mg, S, Na, B, Al, Cu, Fe, Mn, Mo, and Zn for all soil samples, and the total content of C in soil samples from all southern experiments. Analyses were made by inductive-coupled plasma atomic emission spectrometry (ICP-AES, Perkin Elmer, Plasma II Emission Spectrometer; Perkin-Elmer Instruments, Shelton, CT, USA). Before analysis, the soil samples were wet-digested in 10 ml HNO_3 +1 ml $HClO_4$ and 10 ml HF. The total N and C content was analysed with a CHN elemental analyser (Perkin Elmer 2400). Soil *p*H was measured after mixing in deionised water at a ratio of 1:2 by weight (solid/extractant).

Calculations and statistical analysis

Before each test, mean values for height and diameter were calculated for each plot. The frequency of damaged and dead seedlings was also calculated per plot; data were then arcsine-square root-transformed according to Zar (1986). The general linear model (GLM) procedure of the SAS software (SAS Institute, Inc., Cary, NC, USA) for randomised block designs was used for statistical testing.

At Sandbäcken, some seedlings were replaced in the first two years after planting. These seedlings were not included in the analysis of growth and damage. At Norrekvarn, replanted seedlings did not differ significantly as regards growth and damage in the following years, and were therefore not separated in the presentations. The figures for seedlings killed during the first season are therefore not presented in Table 5, but are included in the analysis of frost damage in Fig. 3. The Norway spruce seedlings were divided into two groups before their growth was analysed. The one group consisted of seedlings planted in the same planting position as a Scots pine seedling, while the other consisted of Norway spruce planted without a neighbour. The SAS-GLM procedure for split-plot designs was used to analyse the effect of a neighbouring tree. Growth and survival of seedlings planted after the two intensities of soil treatment, complete and strip-treatment, were also statistically tested by the same procedure. Since the difference between the two soil treatments was not significant, they were not separated in subsequent analyses.

Finally, at Härsängen, original and replanted seedlings were separated in the statistical analyses. At Härsängen and Norrekvarn, an analysis of frost damage was carried out for the planting season and the following year. At Norrekvarn, where frost damage was very severe during the first growing season after planting, frost damage for this year was analysed. At Härsängen, the most severe frost damage for every seedling during the two first seasons after planting was used in the analysis. The classes analysed were severe damage, severe damage + dead, and dead.

Top height, defined as the mean height of the 100 tallest trees ha^{-1}, was calculated for all sites except Trollberget in years 5 and 10. On sites with mixed stands, the species with the largest mean height was used for this calculation.

Results

Mortality and damage

First 5 years

There was great variation in mortality and severe damage between the sites (Table 5).

At both Härsängen and Norrekvarn, low night air temperatures occurred during the first part of the growing season, and a high proportion of the damaged seedlings on these sites was injured by frost. At Norrekvarn, an analysis of the damage by frost during year 1 showed that control plots had both more dead and dead + severely damaged seedlings of both Scots pine and Norway spruce than deep-cultivated plots (Fig. 3: for Scots pine, $P = 0.0029$ for dead plants, 0.0198 for dead + severely damaged plants; for Norway spruce the corresponding P values were 0.0082 and 0.0065). An analysis of Härsängen showed that deep-cultivated plots had significantly fewer dead + severely damaged seedlings than the control plots for year 1 and 2 (Fig. 3, P value = 0.0029). The minimum air temperature at 25 cm height was 3–7 °C higher on deep-cultivated plots than on control plots at Norrekvarn (Fig. 4). The minimum temperature on strip-cultivated blocks was about the same as that on completely cultivated blocks. The minimum temperature was higher at 1.5 m than at 25 cm, and there was only one minor difference between treatments.

Year 10

Deep-cultivated plots generally had lower mortality than control plots ten years after planting,

Table 5. *Dead and severely damaged seedlings, per cent of number of planted seedlings*

			Dead					Dead + severely damaged				
Location	Tree species	Soil treatment	Year 1	Year 2	Year 3	Year 5	Year 10	Year 1	Year 2	Year 3	Year 5	Year 10
Degerön	Lodgepole pine	Control	0.7	1.1	1.1	1.3	–	0.7	1.8	1.3	3.0	
		Deep-cultivated	0.7	0.7	0.9	1.0		0.7	2.4	1.2	1.4	
Trollberget	Silver birch	Control	5.0	6.0	10.3	20.3	64.2	11.5	21.0	44.7	79.3	99.7
		Deep-cultivated	6.7	10.0	14.3	24.5	43.0	12.7	24.0	45.2	82.3	99.8
Trollberget	Norway spruce	Control	0.0	0.3	0.8	8.8	9.5	0.3	12.7	19.3	57.0	16.2
		Deep-cultivated	0.0	0.3	1.5	2.5	5.3	0.0	22.8	24.2	64.0	28.2
Sandbäcken	Silver birch	Control	0.0	15.4	20.4	20.4	33.8	12.9	28.3	29.2	32.1	35.8
		Deep-cultivated	0.0	5.8	6.7	7.5	20.0	10.4	13.8	13.3	12.1	20.0
Norrekvarn	Scots pine	Control	0.0	0.0	2.4	5.6	7.3	79.1	3.8	6.7	7.6	8.7
		Deep-cultivated	0.0	0.2	2.9	3.6	4.7	43.6	3.8	4.0	4.4	5.1
Norrekvarn	Norway spruce	Control	0.0	0.1	1.9	5.4	18.2	18.9	5.3	17.8	25.3	20.9
		Deep-cultivated	0.0	0.0	0.1	0.6	1.3	8.9	0.9	0.7	3.8	1.8
Sperlingsholm	Oak	Control	1.7	3.8	4.6	4.6	6.1	2.9	14.2	11.3	24.3	7.8
		Deep-cultivated	3.5	3.5	3.8	3.8	5.5	5.8	12.7	10.4	13.0	6.4
Sperlingsholm	Small-leaved lime	Control	2.6	3.5	3.5	3.5	4.4	2.6	7.0	5.3	3.5	5.3
		Deep-cultivated	2.6	5.3	10.5	10.5	10.5	2.6	6.1	15.8	10.5	11.4
Härsängen	Norway spruce 90	Control	1.1	2.1	19.1	28.7	43.6	13.2	66.7	56.7	76.1	55.2
		Deep-cultivated	0.0	0.1	0.1	0.2	1.3	7.9	28.6	8.7	31.9	16.1
Härsängen	Norway spruce 94	Control	1.1	12.4	12.7	12.7		10.0	21.7	50.7	47.2	

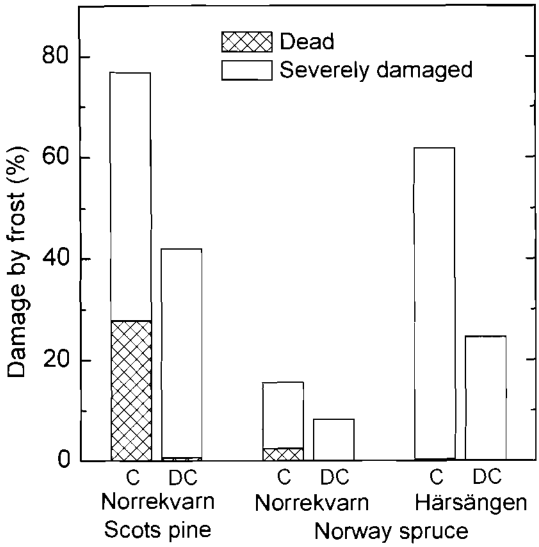

Fig. 3. Seedlings severely damaged or dead from frost during the first growing season at Norrekvarn. Accumulated values from the two first growing seasons are shown at Härsängen. At Norrekvarn both dead and dead + severely damaged seedlings are significantly different for both Scots pine and Norway spruce, but at Härsängen only dead + severely damaged seedlings are significantly different.

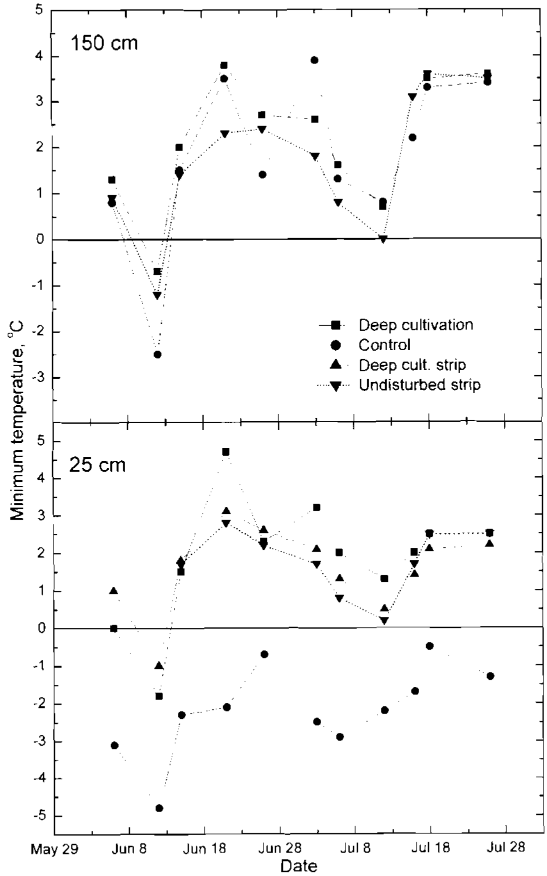

Fig. 4. Minimum temperatures at 25 cm and 1.5 m height, measured during the summer of 1990 at Norrekvarn. Deep-cultivated strip is the deep-cultivated area in the two blocks with partial deep-cultivation, and undisturbed strip is the undisturbed area in between.

excluding lime at Sperlingsholm (Table 5). The positive effect of soil treatment was statistically significant only for Norway spruce at Härsängen and Norrekvarn (P values 0.001 and 0.02, respectively). It is noteworthy that both stands planted with birch showed high mortality and severe damage (Table 5). On both sites, the cause of damage was unknown for most of the trees on which damage was recorded. At Trollberget, which was unfenced, a high proportion of severe damage was caused by browsing. Frost-heaving was recorded in the fine-textured soil at Trollberget for both birch and Norway spruce, especially on deep-cultivated plots. At Sperlingsholm, drought was the most commonly recorded cause of damage to oak seedlings.

Stand development

Five years after planting, deep-cultivation was significantly positive for height growth in Lodgepole pine at Degerön, for Norway spruce at Härsängen, for Norway spruce and Scots pine at Norrekvarn, for oak at Sperlingsholm and for Silver birch at Sandbäcken. In year 10, the significant effect of deep-cultivation remained on all plots, with the exception of birch at Sandbäcken, oak at Sperlingsholm and Scots pine at Norrekvarn (Fig. 5, Table 6). Height growth of lime at Sperlingsholm and of birch at Trollberget was not significantly affected by soil treatment, neither five nor ten years from planting. Only for Norway spruce at Trollberget was height growth on deep-cultivated plots significantly less than that on control plots. No difference was found in height growth between complete deep-cultivation, and deep-cultivation in strips, at Härsängen and Norrekvarn, since no statistically significant block effects were detected in any year (data not shown).

Ten years after planting, basal area was significantly greater for deep-cultivated plots on all sites except Sperlingsholm (Fig. 6). The basal area at Trollberget was not calculated, because of the low mean height of the trees.

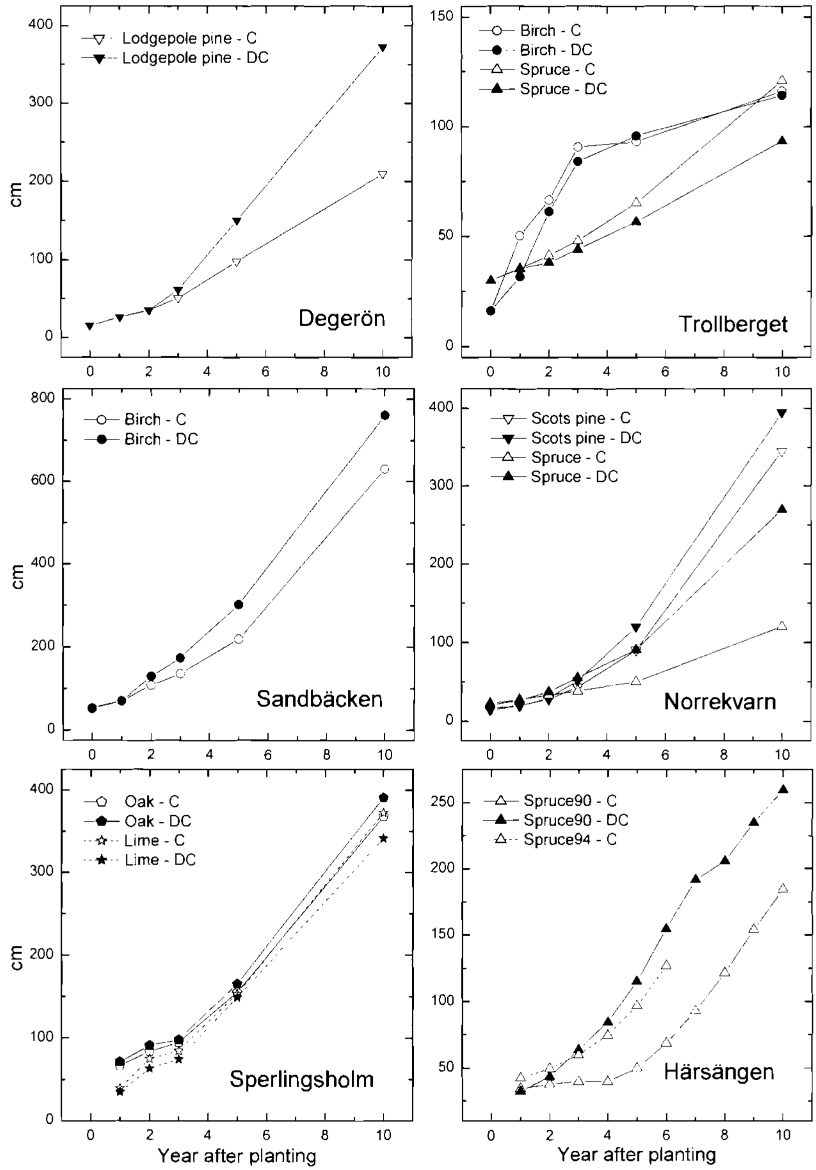

Fig. 5. Effect of soil treatment on mean tree height. C = Control plots and DC = Deep Cultivated plots. At Härsängen, Spruce90 and Spruce94 the seedlings are planted on control plots in the spring of 1990 and 1994, respectively.

At Härsängen, the deep-cultivated treatment mostly improved natural regeneration, especially for Scots pine (Table 7). Only the number of birches + others was not positively affected by deep soil cultivation. The basal area of naturally regenerated trees in year 10 was 3.4 m^2 ha^{-1} and 0.3 m^2 ha^{-1}, for the deep-cultivated and control plots, respectively.

Top height was significantly greater on deep-cultivated plots than on the control at Degerön only (Lodgepole pine, Table 8). On all other sites, soil treatment had no significant effect on top height ten years after planting. The coefficient of variation (CV) for tree height in the stands was calculated for four sites (Trollberget was excluded because of low mean tree height, and Härsängen because of replacement planting). Deep cultivation resulted in a lower CV, *i.e.* lower variability of tree height at Degerön, Sandbäcken and Norrekvarn (Fig. 7).

Table 6. *P-values from ANOVA testing for mean height, years 0–10 after planting, for the soil treatments deep-cultivated and control*

		P values					
Location	Tree species	Year 0	Year 1	Year 2	Year 3	Year 5	Year 10
Degerön	*Lodgepole pine*	0.841	0.975	0.705	0.022	0.007	0.004
Trollberget	*Silver birch*	0.845	0.003	0.113	0.126	0.662	0.452
Trollberget	*Norway spruce*	0.995	0.919	0.120	0.077	0.065	0.036
Sandbäcken	*Silver birch*	0.335	0.064	0.051	0.016	0.006	0.116
Norrekvarn	*Scots pine*	0.060	0.518	0.124	0.024	0.045	0.232
Norrekvarn	*Norway spruce*	0.247	0.443	0.017	0.0004	0.0002	0.002
Sperlingsholm	*Oak*	–	0.130	0.190	0.405	0.012	0.088
Sperlingsholm	*Small-leaved lime*	–	0.277	0.090	0.115	0.430	0.470
Härsängen	*Norway spruce 90*	–	0.031	0.011	0.001	0.003	0.004

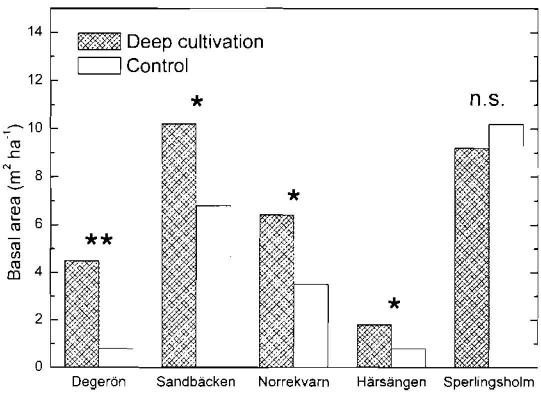

Fig. 6. Basal area for all living trees, ten years after planting, for deep-cultivated and control plots. In the mixed stands at Norrekvarn and Sperlingsholm, the figure shows the basal area for both tree species. Naturally regenerated trees were not included in the calculation.

Discussion

Damage and mortality

In general, complete soil-cultivation decreased damage and improved survival compared with the control. This was expected, and accords with previous Scandinavian studies (Örlander *et al.*, 1990, Neckelmann, 1995, 1998), whereas experiments elsewhere, *e.g.* Great Britain, have shown fewer problems with damage and mortality (Thomson & Neustein, 1973). The most significant positive effect of complete cultivation was the reduction of frost injury. This was especially evident at the frost-prone sites Norrekvarn and Härsängen (Figures 2, 3; *cf.* Kohh, 1970; Neckelmann, 1998). Competition between seedlings and field-layer vegetation was not a significant problem in the present experiment, because vegetation close to the seedlings was removed on the control plots too. Pine weevil usually causes severe damage on regeneration areas in Sweden (*e.g.* Örlander & Nilsson, 1999), but since all plots were either established on old farmland or in clearfelled areas older than four years, this insect did not cause damage in the present study. One significant disadvantage observed for complete soil-cultivation, was the increased risk of frost-heaving. This was most pronounced on the silty site at Trollberget, but the problem was evident also on other sites with fine-textured soils. An increased risk of frost-heaving was expected after deep cultivation, since fine-textured soil was brought up from deep in the soil profile (*cf.* Goulet, 1995).

Even though survival was lower on control plots than on deep-cultivated plots, this is not regarded as a problem for the future analysis of the experiments. However, there is one exception: the plots planted with Silver birch at Trollberget. Birch was established on two sites, both of which showed high mortality. We can only partly explain the reason for the poor survival of Silver birch. At Trollberget, dieback at the top of the seedlings was recorded already in the after first year after planting. A plausible explanation for this was that a fungus infected the seedlings while they were still at the nursery. The infection may have been caused by any one of several fungi, *e.g. Godronia multispora*, *Fusarium* sp, *Botrytis cinerea*, all of which give similar symptoms. Browsing damage was also recorded, as well as damage by frost-heaving, but the agents of most of the damage were

Table 7. *Natural regeneration at Härsängen in years 5 and 10. DC = Deep Cultivation and C = Control*

		Stems ha^{-1}								Height (cm)							
		Year 5				Year 10				Year 5				Year 10			
Block	Treatment	Scots pine	Norway spruce	Birch + others	Total	Scots pine	Norway spruce	Birch + others	Total	Scots pine	Norway spruce	Birch + others	Mean	Scots pine	Norway spruce	Birch + others	Mean
1	DC	25250	2500	0	27750	22700	2150	0	24850	75	44		72	208	65		196
1	C	1750	0	750	2500	3000	0	200	3200	50		43	48	99		74	97
2	DC	14750	1500	750	17000	12750	1600	0	14350	73	42	35	68	191	75		178
2	C	500	250	500	1250	3400	0	200	3600	132	18	57	79	73		90	74
3	DC	9250	3000	250	12500	7950	3200	200	11350	69	42	105	64	204	69	113	165
3	C	250	0	250	500	2000	400	200	2600	19		80	50	89	47	25	78
4	DC	6000	9000	0	15000	6350	6950	0	13300	74	40		54	199	57		125
4	C	2000	0	250	2250	2700	200	400	3300	33		110	41	83	30	126	85
All	DC	13800	4000	250	18100	12450	3500	50	15950	73	41	53	66	202	63	113	171
All	C	1100	50	450	1600	2800	150	250	3200	49	18	62	52	86	41	88	84

Table 8. *Top height, defined as the mean height of the 100 tallest trees ha⁻¹, and p-values from ANOVA*

Location	Tree species	Soil treatment	Height (cm) Year 5	Height (cm) Year 10	P values Year 5	P values Year 10
Degerön	Lodgepole pine	Control	151	315	0.014	0.023
		Deep cultivated	205	460		
Trollberget	Silver birch	Control	148	162	0.432	0.802
		Deep cultivated	151	167		
Trollberget	Norway spruce	Control	97	177	0.306	0.340
		Deep cultivated	89	158		
Sandbäcken	Silver birch	Control	337	882	0.066	0.205
		Deep cultivated	434	957		
Norrekvarn	Scots pine	Control	148	474	0.012	0.159
		Deep cultivated	183	519		
Norrekvarn	Norway spruce	Control	–	–	–	–
		Deep cultivated	–	–	–	–
Sperlingsholm	Oak	Control	211	499	0.056	0.268
		Deep cultivated	235	518		
Sperlingsholm	Small-leaved lime	Control	–	–	–	–
		Deep cultivated	–	–	–	–
Härsängen	Norway spruce 90	Control	137	434	0.002	0.633
		Deep cultivated	219	451		

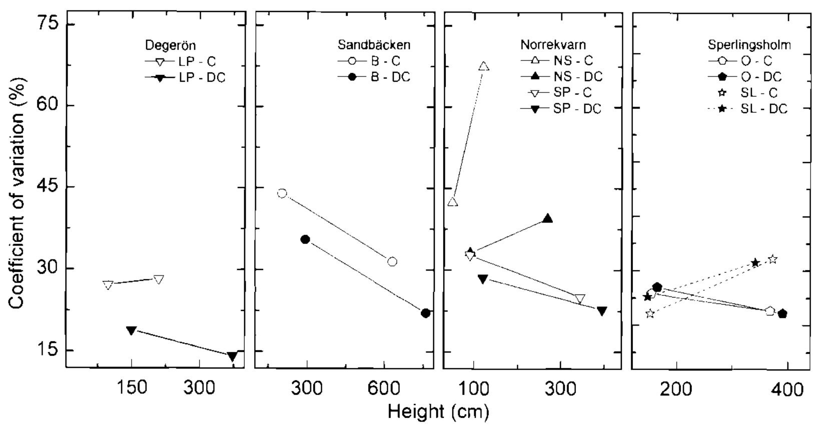

Fig. 7. The coefficient of variation for height for year 5 and 10 at four of the sites. The X-axis shows the mean height at the two inventories. C = Control plots and DC = Deep Cultivated plots. LP = Lodgepole pine, B = Silver birch, NS = Norway spruce, SP = Scots pine, O = Pedunculate oak and SL = Small-leaved lime.

unknown. Mortality was also high in the Silver birch plantation at Sandbäcken, without any obvious explanation. However, enough seedlings survived to make future assessments interesting.

At Härsängen, seedlings from the first planting on control plots were severely injured by summer frosts during the years after planting. Therefore, we decided to replant these plots in 1994. This was done slightly differently than the original planting. The same seedling type and provenance were used, but they were planted in 'inverted' patches (humus and mineral soil placed upside down) instead of in scarified patches. Inversion has proved to be a more favourable establishment method than scarified patches (*cf.* Örlander *et al.*, 1998). Seedlings from the replanting were less affected by frost injury than those originally planted. Data from the most relevant weather station (Torup, 30 km from Härsängen) showed that minimum temperatures during the frost-sensitive period did not differ for the original planting and replanting during the establishment periods. Thus it is likely that a more favourable soil treatment could decrease frost injury (*cf.* Langvall *et al.*, 2001).

Growth

In general, deep-cultivated plots showed considerably higher initial growth than control plots (Fig. 5). The positive relative effect of deep cultivation was larger for basal area (Fig. 6) than for height growth, a finding in accordance with the results of Thomson & Neustein (1973). However, since stems shorter than 1.3 m are not included when basal area is calculated, it is likely that we underestimated basal-area growth on control plots, where there are more small trees. Since basal area was calculated only for the last measurement (year 10), it was not possible to predict whether there was a different growth trend when the two soil treatments were compared. On most sites, height growth data indicated (Fig. 5) that the superiority of deep, complete cultivation, when measured in absolute terms, increased with time, whereas the relative differences tended to decrease with time. This was even more evident for top height (Table 8).

In view of the differences in damage and mortality, lower growth was expected on control plots than on deep-cultivated plots, for some years after planting. The growth reduction was most pronounced for control plots on sites where severe frost damage occurred (Norrekvarn and Härsängen), and for Lodgepole pine at Degerön. It is commonly reported that site preparation results in a relatively short positive growth response period (*e.g.* Nilsson & Örlander, 1999). The site preparation effect achieved in practice often corresponds to 0.5–1 year of growth. The effect is explicable as a result of reduced damage (*e.g.* Nilsson & Örlander, 1995; Örlander & Nilsson, 1999; Langvall, Nilsson & Örlander, 2001). Following site preparation (patches, mounds or trenches), nutrient and water availability usually improves, but with time this effect becomes less important as the seedlings' roots grow and exploit the soil outside the scarified area.

On two of the sites, no positive effect of site preparation on seedling growth was found (Trollberget and Sperlingsholm). Both sites were former farmland and both locations had fine-textured soil. At Trollberget, frost-heaving of the seedlings was certainly a major factor which reduced growth for several years, especially on deep-cultivated plots. Silty sites, such as Trollberget, are sensitive to frost-heaving (Goulet, 1995). The soil movements during frost-heaving injure fine roots, hence leads to reduced seedling growth – if the seedling survives. At Sperlingsholm, both initial damage and growth were similar for both species on control and deep-cultivated plots. Thus growth conditions were probably comparable, regardless of soil treatment. The site quality at Sperlingsholm is very good for Swedish conditions, and the farmland had produced good crops before the experiment was established. Competition between seedlings and vigorously growing grass was probably the only potential growth-limiting factor at that site. However, the vegetation was controlled by deep cultivation, and by herbicides on control plots. The vegetation, therefore, did not significantly influence seedling growth.

The long-term aim of the present experiment is to assess whether deep cultivation improves or reduces site quality. So far, the only site at which top height remained greater over the first ten years on deep-cultivated plots was that with Lodgepole pine at Degerön. Ten years after planting, soil density was still lower and competing field-layer vegetation was still sparser on deep-cultivated plots than on controls. Both factors are important to root and stem growth, and could explain the advantage of deep cultivation (*cf.* Ross & Malcolm, 1982). The positive growth response on poor sandy soil and for pine agrees well with previous findings in Swedish experiments (Örlander *et al.*, 1996). However, it would be unwise to draw conclusions about long-term growth at this early stage of the present experiment.

The results from Norrekvarn indicate that there were positive long-term effects of deep soil cultivation on height growth in Norway spruce. However, we consider that differences in frost damage caused most of the observed difference in growth between treatments. Repeated frost probably reduced growth for several years, especially on the control plot (*cf.* Langvall *et al.*, 2001). Moreover, the superior growth of Norway spruce on deep-cultivated plots probably is also an effect of differences in competition with Scots pine. Norway spruce was more damaged than was Scots pine. Since seedlings on control plots were damaged more than seedlings on deep-cultivated plots, the result was a larger size difference between the two species on control plots. This has probably favoured height growth in Scots pine, and disfavoured Norway spruce on control plots.

At Härsängen, the rate of height growth on deep-cultivated plots decreased for 6–7 years after planting (Fig. 5). It was also clearly observed that the spruce needles were yellower on deep-cultivated plots than on the control. The soil at Härsängen is acidic and relatively poor in nutrients. We therefore suspected that a nutrient deficiency had occurred. Rapid mineralisation of nutrients in the early years after deep cultivation could theoretically have caused a soil nutrient deficiency after several years (Johansson, 1994). Another hypothesis was that competition from the abundant natural regeneration of Scots pine (*cf.* Table 7) caused nutrient deficiency in spruce. Interestingly, there were no signs of nutrient deficiency in Scots pine. A small experiment was therefore established in the buffer zone of the experimental plots. The results from this study have not yet been fully evaluated, and will be reported elsewhere, but so far (at age 10), fertilisation or the removal of Scots pine and field-layer vegetation has not improved growth in spruce. The causes of growth reduction are therefore still unclear.

Stand structure

As expected, deep-cultivation resulted in a more even stand structure (*cf.* Weiner & Thomas, 1986; Nilsson & Allen, in prep.). The lower CV of height is probably a reflection of a more stable environment, a lower degree of competition and less damage during the establishment period, for seedlings planted on deep-cultivated plots than for those on control plots.

Sperlingsholm, which was intensively managed and homogeneous farmland when the experiment began, showed almost no effect of soil treatment on the CV. The relatively intensive herbicide treatment on control plots probably also decreased site heterogeneity.

Variability in forests of equal age generally increases with age or size, but at the onset of self-thinning, variability generally decreases as a result of higher mortality among smaller trees in the stand (Weiner & Thomas, 1986). The stands in this study have not yet attained their maximum leaf area, and self-thinning is very low. In the future, variability between the two soil treatments will probably decrease as a result of both self-thinning and thinning operations.

Practical considerations

The long-term effects on growth of complete deep-cultivation still remain to be evaluated. On the basis of ten years' results, we conclude that the growth and survival of conifer seedlings (Norway spruce, Scots pine and Lodgepole pine) on sandy or frost-prone sites or both, generally will benefit from deep soil-cultivation compared to patch scarification. Silty sites exposed to summer frosts are also positively affected by deep soil-cultivation, but on such sites, the risk of frost-heaving increases after deep soil-cultivation. For deciduous seedlings the result varied, but survival of birch was improved by deep soil-cultivation. Frost-heaving was also a problem for deciduous seedlings planted in fine-textured soils after deep cultivation. On former farmland, deep cultivation may be an effective way of controlling field-layer vegetation. Deep cultivation provides a more uniform environment during the establishment phase, which probably leads to reduced variability in tree size in the future stand. Soil treatment in strips, with half the surface area cultivated, seems to be equally as efficient as complete treatment.

Consideration of future uses of the experiment

With the exception of the Silver birch plots at Trollberget, regeneration has been secured at age ten, and we believe that all other sites can be used in future yield studies. The trees from the different planting occasions on control plots at Härsängen must be separated in future, since the age difference may affect the analyses. The dense natural regeneration of Scots pine on deep-cultivated plots at Härsängen may have affected the growth of Norway spruce seedlings. However, after the ten-year revision, natural regeneration was removed from that plot and the long-term effect of the pines is probably limited. The spots with two seedlings in each position (Scots pine/Norway spruce) at Norrekvarn were cleared after year 10, leaving a first choice Scots pine (undamaged trees only). Since the spots with double seedlings were mixed with plots planted with Norway spruce only, a mixed Scots pine/Norway spruce stand was created. At Sperlingsholm, a cleaning/thinning is planned for year 15, when the species mixture (oak/lime) will also be regulated. On all sites, it is important that thinning is done from below in future, in order to allow for analysis of top-height development.

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