SILVA FENNICA

Silva Fennica 43(1) research articles
www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Frost Heaving of *Picea abies* Seedlings as Influenced by Soil Preparation, Planting Technique, and Location along Gap-Shelterwood Gradients

Michelle de Chantal, Hannu Rita, Urban Bergsten, Mikaell Ottosson Löfvenius and Harald Grip

de Chantal, M., Rita, H., Bergsten, U., Ottosson Löfvenius, M. & Grip, H. 2009. Frost heaving of *Picea abies* seedlings as influenced by soil preparation, planting technique, and location along gap-shelterwood gradients. Silva Fennica 43(1): 39–50.

The effects of soil preparation, planting technique and location along gap-shelterwood gradients (position and orientation) on frost heaving damage to seedlings were studied in Vindeln Experimental Forests, northern Sweden. The forest was harvested in a grid pattern in winter 2004–2005, forming gaps and shelterwood areas of 30×40 m each. Gap-shelterwood gradients were delimited in four orientations and subdivided into five positions: 7 m and 15 m into the gap and shelterwood, and at the gap edge. At each position, three replicates of three soil preparations were made: exposed E and B horizons and HuMinMix (milled vegetation and humus layers mixed with surface mineral soil). In early October 2005, one-year-old containerized *Picea abies* (L.) Karst. seedlings were planted using four techniques: normal and deep planting, and mobile and fixed experimental containers. After one winter, frost heaving damage was highest for seedlings on B horizon combined with the mobile container (51±6%) and normal planting (43±6%). Normal- or deep-planted seedlings in HuMinMix had the least damage (5–6.6±2.5%). Compared to normal planting, deep planting reduced frost heaving damage only on B horizon. When considering the orientation, seedlings in the experimental containers had more or similar frost heaving damage than normal- or deep-planted seedlings. Along the eastern gradient, seedlings incurred more frost heaving damage in the center of the gap than under the canopy.

Keywords deep planting, normal planting, mobile container, fixed container, HuMinMix, soil horizon
Addresses *de Chantal* & *Rita*: University of Helsinki, Dept of Forest Ecology & Dept of Forest Resource Management, Helsinki, Finland; *Bergsten*, *Löfvenius* & *Grip*: Swedish University of Agricultural Sciences, Dept of Forest Ecology and Management, Umeå, Sweden
Email michelle.dechantal@helsinki.fi
Received 29 October 2007 **Revised** 3 December 2008 **Accepted** 21 January 2009
Available at http://www.metla.fi/silvafennica/full/sf43/sf431039.pdf

1 Introduction

Each spring and autumn, many seedlings are damaged by frost heaving in the boreal and temperate forests (Goulet 1995, Sahlén and Goulet 2002, de Chantal et al. 2003a, 2007). Frost heaving occurs due to ice crystals growing from below and upwards, forming needle ice at the soil surface (Goulet 1995). This occurs when near-ground air temperature is a few degrees below the freezing point and there is a constant supply of water to the freezing surface, which is often the case when there is a thin or no snow cover on the ground (Goulet 1995, Bergsten et al. 2001). During frost heaving of soil, seedlings may be totally or partly uplifted from the ground; their roots may be broken in the process, which leaves them susceptible to desiccation and prone to reduced growth in subsequent years (Goulet 1995, de Chantal et al. 2003a, 2004).

Different types of seedling containers have been tested in the past with a goal of alleviating frost heaving damage to seedlings. Containerised seedlings planted with their roots still encased in a solid-wall container or tubing are prone to frost heaving (Davidson and Sowa 1974, Low 1975, Johnson and Walker 1976) most likely because of the restricted lateral growth of roots. The smoothness of the container walls may also have made those seedlings more susceptible to frost heaving. In addition to container type, deep planting has been used to alleviate frost heaving, with variable results (Schwan 1994, Sahlén and Goulet 2002). On the other hand, various mulches or thermal insulating layers at the soil surface (Haasis 1923, Cooper 1940, Ledgard 1976, 1979, Simpson 1990, Bergsten et al. 2001) and artificial shading (Graber 1971) have been successful at reducing frost heaving, through a reduction of capillary water rise to the soil surface or in the number of frost heaving cycles. Likewise, substrates with high contents of organic matter promote seedling root growth, thus providing better anchoring of seedlings and reducing frost heaving damage (de Chantal et al. 2004).

The common practice of tree harvesting followed by soil preparation increases the risk of frost heaving. Firstly, because frost heaving and seedling mortality increase with increasing intensity or depth of soil preparation (de Chantal et al. 2003a, 2006, 2007), especially on soils with a high content of fine particles (Casa Grande 1932, de Chantal et al. 2003a). Secondly, because environmental conditions that affect frost heaving, either directly or indirectly, such as solar radiation, air and soil temperature, and soil moisture, differ according to spatial position along a canopy gap-shelterwood gradient (Gray et al. 2002, de Chantal et al. 2003a, Redding et al. 2003, Ritter et al. 2005). Near-ground radiative cooling during clear and calm nights is reduced under a canopy (Granberg et al. 1993, Ottosson Löfvenius 1998, Langvall and Ottosson Löfvenius 2002), which reduces frost heaving (de Chantal et al. 2007).

A previous study by de Chantal et al. (2007) has shown that gaps of 25 m in diameter increased frost heaving damage compared to uncut forest and gaps of ca. 15 m in diameter, especially in combination with soil preparation that exposed the B horizon. However, that result was obtained for seedlings growing in the center of gaps. In order to examine further the effect of canopy gaps, we verified whether location (position and orientation) along gap-shelterwood gradients affects frost heaving damage to seedlings. We hypothesized that seedlings in the center of canopy gaps have an increased risk of frost heaving due to the higher heat removal rate and larger diurnal temperature variation compared to seedlings in a shelterwood. At high latitudes, the incident angle of solar radiation is rather low; with a more pronounced tree shading effect, the daily total irradiance and timing of maximum irradiance varies according to orientation (Wayne and Bazzaz 1993, de Chantal et al. 2003b), which can affect the occurrence of frost heaving episodes and damage to seedlings.

Regarding planting technique, we hypothesized that frost heaving damage would be avoided, or at least reduced, if the whole seedling and the substrate in the immediate vicinity of the root plug could move as a unit when the surrounding surface soil heaved. In contrast, we also hypothesized that frost heaving damage would be avoided or reduced if the whole seedling and the substrate in the immediate vicinity of the root plug would remain stable in the soil as the surrounding surface soil heaved. This could be achieved using a seedling container with an outer surface that reduced the friction of motion between the root plug and the surrounding surface soil, thus leaving the seedling and root plug less disturbed by frost heaving. To test these hypotheses, we used experimental containers: a mobile container where roots were spread over a wide but shallow area to test the former hypothesis, and a fixed container consisting of a layer of Leca beads (porous ceramic) around the seedling's root plug to test the latter one. As references, we used deep and normal planting.

Finally, we hypothesized that a new soil preparation method, HuMinMix (same as Org.grind in Winsa 1995), which consists of milled organic matter mixed with the first 1–2 cm of mineral soil, would reduce frost heaving damage compared to conventional soil scarification that exposes the E or B horizon. A HuMinMix substrate provides increased thermal insulation at the soil surface and increased organic matter content of the growing medium (Winsa 1995), both qualities that decrease frost heaving of soil and damage to seedlings (see above).

2 Material and Methods

2.1 Study Area

The experimental site was located in Kulbäcksliden in Vindeln Experimental Forests (64º14'N, 19º47'E, 175 m a.s.l.), 65 km NW of Umeå, northern Sweden. Mixed coniferous forests on till soil dominate the area. The soil was a Cambic Podzol (FAO-Unesco, 1988) formed on glacial till with a sandy loam texture (Soil Classification Working Group, 1998). The soil profile consisted of a mor-layer of 5–10 cm in thickness, an E-horizon of 0.5–10 cm and a B-horizon of about 20 cm. The experimental site was above the highest shoreline (260 m above present sea level), such that the soil was not depleted of fine particles due to wave action. The site was also well above (5–10m) the nearby mire area and was well-drained with a groundwater depth of at least 1–1.5 m. The site was located in the cold temperate humid climate type, according to the Köppen climate classification system, with an annual temperature of +1.7°C (average 1970–1996) and annual precipitation close to 610 mm (average 1981–2006, reference climate station at Svartberget Experimental Forests, 15 km from the experimental site). The stand was 53 years old, had a stem density of 899 stem ha^{-1} and a volume of 218 m^3 ha^{-1}.

2.2 Experimental Design

The forest was harvested in a grid pattern in winter 2004–2005, forming gaps and shelterwood areas of 30 × 40 m each. We delimited gap-shelterwood gradients in each of the four cardinal directions across two gaps and the surrounding shelterwood (Fig. 1), for a total of eight gradients. Each gradient was subdivided into five positions: –15 m and –7 m into the gap, at the gap edge, as well as +7 m and +15 m into the shelterwood. At each position, three replicates (40 × 40 cm plots) of three soil preparations were laid out close together, avoiding obstacles such as stumps and roots: exposed E horizon, exposed B horizon, and HuMinMix. The HuMinMix substrate was prepared using a clearing saw equipped with a rototiller (Eco-cultivator) moved over the plot to mill the vegetation and humus layers and mix them with approximately 1–2 cm of the surface mineral soil, whereas E and B horizons were manually exposed without disturbing the soil structure.

Four one-year-old containerized *Picea abies* (L.) Karst. seedlings were planted at least 10 cm apart in the center of each soil preparation plot, avoiding obstacles, in early October 2005. Although not representative of established regeneration practices, a late planting date was chosen in order to make sure that seedlings did not have time to establish roots and thus were vulnerable to frost heaving. Seedlings were grown in a greenhouse from seeds of local provenance sown in spring 2004 in peat in multipot trays (Flexipot 1000, 288 cavities per tray, 45 cm^3 per cavity). The transplanted seedlings were 10–12 cm in height, and root plugs were maximum 10 cm in length, i.e. the depth of the tray cavities. Four planting techniques (one seedling each) were used: 1) normal planting; 2) deep planting; 3) an experimental mobile container (the whole seedling and the substrate in the immediate vicinity of the root plug are mobile); and 4) an experimental fixed container (the whole seedling and the substrate

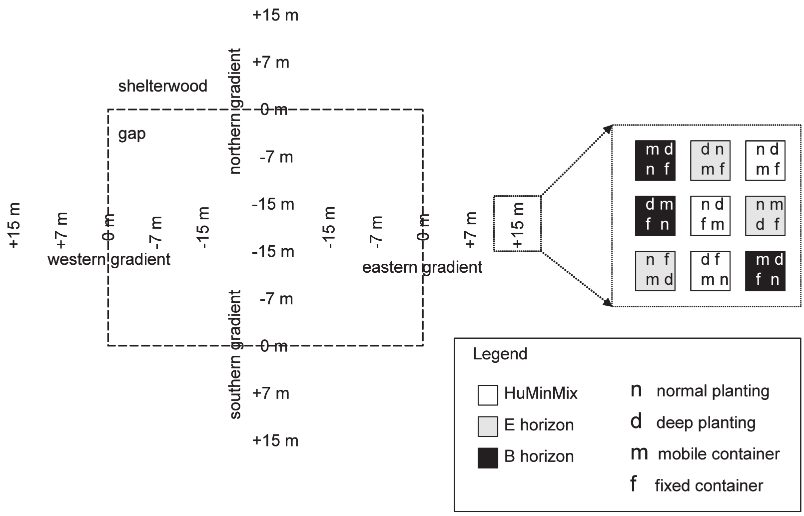

Fig. 1. Experimental design across one gap and the surrounding shelterwood.

in the immediate vicinity of the root plug remain stationary as the surrounding surface soil heaves). Normal and deep planting consisted of planting seedlings with the root collar at the soil surface and 5 cm below, respectively. To plant seedlings using the mobile container, the roots were gently untangled and spread flat over an area of 10 cm in diameter and 2 cm deep. The roots were then covered with 200–250 ml of peat mixture (95% peat, 5% sand) to form a small, gently compacted mound around the stem. To plant seedlings using the fixed container, a hole of 10 cm in depth and 7 cm in diameter was dug out using a corer. A seedling was held in the center of the hole, with the top of the root plug at the same level as the soil surface, and 200–250 ml of Leca (2–6 mm porous ceramic) beads were added to fill the area around the roots and form a small mound.

2.3 Measurements

In November 2005 and May 2006, damage to seedlings was evaluated qualitatively using the following damage categories: 1) roots exposed (partially uplifted); 2) totally uplifted seedling; 3) broken stem; 4) seedling leaning > 30º; 5) bent stem (snow damage); 6) seedling washed out by flooding; 7) partly or totally dry seedling; 8) no apparent damage. Frost heaving damage comprised categories 1–4. Dryness may or may not have been caused by broken roots due to frost heaving, therefore, it was not included in frost heaving damage categories. In the case of seedlings washed out by flooding, it is possible that they were partially or totally uplifted, or leaning, before being washed out, in which case, the damage could not be identified as caused by frost heaving. Some seedlings incurred more than one type of damage, for example, their roots were exposed and they were partly dry.

Air temperature was measured at 25 cm above the ground using small temperature dataloggers (Optic Stowaway, Onset Computer Corporation, MA, USA) in unventilated radiation shields. The dataloggers were installed in the center of each group of soil preparation plots at each position along two gradients following a transect from west to east from the western gap through shelterwood and into the eastern gap. One additional temperature logger was installed at 1.5 meter above the ground in the centre of the western gap and used as a reference for the near-ground measurements. The recording interval of all loggers was 10 minutes, except for the logger located at the edge between the western gap and the shelterwood, which by mishap was set to 40 minutes; the data has been adjusted to 10-minute intervals by interpolation, and may thus be less accurate.

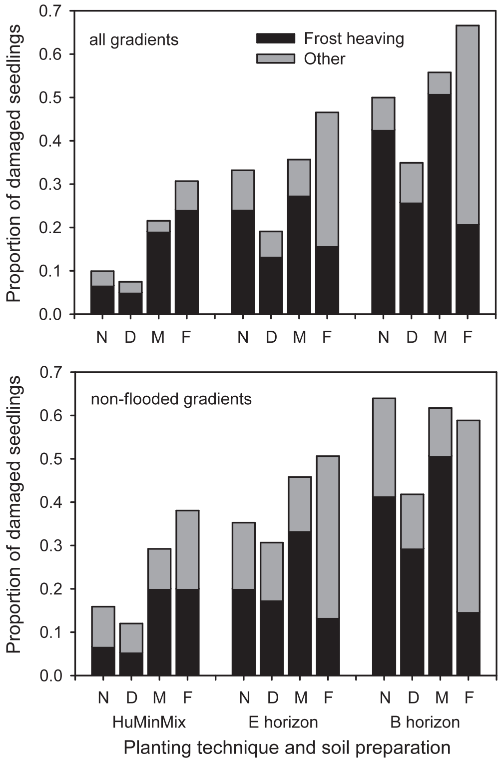

Fig. 2. Proportion of seedlings damaged by frost heaving and other causes, according to planting technique (N: normal planting, D: deep planting, M: mobile container, F: fixed container) and soil preparation. The top figure shows all gap-shelterwood gradients whereas the bottom figure shows only gradients that were not flooded during snowmelt in spring.

2.4 Statistical Analyses

As our response variable was binary (presence or absence of frost heaving or other type of damage in a seedling), logit models were used to analyze the data (Collett 1991). Although the position along the gap-shelterwood gradient was measured quantitatively, we analysed it as a five-level factor on ordinal scale. Gradient orientation (four levels), soil preparation (three levels) and planting technique (four levels) were included as factors on a nominal scale.

In logit models, comparisons of the proportions of seedlings with frost heaving or other types of damage between the levels of the four factors are represented as odds ratios. They were tested against the null "no difference" at the 0.05-level of significance (represented by odds ratios). Only first-order interactions, in addition to main effects, were estimated as there were not enough degrees of freedom for estimation of higher-order interactions. The ordinal character of the gap-shelterwood factor was taken into account by the use of linear (L) and quadratic (Q) contrasts (all with one degree of freedom). All analyses were carried out using the GENMOD procedure of SAS (SAS Institute Inc. 1989).

Part of the experimental site was very wet during snowmelt in spring and several plots under the canopy along the two replicates of the northern gradient and one replicate of the western gradient were temporarily flooded, especially the B horizon plots as they were deeper than plots on HuMinMix and E horizons. However, the means of frost heaving damage by soil preparation and planting technique with and without the flooded gradients showed little differences and relationships between treatments and soil preparations were similar (Fig. 2). Instead, differences were more obvious with other causes of damage. Therefore, we did all frost heaving damage analyses on the full set of data.

3 Results

The autumn of 2005 was warmer and drier than the average for 1981–2006 (Fig. 3). The first real frost night occurred on October 10 and appeared to be a typical radiation frost (Fig. 4). Above-zero temperatures at the end of October replaced a cold period and lasted until the middle of November. During the period before snow covered the ground permanently, i.e. 3 October–1 December 2005, the number of days with a temperature both below and above 0 °C was higher in the center of the gaps and decreased towards the center of the shelterwood (Fig. 5).

Gradient orientation, position along the gap-shelterwood gradient, soil preparation and planting technique all had an effect on the proportion of *Picea abies* seedlings with frost heaving and other types of damage (Table 1). Moreover, the effect of gradient orientation differed between

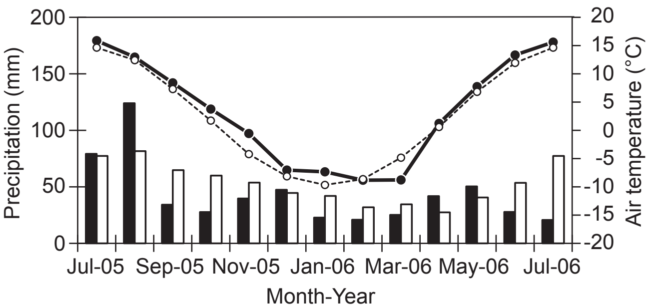

Fig. 3. Average air temperature (solid line) and precipitation (filled bar) during the study period compared with the long-term average 1981–2006 (dashed line and open bar) from the reference climate station at Svartberget Experimental Forests, about 15 km from the experimental site.

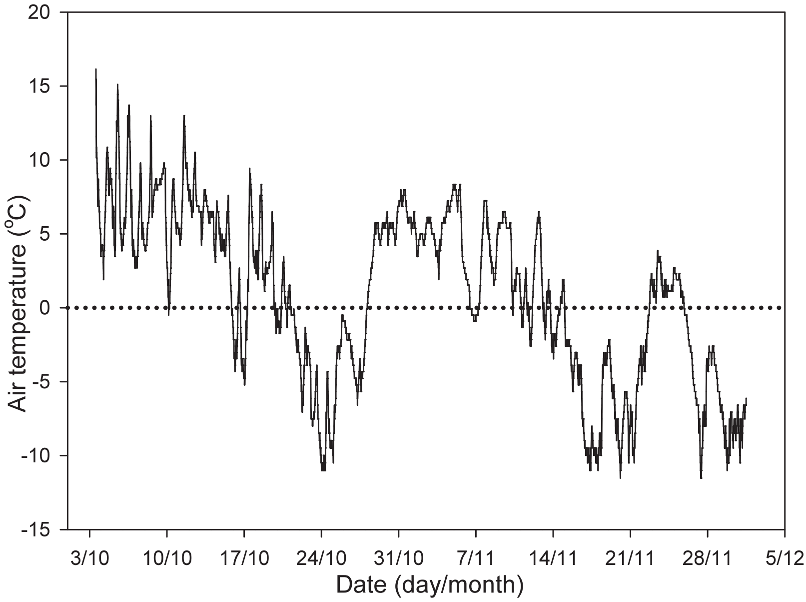

Fig. 4. Air temperature (10-minute intervals) at 1.5 meter above the ground in the center of the gap for the period of 3 October–1 December, 2005.

positions along gap-shelterwood gradients and planting technique, and the effect of planting technique varied according to soil preparation (Table 1).

Frost heaving damage increased with increasing depth of soil preparation with each planting technique and was highest for seedlings on B horizon combined with the mobile container or normal planting (Fig. 2). Other types of damage, i.e. dryness, bent stem, or flooding, were highest for seedlings in the fixed container on E and B horizons (Fig. 2). Total damage was greatest on B horizon (up to 51 ± 6%), regardless of planting technique. Seedlings planted in HuMinMix using normal or deep planting had the least damage (5–6.6 ± 2.5%).

Compared to normal planting, deep planting reduced frost heaving damage on B horizons, but there was no difference on HuMinMix and E horizon (Table 2). On HuMinMix, the proportion of seedlings with frost heaving damage was higher with the mobile or fixed containers than

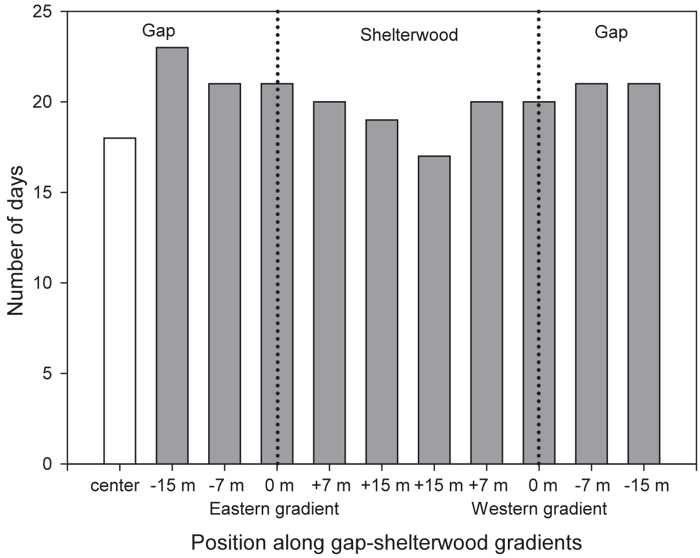

Fig. 5. Number of days with the maximum temperature above 0°C and minimum temperature below 0°C during the period of 3 October–1 December, 2005 along two adjacent gap-shelterwood gradients. White bar: air temperature at 1.5 m above the soil surface; grey bars: air temperature at 25 cm above the soil surface.

Table 1. Statistical testing of the main and interaction effects of gradient orientation, position along the gap-shelterwood gradient, soil preparation and planting technique on the proportion of *Picea abies* seedlings with frost heaving and other types of damage.

Parameter	d.f.	Frost heaving damage χ^2	p	Other damage χ^2	p
Orientation (O)	3	51.82	<0.001	18.73	<0.001
Position (P)	4	20.98	<0.001	12.41	0.015
Soil preparation (S)	2	57.09	<0.001	18.69	<0.001
Planting technique (T)	3	35.13	<0.001	56.22	<0.001
O × P	12	42.68	<0.001	21.33	0.046
O × S	6	5.30	0.506	8.10	0.231
O × T	9	25.97	0.002	28.85	<0.001
P × S	8	6.54	0.587	17.11	0.029
P × T	12	12.71	0.391	12.30	0.422
S × T	6	36.33	<0.001	13.31	0.038

with normal or deep planting (Table 2, Fig. 2). There was no difference in other types of damage between planting techniques on HuMinMix. On E and B horizons, seedlings in the mobile container incurred more frost heaving damage than deep-planted seedlings. However on B horizon, the proportion of seedlings with frost heaving damage was lower with the fixed container than with normal planting. The proportion of seedlings that incurred other types of damage on E and B horizons was greater with the fixed container than with normal or deep planting (Table 2).

When considering the orientation, the proportion of frost heaving damage was higher with the mobile or fixed containers than with deep planting in the northern and eastern gradients (Table 3, Fig. 6). In the western gradient, the proportion of frost heaving damage was higher with the mobile container than with normal or deep planting (Table 3). However, seedlings incurred less frost heav-

Table 2. Estimated values of odds ratios[a] for differences between planting techniques in the proportion of *Picea abies* seedlings with frost heaving and other types of damage represented separately for the three soil preparations.

Comparison of planting techniques	HuMinMix odds ratio	*p*	E horizon odds ratio	*p*	B horizon odds ratio	*p*
Frost heaving damage:						
Deep vs normal	1.02^{-1}	0.638	1.11^{-1}	0.061	1.18^{-1}	0.025
Mobile vs normal	1.13	0.009	1.03	0.628	1.09	0.322
Fixed vs normal	1.19	<0.001	1.09^{-1}	0.122	1.24^{-1}	0.003
Mobile vs deep	1.15	0.003	1.15	0.032	1.28	0.002
Fixed vs deep	1.21	<0.001	1.03	0.611	1.05^{-1}	0.406
Other damage:						
Deep vs normal	1.01^{-1}	0.697	1.03^{-1}	0.377	1.02	0.694
Mobile vs normal	1.01^{-1}	0.697	1.02^{-1}	0.633	1.03^{-1}	0.488
Fixed vs normal	1.03	0.258	1.24	0.001	1.47	<0.001
Mobile vs deep	1.00	1.000	1.02	0.631	1.04^{-1}	0.236
Fixed vs deep	1.04	0.144	1.28	<0.001	1.44	<0.001

Soil preparations: HuMinMix, E horizon, B horizon.

[a] To make odds ratios for increasing and decreasing proportions comparable, we always represent odds ratios as numbers larger than 1. Exponent –1 indicates that a smaller proportion has been compared to a larger one. For example, if 10% is compared to 5%, the odds ratio is 2.11; if 5% is compared to 10%, the odds ratio is 0.473, which is equal to 2.11^{-1}.

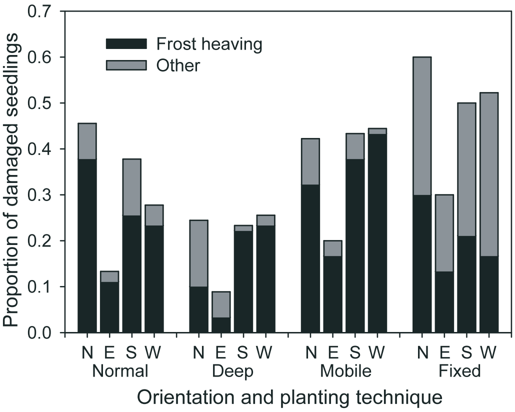

Fig. 6. Proportion of seedlings damaged by frost heaving and other causes, according to orientation and planting technique.

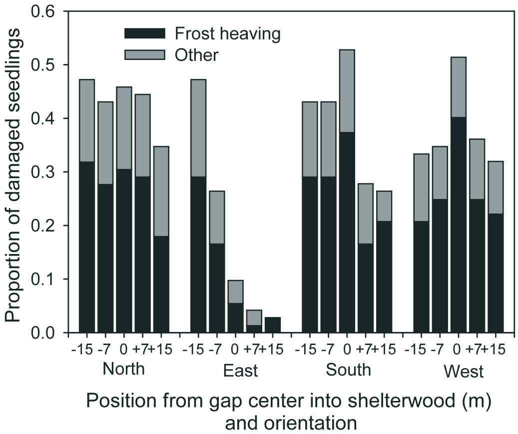

Fig. 7. Proportion of seedlings damaged by frost heaving and other causes at different positions along gap-shelterwood gradients in each orientation.

ing damage with deep planting than with normal planting in the northern gradient. There were no differences between planting techniques in the southern gradient. The proportion of seedlings with other types of damage was greater with the fixed container than with normal or deep planting, except between the fixed container and deep planting in the northern gradient (Table 3, Fig. 6).

Along the eastern gradient, the proportion of seedlings with frost heaving damage was much larger in the center of the gap than under the canopy (odds ratio 1.98^{-1}); the decrease in the proportion of frost heaving damage towards the shelterwood was slightly convex (Table 4, Fig. 7). The proportion of seedlings with other types of damage was also greater in the center of the gap than under the shelterwood along the eastern gradient (Table 4, Fig. 7).

Table 3. Estimated values of odds ratios[a] for differences between planting techniques in the proportion of *Picea abies* seedlings with frost heaving and other types of damage represented separately for the four orientations.

Comparison of planting techniques	Orientation North odds ratio	*p*	East odds ratio	*p*	South odds ratio	*p*	West odds ratio	*p*
Frost heaving damage:								
Deep vs normal	1.13^{-1}	<0.001	1.08^{-1}	0.065	1.03^{-1}	0.684	1.00	1.000
Mobile vs normal	1.06^{-1}	0.523	1.06	0.390	1.13	0.157	1.22	0.037
Fixed vs normal	1.08^{-1}	0.326	1.02	0.676	1.05^{-1}	0.517	1.07^{-1}	0.376
Mobile vs deep	1.25	0.001	1.14	0.020	1.17	0.086	1.22	0.027
Fixed vs deep	1.22	<0.001	1.11	0.021	1.01^{-1}	0.879	1.07	0.328
Other damage:								
Deep vs normal	1.07	0.200	1.03	0.302	1.12^{-1}	0.011	1.02^{-1}	0.399
Mobile vs normal	1.02	0.597	1.01	0.647	1.07^{-1}	0.160	1.03^{-1}	0.167
Fixed vs normal	1.25	0.006	1.16	0.005	1.18	0.042	1.36	<0.001
Mobile vs deep	1.05^{-1}	0.679	1.02	0.512	1.05	0.088	1.01^{-1}	0.561
Fixed vs deep	1.17	0.066	1.12	0.048	1.32	<0.001	1.40	<0.001

[a] See note on Table 2.

Table 4. Estimated value of odds ratios for differences between the five positions along the gap-shelterwood gradients in the proportion of *Picea abies* seedlings with frost heaving and other types of damage represented separately for the four orientations.

Orientation	Linear[a]	*p*	Quadratic[b]	*p*
Frost heaving damage:				
North	1.30^{-1}	0.170	1.20^{-1}	0.426
East	1.98^{-1}	<0.001	1.42	0.017
South	1.34^{-1}	0.144	1.23^{-1}	0.376
West	1.03	0.895	1.56^{-1}	0.077
Other damage:				
North	0.03	0.874	0.03	0.893
East	1.54^{-1}	<0.001	0.15	0.221
South	1.21^{-1}	0.236	1.18^{-1}	0.390
West	1.04^{-1}	0.815	0.01	0.947

[a] Values of the parameter estimate exceeding 1 indicate an increase in the proportion of damaged seedlings with increasing distance from the center of the gap; values smaller than 1 indicate a decrease.
[b] Values of the parameter estimate exceeding 1 indicate a concave change in the proportion of damaged seedlings with increasing distance from the center of the gap; values smaller than 1 indicate a convex change.

4 Discussion

The manual soil preparation used in this study simulated patch scarification or disc trenching to various depths, which are common soil preparations in Fennoscandia. However, the quality of manual soil preparation was more uniform and the soil structure was less disturbed compared with mechanical soil preparation. While this may not represent operational conditions, the data was not confounded by the effect of non-uniform soil preparation, e.g. due to spatial variation in horizon thickness or disturbed soil structure resulting from the mechanical dislodging of stones or roots. Since frost heaving increases with intensity of soil preparation and disturbance of soil structure (de Chantal et al. 2006, 2007), the frost heaving damage observed under operational conditions may be higher than that reported in this study.

Frost heaving damage increased with increasing depth of soil preparation with each planting technique, which agrees with other recent results by the same team (de Chantal et al. 2006, 2007). Normal and deep planting on the HuMinMix substrate were most effective in reducing frost heaving damage. Since there was no difference between these two techniques on HuMinMix and E horizon, there was no advantage of deep planting using these soil preparations. With HuMinMix, the thermal insulation provided by the milled vegetation and humus were effective in reducing frost heaving, similarly as with unmilled humus (Sahlén and Goulet 2002, de Chantal et al. 2007). The advantage of planting in HuMinMix over planting in unmilled humus is that decomposition may be accelerated and nutrient availability increased in milled humus (Winsa 1995).

Results with the experimental containers did not confirm our hypotheses. Seedlings in mobile containers always incurred more frost heaving damage than with normal or deep planting. Because these seedlings had a wide but shallow root plug, uneven heaving could have caused them to lean. Were it not for the late planting date, leaning may have been reduced or prevented if these seedlings had had enough time to grow roots and become firmly anchored in the soil. Although seedlings in the fixed container incurred less frost heaving damage than with normal planting on B horizon, damage was comparable to that with normal or deep planting on E horizon, but was even worse on HuMinMix. The increased frost heaving damage with the fixed container on HuMinMix may have been due to the removal of the insulating layer of milled humus around the root plug. The results with the fixed container (on all soil preparations) may also have been confounded by the fact that the growing medium around the root plug (Leca beads) was different than with the other planting techniques. Therefore, there was no advantage of having a container with an outer surface that reduced the friction of motion between the root plug and the surrounding surface soil instead of proper root anchoring. Furthermore, seedlings in the fixed containers were at risk of being uprooted by flooding in spring, especially on B horizon in wet areas, because of the low density of the Leca beads used. They also suffered from dryness more often than seedlings planted using other techniques. Therefore, seedlings that are properly anchored in the soil have the best prognosis of being able to sustain frost heaving damage since they can better withstand soil movement (Goulet 1995, de Chantal et al. 2004). Good anchoring can be insured either through early planting to allow sufficient time for root growth to take place (Luoranen et al. 2006) or through planting in a substrate rich in organic matter and nutrients that promotes fast and ample root growth (de Chantal et al. 2004).

Contrary to previously reported findings for frost heaving damage to one-month-old containerized seedlings planted in uncut forest versus canopy gap (de Chantal et al. 2007), there was no difference in frost heaving damage to 1-year-old containerized seedlings planted in the gap versus shelterwood, except along the eastern gradient. This contradictory result may be due to the fact that large seedlings such as those used in this study are more resistant to frost heaving than small seedlings (Goulet 1995). In addition, the difference in the near ground temperature is less pronounced between canopy gap and shelterwood (this study) than between uncut forest and canopy gap (de Chantal et al. 2007), which may also explain the contradicting results. Another explanation can be the small size of our shelterwood patches: conditions within 15 m into the shelterwood may have been more like those in an extended gap edge than in uncut forest since the spatial extent of a canopy gap is not restricted to the physical edge of the gap (Gray et al. 2002, de Chantal et al. 2003b, Redding et al. 2003, Ritter et al. 2005). Due to the angle of the sun at northern latitudes and the path of the sun's trajectory, gap conditions often extend non-uniformly across the physical gap edges according to orientation (Geiger et al. 1995). For example, conditions in the shelterwood at the northern edge of a gap may be similar to conditions in the northern part of the gap. This could explain the small differences in the number of freezing/thawing days between positions along the gap-shelterwood gradients as shown on Fig. 3. Soil preparation, large stones, and the local topography (e.g. a nearby slope) may have introduced air movements and turbulent mixing that counteracted the build-up of near-ground radiative-cooled air. Therefore, if the aim is to reduce frost heaving damage to seedlings by planting under a forest canopy, the extended gap edge should be taken into account.

5 Conclusion

To reduce the risk of frost heaving damage, we suggest to plant seedlings in HuMinMix or E horizon substrates using normal planting. If exposing the B horizon is necessary, e.g. if the E horizon is thin and thus easily disturbed by soil scarification, deep planting (5 cm below the surface) is preferable over normal planting. There seems to be no clear advantage of using or developing a seedling container that would allow seedlings to be either more mobile or more fixed with respect to the soil surface. Instead, planting seedlings in a conventional way at normal or deeper depth, depending on the soil preparation used, should be used to reduce frost heaving damage.

There was no clear effect of position along gap-shelterwood gradients, except along the eastern gradients where frost heaving damage was twice as low in the shelterwood as in the gap. There could be a critical size of gaps that makes the risk of frost heaving as low as in shelterwood or uncut forest.

References

Bergsten, U., Goulet, F., Lundmark, T. & Ottosson Löfvenius, M. 2001. Frost heaving in a boreal soil in relation to soil scarification and snow cover. Canadian Journal of Forest Research 31(6): 1084–1092.

Casa Grande, A. 1932. Discussion of ”A new theory of frost heaving”. Proceedings of the Highway Research Board. II: 168–172.

Collett, D. 1991. Modelling binary data. Chapman & Hall, London. 369 p.

Cooper, W.E. 1940. Frost heaving and damage to Black Locust seedlings. Ecology 21(4): 501–504.

Davidson, W.H. & Sowa, E.A. 1974. Container-grown seedlings show potential for afforestation of Pennsylvania coal-mine spoils. Tree Planters' Notes 25(4): 6–9.

de Chantal, M., Leinonen, K., Ilvesniemi, H. & Westman, C.J. 2003a. Combined effects of site preparation, soil properties, and sowing date on the establishment of Pinus sylvestris and Picea abies from seeds. Canadian Journal of Forest Research 33(5): 931–945.

— , Leinonen, K., Kuuluvainen, T. & Cescatti, A. 2003b. Early response of Pinus sylvestris and Picea abies seedlings to an experimental canopy gap in a boreal spruce forest. Forest Ecology and Management 176(1–3): 321–336.

— , Leinonen, K., Ilvesniemi, H. & Westman, C.J. 2004. Effects of site preparation on soil properties and on morphology of Pinus sylvestris and Picea abies seedlings sown at different dates. New Forests 27(2): 159–173.

— , Rita, H., Bergsten, U., Ottosson Löfvenius, M. & Grip, H. 2006. Effect of soil properties and soil disturbance on frost heaving of mineral soil: a laboratory experiment. Canadian Journal of Forest Research 36(11): 2885–2893.

— , Hanssen, K.H., Granhus, A., Bergsten, U., Ottosson Löfvenius, M. & Grip, H. 2007. Frost heaving damage to one-year-old Picea abies seedlings increases with soil horizon depth and canopy gap size. Canadian Journal of Forest Research 37(7): 1236–1243.

FAO-Unesco 1988. Soil Map of the World. Revised Legend. World Soil Resources Report 60, Rome, Italy. 119 p.

Geiger, R., Aron, R. & Todhunter, P. 1995. The climate near the ground. 5th ed. Harvard University Press, Cambridge, Mass., USA. 528 p.

Goulet, F. 1995. Frost heaving of forest tree seedlings: A review. New Forests 9: 67–94.

Graber, R.E. 1971. Frost heaving seedling losses can be reduced. Tree Planters' Notes 22(4): 1–5.

Granberg, H.B., Ottosson Lofvenius, M. & Odin, H. 1993. Radiative and aerodynamic effects of an open pine shelterwood on calm, clear nights. Agriculture and Forest Meteorology 63(3–4): 171–188.

Gray, A.N., Spies, T.A. & Easter, M.J. 2002. Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests. Canadian Journal of Forest Research 32(2): 332–343.

Haasis, F.W. 1923. Frost heaving of Western Yellow Pine seedlings. Ecology 4(4): 378–390.

Johnson, H.J. & Walker, N.R. 1976. Five-year field performance of Pine and Spruce styroplugs in Alberta. Forestry Chronicle 52(4): 197–198.

Langvall, O. & Ottosson Löfvenius, M. 2002. Effect of shelterwood density on nocturnal near-ground temperature, frost injury risk and budburst date of Norway spruce. Forest Ecology and Management 168(1–3): 149–161.

Ledgard, N.J. 1976. Research into the direct seeding of woody plants in high country revegetation. New Zealand Journal of Forestry 21(2): 253–264.
— 1979. First-year losses of Pinus mugo seed and seedlings on an exposed high-country subsoil. New Zealand Journal of Forestry 24(1): 90–100.
Low, A.J. 1975. Production and use of tubed seedlings. Forestry Commission, Bulletin 53. 46 p.
Luoranen, J., Rikala, R., Konttinen, K. & Smolander, H. 2006. Summer planting of Picea abies container-grown seedlings: Effects of planting date on survival, height growth and root egress. Forest Ecology and Management 237(1–3): 534–544.
Ottosson Löfvenius, M. 1998. Temperature and radiation regimes in selective thinned forest stand. In: Haataja, S. & Murtovaara, I. (eds). New stand types in boreal forestry – ecological features and silvicultural consequences. Proceedings of a Nordic symposium, February 10–11, 1998, Vaasa, Finland. Metla, Vantaa, Finland. p. 29–32.
Redding, T.E., Hope, G.D., Fortin, M., Schmidt, M.G. & Bailey, W.G. 2003. Spatial pattern of soil temperature and moisture across subalpine forest-clearcut edges in the southern interior of British Columbia. Canadian Journal of Soil Science 83(1): 121–130.
Ritter, E., Dalsgaard, L. & Einhorn, K.S. 2005. Light, temperature and soil moisture regimes following gap formation in a semi-natural beech-dominated forest in Denmark. Forest Ecology and Management 206(1–3): 15–33.
Sahlén, K. & Goulet, F. 2002. Reduction of frost heaving of Norway spruce and Scots pine seedlings by planting in mounds or in humus. New Forests 24(3): 175–182.
SAS Institute Inc. 1989. SAS/STAT. User's guide. Version 6. SAS Institute Inc, Cary, N.C. p. 891–1676.
Schwan, T. 1994. Planting depth and its influence on survival and growth: a literature review with emphasis on jack pine, black spruce, and white spruce. Northeast Science and Technology Technical Report TR-017. Northeast Science and Technology, Ontario, Canada. 36 p.
Simpson, D.G. 1990. Seedbed coverings affect germination, growth, and frost heaving in bareroot nurseries. Tree Planters' Notes 41(4): 13–16.
Soil Classification Working Group. 1998. The Canadian system of soil classification, 3rd ed. Agriculture and Agri-Food Canada Publication 1646. NRC Press, Ottawa, Ontario, Canada. 187 p.
Wayne, P.M. & Bazzaz, F.A. 1993. Morning vs afternoon sun patches in experimental forest gaps: Consequences of temporal incongruency of resources to birch regeneration. Oecologia 94(2): 235–243.
Winsa, H. 1995. Effects of seed properties and environment on seedling emergence and early establishment of Pinus sylvestris L. after direct seeding. Doctoral disseration, Swedish University of Agricultural Sciences, Umeå. 26 p. + 5 papers. ISBN 91-576-7982-0

Total of 33 references