Dissertationes Forestales 80

Soil hydrological properties and conditions, site preparation, and the long-term performance of planted Scots pine (*Pinus sylvestris* L.) on upland forest sites in Finnish Lapland

Kari Mäkitalo

Department of Forest Ecology
Faculty of Agriculture and Forestry
University of Helsinki

Academic dissertation

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Author: Kari Mäkitalo

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Thesis Supervisors:
Dr. Juha Heiskanen
Finnish Forest Research Institute (Metla) Suonenjoki Research Unit, Finland
Prof. Leena Finér
Finnish Forest Research Institute (Metla) Joensuu Research Unit, Finland
Prof. Pasi Puttonen
Finnish Forest Research Institute (Metla) Vantaa Unit, Finland
Dr. Martti Varmola
Finnish Forest Research Institute (Metla) Rovaniemi Research Unit, Finland

Pre-examiners:
Prof. Lars Lundin
Swedish University of Agricultural Sciences, Department of Soil and Environment, Uppsala, Sweden
Prof. Göran Örlander
Södra Skogsägarna, Växjö, Sweden

Opponent:
Docent Ari Laurén
Finnish Forest Research Institute (Metla) Joensuu Research Unit, Finland

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ABSTRACT

Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) forests, which differ from each other both ecologically and economically, predominate in Finnish Lapland. The need to study the effect of both soil factors and site preparation on the performance of planted Scots pine has increased due to the problems encountered in reforestation, especially on mesic and moist, formerly spruce-dominated sites. This thesis examines the soil hydrological properties and conditions, and related physical properties, on 10 pine- and 10 spruce-dominated upland forest sites in Finnish Lapland. The long-term effects of site preparation on soil factors are also studied. Finally, the effects of both site preparation and reforestation methods, as well as soil hydrological factors, on the long-term performance of planted Scots pine are summarized.

In general, the soil properties were comparable to those reported earlier for till soils in Finnish Lapland and Fennoscandia. The results showed that pine and spruce sites in Lapland have significantly different soil physical properties. Under field capacity or wetter soil moisture conditions, planted pines presumably suffer from excessive soil water and poor soil aeration on most of the originally spruce sites, but not on the pine sites. The studies also suggested that the changes in soil physical properties and organic matter content due to site preparation may affect the soil water regime and, as a result, the prerequisites for forest growth for more than two decades after site preparation. The air-filled porosity at field capacity (–10 kPa) and *in situ* in the ploughed ridges were significantly higher, and the bulk density and in situ soil water content lower than in the untreated intermediate areas.

There was high variation in the survival and mean height of the planted pines. The study suggested that on formerly spruce-dominated sites, pine survival is the lowest on sites that dry out slowly after rainfall events, and that height growth is the fastest on soils that reach favourable aeration conditions for root growth rapidly after saturation, and/or where the average air-filled porosity near field capacity is large enough for good root growth. Survival, but not mean height, could be enhanced by employing intensive site preparation methods like ploughing instead of lighter site preparation methods on spruce sites. From the point of view of survival, there seems to be a relatively broad assortment of site preparation methods suitable for coarser-textured pine sites. Site preparation methods affecting the nutrient status of the soil, such as ploughing and especially prescribed burning, seem to enhance the height growth of Scots pine over several decades after reforestation on formerly pine-dominated sites.

The use of soil water content *in situ* as the sole criterion for sites suitable for pine reforestation was tested and found to be a relatively uncertain parameter. However, the thesis identified new potential soil variables, such as the water retention curve parameters α and n, affecting either the long-term survival or height growth of planted Scots pine. The use of these variables as criteria for sites suitable for pine should be tested using other data in the future.

Keywords: Artificial regeneration, disk trenching, patch scarification, till soil, van Genuchten function

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LIST OF ORIGINAL ARTICLES

The thesis is based on the following articles, which are referred to in the text by their Roman numerals. The articles are reprinted with kind permission of the publishers.

I Heiskanen, J. & Mäkitalo, K. 2002. Soil water-retention characteristics of Scots pine and Norway spruce forest sites in Finnish Lapland. Forest Ecology and Management 162: 137–152.

II Heiskanen J., Mäkitalo, K. & Hyvönen, J. 2007. Long-term influence of site preparation on water-retention characteristics of forest soil in Finnish Lapland. Forest Ecology and Management 241: 127–133.

III Mäkitalo, K. & Hyvönen, J. 2004. Late-summer soil water content on clear-cut reforestation areas two decades after site preparation in Finnish Lapland. Forest Ecology and Management 189: 57–75.

IV Mäkitalo, K., Heiskanen, J. & Hallikainen, V. 2006. Long-term effect of ploughing on soil hydrology in northern Finland. In: Amatya, D.M. & Nettles, J. (Eds.). Hydrology and Management of Forested Wetlands. Proceedings of the International Conference, April 8–12, 2006, New Bern, North Carolina. ASABE, Michigan, USA. p. 284–291.

V Mäkitalo, K. 1999. Effect of site preparation and reforestation method on survival and height growth of Scots pine. Scandinavian Journal of Forest Research 14: 512–525.

VI Mäkitalo, K., Alenius, V., Heiskanen, J. & Mikkola, K. 2008. Effect of soil physical properties on the performance of planted Scots pine in Finnish Lapland. Submitted manuscript.

AUTHOR'S CONTRIBUTION

The author is fully responsible for the text of this doctoral thesis. He participated in planning all the articles together with the co-authors. The author was partly responsible for the field-work in article I, and fully in articles II, III, IV and VI, partly responsible for the laboratory measurements in articles I, II, IV and VI, and fully in article III. He participated in the statistical analysis of the data in all the articles, and was fully responsible for the water retention modelling in articles II and VI. He participated in writing the articles I and II, and was fully responsible the articles III, IV and VI as the corresponding author.

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1 INTRODUCTION

1.1 Background

Finnish Lapland is one of the northernmost parts of the world with a coniferous forest cover (Hustich 1952). It belongs to the northern boreal zone, where old-growth Norway spruce (*Picea abies* (L.) Karst.) or downy birch (*Betula pubescens* Ehrh.) stands commonly dominate on upland mesic heath forest sites, e.g. on HMT (*Hylocomium-Myrtillus* Type) sites. In contrast, Scots pine (*Pinus sylvestris* L.) typically occupies upland sub-xeric heath forest sites, e.g. EVT (*Empetrum-Vaccinium* Type) and EMT (*Empetrum-Myrtillus* Type) sites (Cajander 1949, Siren 1955, Hotanen et al. 2008). In Finnish Lapland, Scots pine and Norway spruce are the main tree species, dominating 76.8% and 15.7%, respectively, of the total forestland area (Finnish Statistical... 2007). Broadleaf species, mainly downy birch, are dominant on 7.5% of the area. The majority of Finnish forests are located on till soils (Kujansuu, 1985), the most common type of which is fine sandy till (Virkkala 1969, Haavisto 1983, Tamminen 1991). In Lapland, as in the rest of Finland, most of the mineral soils are ferric or haplic Podzols with an overlying mor layer a few centimeters thick (Sepponen et al. 1979, FAO 1990, Tamminen and Tomppo 2008). The climate in Finnish Lapland is relatively severe. However, the proximity of the Gulf Stream, prevailing south-westerly winds and the relatively low topography make the climate milder than in parts of Siberia, Alaska and northern Canada located at the same latitudes (Pohtila 1977).

Sustainable forestry is practiced in Finnish Lapland north of latitude 69^{o}, i.e. farther north than anywhere else in the world, and the region has a highly developed forest industry (Varmola et al. 2004). Forest cuttings increased after the Second World War and, since the late 1950s, clear-cutting and artificial regeneration with conifers have been the most common way to regenerate forests in Finnish Lapland. In 2006, for example, the proportion of clear-cutting combined with artificial regeneration was 69.2%, and that of natural regeneration using the seed tree or shelter-wood method 30.8%, of the total regeneration area of 16 800 ha (Finnish Statistical... 2007).

In Finnish Lapland, forest sites are commonly prepared mechanically prior to reforestation, because site preparation reduces the high soil water content and increases the soil temperature in planting spots, thus improving the reforestation conditions (Leikola 1974, Lähde 1978, Lähde et al. 1981, Salonius 1983, Örlander et al. 1990a, Kubin and Kemppainen 1994). Intensive site preparation has been widely used in forest reforestation since the 1960s (Pohtila 1977). Reforestation ploughing was originally developed to improve the site conditions on peatlands. In the late 1960s, however, ploughing almost completely displaced other site preparation methods on upland sites as well (Pohtila 1977). Over half a million hectares have been ploughed in Finnish Lapland. Since the early 1990s, the use of ploughing has strongly diminished and the use of lighter methods such as patch scarification and disk trenching increased. Mounding has partly displaced ploughing on moist and wet sites. In 2006, for example, 18 250 ha was site-prepared in Finnish Lapland, of which 3.1% was prescribed burning, 8.6% patch scarification, 41.8% disk trenching, 13.3% ploughing and 33.2% mounding (Finnish Statistical... 2007).

In recent decades Scots pine has been planted on sites where Norway spruce is the natural climax species. In Lapland, this was due to problems in the natural regeneration of spruce (Heikinheimo 1922, Sirén 1955), better productivity of pine compared with that of spruce or birch (Ilvessalo 1937, Sirén 1955), and the promising early results achieved with pine reforestation (Heikinheimo 1939). The slower height growth of planted spruce compared with that of pine has since been documented in several studies (Norokorpi 1972, Pohtila 1972, Pohtila and Pohjola 1983). However, severe dieback of pine seedlings on reforestation sites treated with prescribed burning or patch scarification was observed in the 1960s in northern Finland (Pohtila 1977). Such damage was the most severe on sites formerly occupied by spruce.

One suspected reason for these failures was the establishment of pine plantations on excessively wet sites, (Lähde 1974, Lähde and Mutka 1974, Pohtila 1977, Lähde 1978), where the high soil water content could not have been detected visually or tactily from the surface layer of the soil or on the basis of the site type. In the boreal forests of northern Finland, the growing seasons are short and the climate cool and humid, even though annual precipitation is relatively low, ranging from 400 to 500 mm. Precipitation exceeds soil evaporation in all the summer months except June (Solantie 1974). Excess soil water content, resulting in poor aeration and low temperature in the soil, was considered to be one reason for e.g. the extensive fungal disease epidemics and high pine mortality on patch-scarified or burned sites (Lähde 1974, Pohtila 1977). Thus, it is possible that a better knowledge of the soil hydraulic properties and conditions, such as soil water retention characteristics and soil water content *in situ*, and of related physical properties, such as soil texture and organic matter content, would help to guide the practical forest managers towards more sustainable reforestation solutions in the future.

1.2 Soil hydrological properties and conditions of forest sites

In addition to the effects of site fertility, the forest cover on a site tends to differentiate according to the soil water and aeration regime in the soil (Sims et al. 1996, Wang and Klinka 1996). Therefore, the hydrological conditions and related physical properties of the soil are important factors contributing to tree growth and the succession of forest site types, and are features which should be taken into account when selecting appropriate measures for different sites with respect to silviculture, soil and water conservation and road construction. The hydrological conditions of a site depend not only on the physical properties of the soil, but also on the topographical location and the ambient weather conditions (Lundin 1982, 1995, Heiskanen 1988, Espeby 1989, Nordén 1989, Nyberg 1995, 1996, Laurén et al. 2005). Thus, although soil texture may have a considerable impact, neither soil moisture nor forest site type in boreal forests can be determined solely on the basis of the soil texture (Aaltonen 1941, Urvas and Erviö 1974, Heiskanen 1988, Tamminen 1998).

In order to determine the hydrological conditions *in situ* and their significance from the viewpoint of forest production and reforestation or other management practices on different sites, the relevant soil properties and their variability should be known. In southern Finland, soil physical properties of both the mor (e.g. Heiskanen 1988, Laurén 1997a, 1997b, Laurén and Heiskanen 1997, Laurén and Mannerkoski 2001) and mineral soil layers (e.g. Heiskanen 1988, Mannerkoski and Möttönen 1990, Tamminen and Starr 1994, Westman and Jauhiainen 1994, Mecke and Ilvesniemi 1999, Mecke et al. 2000, 2002, Jauhiainen 2004, Wall 2005) have been widely studied during the last two decades. In Finnish Lapland, although the conditions and properties of forest soils have earlier been studied to only a minor extent, the forest cover and the hydrological and related physical properties and conditions of the soil have been shown to vary both spatially and temporally (e.g. Viro 1962, Lähde 1978, Sepponen et al. 1979, Hänninen 1997, Penttinen 2000). It has been suggested that there are moisture limits for the natural occurrence of Scots pine and Norway spruce in Finnish Lapland (Mäkitalo et al. 1993, 1995, Sutinen et al. 1996, 2002a, 2007a). In southern Finland, Levula et al. (2003) suggested that Scots pine is more competitive both in natural regeneration and growth than Norway spruce above certain soil texture limits. However, our understanding of the ecology of northern boreal forest sites and information about the differences in the hydrological and related physical properties of the soils, as well as about the prerequisites of forest reforestation among the site types, are still rather sparse and scattered.

1.3 Effect of site preparation on soil hydrological properties and conditions

Site-preparation methods usually mix and loosen the topsoil, but may also expose the C-horizon, which has a higher bulk density than the topsoil (Tamminen and Starr 1994, de Chantal et al. 2003). Ploughing, as well as mounding, increases soil temperature and both the total and air-filled porosity of the soil, as well as improving the nutrient status of the soil through enhanced microbial activity. The heavy machines used in site preparation, however, may also compact the topsoil and even cause changes in the soil properties on untreated intermediate areas. Possible changes in soil density and porosity can, in turn, significantly affect the growth of planted seedlings (Eavis 1972, Glinski and Stepniewski 1985, Corns 1988, Örlander et al. 1990a, Sutton 1991, Korotaev 1992, Unger and Kaspar 1994, Kozlowski 1999). The environmental aspects of site preparation, such as visual impacts, changes in soil density and structure, and their possible effects on nutrient leaching, have been widely discussed (Curran et al. 1993, Kubin 1995, 1998).

The short-term effects of soil tillage and site preparation on soil porosity, water retention, water content and other soil physical properties and conditions have been studied extensively worldwide (e.g. Mälkönen 1972, Lindstrom and Onstad 1984, Mapa et al. 1986, Canarache 1991, Örlander et al. 1990a, Sutton 1993, Ahuja et al. 1998, McNabb et al. 2001, Startsev and McNabb 2001). Clear-cutting is usually followed by a rise in the water table and an increase in the soil water content (Lundin 1979, Magnusson 1992, Elliott et al. 1998, cf. Mannerkoski et al. 2005), a decrease in available oxygen in the soil (Söderström 1974, Wilson and Pyatt 1984), and an increase in runoff (Swift et al. 1975, Grip 1987, Rosén 1984, Lundin 1994, Koivusalo et al. 2006). Site preparation may further increase the effects of clear-cutting because of the more intensive removal of transpiring vegetation. On dry sites, site preparation may therefore improve the water supply in the root zone (Fleming et al. 1994). On moist and wet sites, ploughing or mounding associated with ditching provide drainage channels for snowmelt and rain water, and increase soil porosity and decrease the soil water content, thus improving soil aeration at the planting micro-sites (Söderström et al. 1978, Ross and Malcolm 1982, Örlander et al. 1990a, Sutton 1993). Prescribed burning has been found to decrease both the water-retention capacity and ability of the humus layer to reduce evaporation (Viro 1974). This practice may have varying effects on the soil water content on different site and soil types and under different climatic conditions (Lutz 1956, Ahlgren and Ahlgren 1960).

Information about the longer-term effects, i.e. several years after site preparation, on boreal forest soils is far less readily available (Corns 1988, Heineman 1999). The effects of site preparation on forest soil properties and conditions in Finnish Lapland have in fact been studied to some extent (e.g. Kauppila and Lähde 1975, Lähde 1978, Ritari and Lähde 1978, Lähde et al. 1981), but information about the long-term effects is scarce. The changes in the soil physical properties diminish gradually over time as a result of reconsolidation caused by rain, wetting and drying as well as freezing and thawing of the soil (Ahuja et al. 1998, Chamberlain and Gow 1979, Miller 1980, Cassel 1983, Mapa et al. 1986). As a result of compaction, settling and surface crust formation, air-filled porosity and water infiltration decrease and bulk density increases (Kauppila and Lähde 1975, Kozlowski 1999, Hillel 2004). However, mild compaction may be beneficial since it could improve the capillary movement of soil water to the planted tree seedlings (Mannerkoski and Möttönen 1990, Kozlowski 1999). On mounds, settling is further enhanced by the weight of snow (Heineman 1999). The erosion and compression of ridges or mounds, the decrease in the drainage capacity of ploughed ditches, and the revegetation of scarified or burned sites, may all have considerable effects on the soil physical properties and conditions (Viro 1974, Ferm and Sepponen 1981, Adams et al. 1991). However, no studies have been published on the long-term effects of the levelling and compression of mounds or ploughed ridges on soil hydraulic properties and conditions.

In addition to treated micro-sites, the long-term effects of site preparation in untreated micro-sites are poorly known. The untreated intermediate areas may account for 40–60% of the total reforestation area. The roots of the planted seedlings tend to spread out of the treated micro-sites into the intact intermediate areas (Rusanen 1986). Thus, part of the root system may be exposed to unfavourable soil aeration conditions if the site preparation method does not affect the soil outside the treated micro-sites (Mannerkoski and Möttönen 1990).

1.4 Effect of site preparation on Scots pine performance

The early development of pine seedlings in northern Finland has usually been better on ploughed sites than on sites treated with lighter methods, such as prescribed burning, patch scarification or disk trenching (e.g. Pohtila 1977, Lähde 1978, Pohtila and Pohjola 1985, Valtanen and Tasanen 1996). However, the long-term effect of ploughing on soil physical properties and on the performance of planted pine seedlings is not, however, comprehensively known. Most site preparation experiments have been designed as relatively short term studies, and only a few reports have been published on the long-term effects of different site preparation methods on Scots pine seedling development in northern Fennoscandia (Örlander et al. 1990b, 1996, Valtanen and Tasanen 1996). Even less research has been carried out on the effects of combinations of these methods on different site types. Long-term regeneration results are available from inventory studies, but the comparison of site preparation methods is somewhat uncertain because the different methods may have not been used on the same types of site (Saksa 1992).

Despite the use of intensive site preparation, there has still been a wide variation in reforestation success, especially on formerly spruce-dominant sites, and almost total failures have occurred (Valkonen 1992, Varmola et al. 2004). Severe seedling dieback again occurred in the 1980s in northern Finland, and this time even in 10- to 15-year-old stands treated by ploughing in which reforestation should already have been achieved. It has been hypothesized that ploughing has an unfavourable, long-term effect on Scots pine seedling development due to phosphorus deficiency and the mobilisation of heavy metals in the ridges (Tikkanen and Raitio 1984). However, it is possible that the outbreaks of pine seedling dieback in the 1980s, which mainly occurred on moist, fine-textured areas treated by ploughing, are similar to those found in 1960s on areas treated by light site preparation methods (Lähde 1974). Thus, the poor performance of pines may be due to unfavourable soil hydrological properties and conditions in the soil of untreated intermediate areas, as well as to a decrease in the effects of site preparation in the planting spots.

1.5 Effect of soil hydrological properties and conditions on tree growth

In the boreal forest zone, tree species occurrence and dominance have been shown to be dependent on soil moisture and aeration regimes (Ahlgren and Hansen 1957, Sims et al. 1996, Wang and Klinka 1996). The dominance or occurrence of a tree species within a specific soil-moisture range is not necessarily closely related to tree growth, but growth may be relatively low at both the wet and dry end of the occurrence range (Ilvessalo 1937, Sirén 1955, Jokela et al. 1988, Wang and Klinka 1996). However, there are differences among tree species. Although Norway spruce seems to favour a higher soil water content than Scots pine, spruce can actually suffer to a greater extent from hypoxia than pine during short-term flooding at the seedling stage (Orlov 1966, Pelkonen 1979, Zaerr 1983, cf. Huikari 1959). Spruce typically has a shallow rooting system (Aaltonen 1920, Köstler et al. 1968), as is the case for many shade-tolerant, climax-tree species (Gale and Grigal 1987). Spruce roots are also more sensitive to drought than pine roots (Hoffmann 1974, Bartsch 1987). Pine is more flexible in regulating transpiration under decreasing soil moisture conditions than spruce (Eidmann and Schwenke 1967). The recovery of the fine root growth of spruce after both flooding and water deficit is slower than that of pine (Orlov 1966, Hoffmann 1974). On the other hand, the ability of spruce to grow adventitious roots above the root collar into the humus layer may partly explain the dominance of spruce on moist mineral sites, where poor soil aeration conditions may prevail during the growing season (Lähde 1974, Lähde and Mutka 1974).

An air-filled porosity of 0.10 $m^3\,m^{-3}$ is generally considered to be the lowest limit for gaseous diffusion, and of 0.10–0.15 $m^3\,m^{-3}$ as the minimum for root growth (Wesseling and Wijk 1957, Vocomil and Flocker 1961, Heiskanen 1993a). According to Heiskanen (1993a), the air space in mineral soil should be at least ca. 0.20 $m^3\,m^{-3}$. In a laboratory study, the root elongation rate of radiata pine (*Pinus radiata* D. Don.) reached its maximum at an air-filled porosity of 0.15 $m^3\,m^{-3}$ (Zou et al. 2001). Wall and Heiskanen (2003) reported the best growth for one-year-old Norway spruce seedlings at air-filled porosities of 0.20–0.40 $m^3\,m^{-3}$, depending on the organic matter content of the soil. However, only a few studies have been published on the effect of soil air-filled porosity or water content on the growth of tree saplings *in situ* in Finnish Lapland, and most of them deal with the early development of saplings on formerly spruce-dominated sites with fine-textured soil (Lähde 1978, Lähde et al. 1981).

In the fine-textured soils of Finnish Lapland, moisture conditions close to saturation in the root zone may last for weeks after snowmelt and after heavy rain events later in summer, especially on high-altitude sites with a low air and soil temperature in the summer, and a thick snow cover in the winter (Lähde 1978, Ritari and Lähde 1978, Lähde et al. 1981, Sutinen et al. 1997). During wet growing seasons, the air-filled porosity has been found to remain below 0.15 $m^3\,m^{-3}$ on sites that are usually covered with old-growth spruce forests. Soil texture is closely related to soil water retention characteristics and hydraulic conductivity. In fine-textured silty soils, the saturated hydraulic conductivity is low and the bubbling pressure, i.e. the air-entry value, is high compared with coarser-textured sandy soils (Rawls et al. 1982). Thus, favourable aeration conditions for root growth are reached at lower matric potentials in silty soils than in sandy soils. The importance of soil properties affecting the soil moisture regime, such as the air-entry value or matric potential at favourable soil aeration, in explaining variation in Scots pine performance has not, however, been studied.

Lähde (1974) suggested that Scots pine should not be planted on scarified patches on sites where the fine particle fraction (<0.06 mm) in the topmost mineral soil layer exceeds 25%. However, there are no other studies confirming this result. Recently, it has been argued that an upper dielectric limit (dielectric permittivity κ = 13–16 in different studies) for both the natural occurrence and artificial regeneration of Scots pine exists in soils in Finnish Lapland (e.g. Mäkitalo et al. 1993, Sutinen et al. 1994, 2002a, 2002b, 2007a, Hänninen 1997, Penttinen 2000). This limit coincides with a soil water content of 0.24–0.29 $m^3\,m^{-3}$ (Topp et al. 1980). However, there is only one study with statistical data analysis to support the hypothesis of the upper soil water content limiting pine plantation performance (Sutinen et al. 2002b). Furthermore, there are no previously published studies on the possible impacts of soil water retention characteristics and related soil physical properties on the survival and height growth of planted Scots pine.

Viro (1962) found that the water-holding capacity and proportion of fine soil particles correlated positively with the site index on pine-dominated xeric and sub-xeric heath forest sites in Finnish Lapland. Thus, especially on sites with coarse-textured soil, a soil moisture deficit may restrict tree growth despite the humid climate prevailing in Finnish Lapland. For young planted Scots pine seedlings, soil drought may cause reduced growth and severe damage. Especially in the soil of elevated micro-sites, such as mounds and ploughed ridges, soil moisture has occasionally been found to sink to close to the wilting point (Örlander 1984, 1986, Örlander et al. 1990a). This has been reported also in Finnish Lapland (Kauppila and Lähde 1975, Lähde 1978). The water uptake of planted seedlings may be reduced for several years after planting (Hallman et al. 1978, Örlander 1986). Although excess soil moisture evidently causes the most serious problems in Scots pine reforestation in Finnish Lapland, the role of soil hydrology and site preparation in the performance of planted Scots pine should be studied more closely also on xeric and sub-xeric heath forest sites, natively occupied by Scots pine.

2 OBJECTIVES OF THE THESIS

The aim of this thesis was to study the hydrological and related physical properties and conditions in the soil, as well as site preparation methods, and their effects on the long-term performance of Scots pine plantations on sub-xeric and mesic upland heath forest sites in Finnish Lapland, dominated either by Scots pine or Norway spruce prior to clear-cutting. The term "long-term performance" indicates here that the mean stem height of the studied plantations has clearly passed the top level of the snow cover which, in practice, means that the plantations are 15 years or older.

This thesis examined:

i) **The variation and its causes in soil hydrological and related physical properties and conditions (I, III, IV, VI).** The specific objective in this part of the thesis was to study how those soil hydraulic properties and conditions in the mineral topsoil that are important for pine root growth, such as the water retention characteristics and the respective air-filled porosities, and soil water content and air-filled porosity in situ, vary spatially and temporally, and which factors affect these properties and conditions. Whether these properties and conditions differ on the pine- and spruce-dominated sites was also studied.

ii) **The long-term effects of site preparation methods on soil hydrological and related physical properties and conditions (II, III, IV).** The main focus in this part was to study the long-term impacts of intensive site preparation on these properties and conditions on both the planting spots and the adjacent intermediate areas. The effect of ploughing was especially studied by comparing ploughed ridges and untreated intermediate areas. Whether these properties and conditions differ on untreated intermediate areas when different site preparation techniques – ranging from manual scarification to heavy machines – have been applied was also examined.

iii) **The performance of planted Scots pine and its variation caused by the different site preparation methods and reforestation methods (V).** The main aim of this part was to evaluate the long-term effects of four site preparation and three reforestation methods on the survival and height growth of Scots pine with a time-span reaching up to 25–27 growing seasons after stand establishment. Survival and height growth patterns on the pine-dominated and spruce-dominated sites were compared. Furthermore, the seedling mortality dynamics and impacts of different damaging agents on seedling mortality were also assessed.

iv) **The effect of soil hydrological and related physical properties and conditions on the performance of planted Scots pine (VI).** This part of the thesis focused on studying the long-term influence of these properties and site preparation on the survival and height growth of containerized Scots pine seedlings planted 25–27 years earlier. Whether a high soil water content in situ decreases and a good soil aeration in situ increases survival and height growth were also studied. The soil properties and conditions were sampled on the untreated intermediate areas, thus presenting the original soil on the site. Models were compiled separately for the combined data, and for the pine- and spruce-dominated sites. In addition, the use of soil water content in situ as a criterion for sites suitable for Scots pine reforestation was also tested.

3 MATERIALS AND METHODS

3.1 Study sites and experimental designs

3.1.1 Dataset 1

The data of this thesis consisted of two datasets, which included data from 20 study sites in southern and central Finnish Lapland (Fig. 1). For dataset 1 (data 1 in I), six Scots pine-dominated and six Norway spruce-dominated sites, further referred to as pine and spruce sites in this thesis, were selected in central Lapland using the expertise of Metsähallitus, which is responsible for managing these state-owned forests (Table 1). Tree species (pine, spruce or broadleaved) dominance means here that the basal area (at breast height or stump level) of the tree species exceeds that of the other species. A part of the sites have a mature, naturally established stand (nos. 1, 2, 4 and 6), and a part were clear-cut and reforested with pine or spruce seedlings. The soil on the sites is till, except on site no. 3 where the soil is outwashed sand and gravel. Site no. 5 is situated on a hill slope and the others on relatively flat sites.

The measurements on living trees and cut stumps showed that the proportion of pine (out of total basal area, $m^2\,ha^{-1}$) varied from 84 to 95% on the pine sites, and that of spruce from 71 to 81% on the spruce sites. In addition, two birch-dominated sites (nos. 9 and 12) with a spruce admixture and no pines were included in the spruce sites in this study.

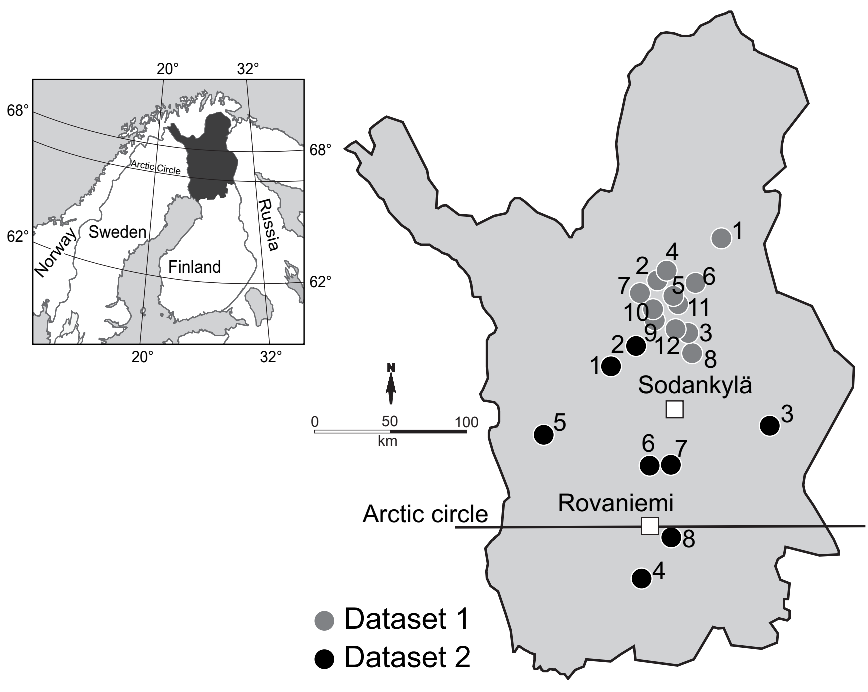

Figure 1. Location of the 12 experimental areas of dataset 1 (grey dots) and the 8 areas of dataset 2 (black dots) in Finnish Lapland.

Table 1. General description of the study sites. Forest types are expressed according to Cajander (1949).

Site	Latitude, North	Longitude, East	Altitude, m	Temperature sum 1961–1990, d.d.	Native dominant tree species	Tree species composition, %			Forest type	Soil particles <0.06 mm, mass%
						Pine	Spruce	Broadl.		
Dataset 1										
1.	68°33'	27°34'	190	695	Pine	95	0	5	EVT	7.6
2.	68°03'	26°28'	295	665	Pine	-	-	-	EVT	11.1
3.	67°51'	26°46'	215	715	Pine	-	-	-	EVT	2.0
4.	68°03'	26°30'	300	665	Pine	-	-	-	EVT	11.9
5.	67°58'	26°50'	270	685	Pine	95	0	5	EVT	19.6
6.	68°05'	27°11'	250	680	Pine	82	4	14	EVT	3.0
7.	67°59'	26°09'	285	655	Spruce	1	71	28	HMT	10.8
8.	67°42'	26°55'	225	710	Spruce	7	81	11	HMT	14.0
9.	67°53'	26°12'	340	645	Spruce/Birch	-	-	-	HMT	11.7
10.	67°53'	26°11'	350	630	Spruce	0	75	25	HMT	9.9
11.	67°52'	26°38'	235	690	Spruce	0	72	28	HMT	17.0
12.	67°56'	27°52'	250	690	Spruce/Birch	0	12	88	HMT	11.6
Dataset 2										
1.	67°37'	25°30'	240	725	Spruce	22	62	16	HMT	29.6
2.	67°45'	25°56'	290	680	Spruce	4	83	13	EMT	26.4
3.	67°06'	28°01'	240	760	Spruce	9	59	32	HMT	35.5
4.	66°10'	26°04'	195	855	Spruce	20	65	15	HMT	14.2
5.	67°02'	24°29'	190	800	Pine/Spruce	46	42	12	EMT	16.6
6.	66°54'	26°22'	180	805	Pine	64	26	10	EVT	22.3
7.	66°54'	26°22'	180	805	Pine	58	33	9	EVT	25.4
8.	66°26'	26°29'	190	860	Pine	90	5	5	EMT	9.9

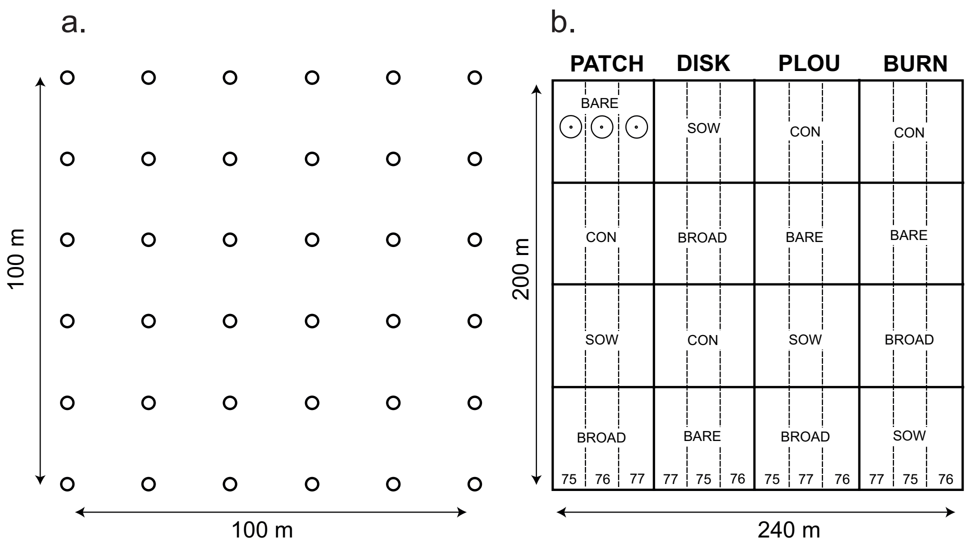

Figure 2. The experimental design of dataset 1 (a) and dataset 2 (b).

Each of the 12 experimental sites of dataset 1 was a 1 ha square area that included a grid of 30 or 36 sample points sample points at a spacing of 20 m (Fig. 2a). In addition to the grid data, a 150 m long transect was sampled at a spacing of 1 m on a natural spruce site (no. 11) for the more intensive variability study (I).

A part of the sites of dataset 1 have been used earlier for soil, vegetation and reforestation studies (Lähde 1978, Ritari and Lähde 1978, Mäkitalo 1983, Ritari 1985, Hänninen 1997, Liwata 1999, Penttinen 2000, Salmela et al. 2001).

3.1.2 Dataset 2

For dataset 2 (data 2 and 3 in I), eight experimental sites were established in southern and central Lapland (Fig. 1), four of which were formerly dominated by pine and four by spruce (Pohtila and Pohjola 1985, V). Clear-cutting was carried out primarily in 1974. According to the measurements on the stumps, the proportion of pine had varied from 46 to 90% on the pine sites and that of spruce from 59 to 83% on the spruce sites before clear-cutting (Table 1).

The measured tree species composition on the sites coincided well with the data in the forest inventory documents of Metsähallitus from the years of 1953–1967 (data not shown). At that time, the age of the naturally established old forests varied from 170 to >200 years on the pine sites, and from 150 to >200 years on the spruce sites. The dominant height of the forests ranged within 16–20 m on the pine sites and within 14–16 m on the spruce sites. The respective values for the volume of the growing stock were 90–140 m^3 ha^{-1} on the pine sites and 50–80 m^3 ha^{-1} on the spruce sites.

The soil on the sites of dataset 2 is till. According to the soil-slope classification of the Soil Survey Division Staff (1993), site nos. 1 and 3 are strongly sloping, nos. 1 and 6–8 rolling, and no. 5 moderately steep. For more details about the sites in dataset 2, see Table 1 in III.

A split-plot design was used in dataset 2 (Pohtila and Pohjola (1985, V). Each of the eight experimental sites, 4.8 ha in area, was divided into four plots, and the four site-preparation methods were randomized among the plots (Fig. 2b). Each site preparation plot was further divided into four subplots. Four reforestation methods were then randomized among these subplots. Each subplot was further divided into three sections. The three reforestation years, 1975, 1976 and 1977, were randomized in these sections.

Pohtila (1977) and Pohtila and Pohjola (1985) have published the results from the Scots pine reforestation experiment on the sites of dataset 2 up until the end of the sixth growing season after reforestation. In the present thesis the results are reported after 16 (V) and 25–27 growing seasons (VI). In addition to soil studies conducted in this thesis (I, II, III, IV and VI), Liwata (1999) also studied frost heaving in a laboratory study using samples from the sites of dataset 2.

3.2 Site preparation and reforestation methods in dataset 2

Disk trenching and ploughing were carried out in summer 1974, and prescribed burning and patch scarification the following spring. Patch scarification was performed by means of a caterpillar-drawn scarifier, disk trenching by means of a TTS–35 disk-trencher, and ploughing by means of a ridge plough or shoulder plough (sites 2 and 3) (Pohtila and Pohjola 1985, V). The treatment covered 60% of the plot area on the ploughed plots, 49% on the patch-scarified plots and 50% on the disk-trenched plots. In the case of burnt plots, 25% of the area was classified as well burnt and 61% poorly burnt, while 14% of the area was not burnt at all. The main reasons for incomplete burning were rainy weather and small amounts of logging residues (Pohtila and Pohjola 1985).

The term "intermediate area" used in this thesis means the mechanically untreated, intact part of the sites between the ploughed or disk-trenched tracks (consisting of ridges and furrows), and outside of the mechanically or manually prepared mineral soil patches in the patch-scarified and burnt areas. Consequently, intermediate areas covered 40% in the ploughed, 50% in the disk-trenched, 51% in the patch-scarified and approximately 70–80% in the burnt areas. In the intermediate areas, the mineral soil surface was covered with an organic soil horizon of varying depth and vegetation of varying height.

The reforestation methods used in dataset 2 were broadcast sowing (not included in the present study), band sowing, and planting with containerized 1-year-old seedlings and 2-year-old bare-rooted transplants. Reforestation was carried out in June each reforestation year (1975–1977). In sowing, a drill punch was used to prepare the sowing spots and 25 germinable seeds were sown per spot. The bare-rooted transplants were planted using a semicircular planting hoe and the containerized seedlings using a planting tube. In the case of the plots treated with prescribed burning, the reforestation spots were prepared by means of a peat hoe immediately before sowing or planting. The reforestation density was 2500 spots ha^{-1}. The seed provenances used in sowing and planting were as local as possible. The same provenances were used each reforestation year (Pohtila and Pohjola 1985, V).

3.3 Soil sampling, measurements, analyses and modelling

3.3.1 Soil sampling

In dataset 1, all the measurements and soil sampling were carried out during summer 1996 on untreated soil from the 12 study sites. On each site, soil was sampled from the intersection points of a grid at a spacing of 20 m (30 or 36 samples). At these points, undisturbed volumetric samples were taken at the depth of 2–8 cm below the organic O horizon using metal cylinders (height 60 mm, diameter 58 mm), as well as disturbed samples directly into plastic bags. In addition to the grids, samples were collected along a 150 m long transect at the Vaalolehto site (I).

In dataset 2, 12 samples were taken on each site using the sampling procedures as for dataset 1. One undisturbed volumetric sample and one disturbed sample were taken at the depth of 7.5 cm (4.5–10.5 cm) below the O horizon of the untreated intermediate area (not affected by site preparation) in the middle of each containerized-seedling plot in 1995–1996 (I). In addition, three volumetric samples were taken from ploughed ridges on each site (II).

A pit was dug in the untreated intermediate part of each plot planted with containerized seedlings in 1976 of the dataset 2 (four pits per site). Undisturbed volumetric samples and disturbed samples were taken from depths of 3 (0–6 cm), 20 (17–23 cm) and 50 cm (47–53 cm) below the O horizon. The number of samples on each site was 12. The sampling procedure was the same as for dataset 1. A volumetric sample was also taken from the O horizon in two of the pits on each site (I).

3.3.2 Topography

The inclination of the plots was measured and converted into slope gradient (%). The topographical position of each plot was determined using a five-class classification (McConkey et al. 1997). The classes were: summit, shoulder, back-slope, foot-slope and toe-slope (Fig. 6 in III). In addition, the topographic wetness index (TWI) was calculated for each plot (Beven and Kirkby 1979, Moore et al. 1991) (IV, VI). In order to calculate the upslope contributing area for each plot, a digital elevation model (DEM) was constructed using 1:20 000 digital contour data. The TOPOGRID method (Hutchinson 1989) was used. The output grid cell length was 5 m, which corresponds to the spatial resolution of the input data. The catchment delineation calculations were carried out with a desktop GIS program (ArcView v. 3.2). A script was written to build a catchment for every sample area centroid, and the areas of these polygons were used in the analysis.

3.3.3 Soil horizons and stoniness

In dataset 1, the thickness of each genetic soil horizon (organic (O), eluvial (A, E), illuvial (B)) was measured at each sampling point in 1995 (I). In dataset 2, the horizons were measured on each site preparation plot in 1974 (Pohtila and Pohjola 1985) and at the soil sampling points in 1995–1996. In addition, the thickness of the O horizon and height of the ground vegetation (mosses and lichens) was measured at each untreated point where the soil volumetric water content was measured in 1993 and in 1995-1996 (II, III, IV, VI).

On site no. 4 of dataset 2, a dense cemented B-horizon (hardpan) was found. The bedrock was exposed on site no. 8, where the thickness of the mineral soil on the patch-scarified plots was at a minimum of only about 10–15 cm. In 1974, before site preparation and burning, the mean thickness of the O horizon varied from 3.8 to 4.4 cm (4.0 cm on burnt plots) (Pohtila and Pohjola, 1985). In 1993, the O horizon was significantly thinner on the burnt plots (1.7 cm) than on the ploughed (2.8 cm) and disk-trenched plots (2.7 cm). The mean height of the ploughed ridges was 12.6 cm, and the depth of the ditches approximately 25 cm in 1996 (III). The stoniness of the top 30-cm mineral soil layer was measured five times near to each soil water-content measuring point in dataset 2 by the rod method of Viro (1952) (III, IV, VI).

3.3.4 Soil water content and air-filled porosity in situ

An electrical capacitance probe (Adek Ltd., Saku, Estonia) was used to measure the dielectric permittivity of the soil matrix surrounding the probe within a radius of a few centimetres (Hänninen 1997) horizontally at the time of sampling along the Vaalolehto transect in dataset 1 in 1995 (I), and vertically on containerized-seedling plots in dataset 2 in 1993 (III). The distance between the capacitance plates at the tip of the aluminium probe was 2.5 cm, allowing simultaneous dielectric profiling at 2.5 cm depth intervals down the holes made with a portable hand percussion drill. The measurements were started from a point 2.5 cm below the mineral soil surface. Before making the measurements in a hole, the CP device was calibrated in air.

Between the 5th of August and 9th of September, 1993 (later in the text referred to as August), a total of 600 points were measured in dataset 2 (III). The measurements were made at least two days after a rainfall event in order to minimise the effect of rain. To assess the temporal variation of the soil water content, measurements were made on one fine-textured plot on a spruce (site no. 2, proportion of fine particle fraction <0.06 mm was 45 mass%) and a pine site (no. 7, 64 mass%), and on one plot on a coarse-textured spruce (no. 4, 18 mass%) and a pine site (no. 8, 15 mass%) between the 6th and 15th of July. In addition, all the sites were measured between the 28th of September and 20th of October (later referred to as October).

On each circular 200-m^2 plot, one profile-measurement was made in untreated soil, in the middle of the plot, and four measurements diametrically, 4 m away from the mid-point of a plot. On the ploughed plots, five measurements were made also on the ridges. In October, only one measurement was made in untreated soil in the middle of each plot. At points where there were stones, stumps or other obstacles such as saplings, the measuring point was moved, but kept as close as possible to the original point. It was difficult on the ridges to avoid making the measurements close to saplings. The target depth was 30 cm but, owing to the incidence of stony soils, hardpan or bedrock, only a depth of 27.5 cm was achieved on all of the plots, and the statistical analyses were therefore computed down to this depth. In the October data, the analyses were computed down to a depth of 22.5 cm.

In 1995–1996, the time domain reflectometry method (TDR) was used to measure the soil dielectric permittivity in the 0–15 cm uppermost mineral soil layer on the containerized-seedling plots of dataset 2 (IV, VI). The measurements were performed using a Tektronix 1502B/C cable tester (Tektronix Inc., Beaverton, OR, USA) equipped with a balanced transmission line. The TDR probe consisted of two parallel, 15-cm-long stainless steel rods (diameter 6 mm) inserted vertically into the mineral soil under the organic soil layer. The spacing between the rods was 5.5 cm.

On each of the 96 circular 200-m^2 plots, five TDR probes were installed in the untreated intermediate area and ploughed ridges following the same layout as in 1993 (III, IV, VI). The total of 600 probes was installed in June 1995. In the summer of 1995 three measurements and in the summer of 1996 five measurements were made between June and September. The organic layer and ground vegetation were removed before and then replaced after each measurement.

The conversion equation presented by Topp et al. (1980) was used for converting the dielectric permittivity values into soil water contents. The mean air-filled porosity *in situ* was calculated for each plot using the procedure: Air-filled porosity = Saturated water content (θ_s) (Calculated total porosity in IV) – Soil water content.

The mean values from the measurements of five probes on a 200-m^2 plot were used as the *in situ* dielectric permittivity, soil water content and air-filled porosity values for a plot. The mean of the eight observations made in 1995–1996 was used in the data analysis (III, IV, VI).

3.3.5 Laboratory analyses

The water retention capacity was measured at desorption using a pressure-plate apparatus (Soilmoisture Corp., USA) and the same cylinder samples at successive pressures (matric potentials of –0.3, –1, –5, –10 and –100 kPa) (I, II). The water content at a matric potential of –1500 kPa was measured on disturbed samples and converted into volumetric values using the bulk density (Heiskanen 1993b).

Bulk density was measured on the cylinder samples as the ratio of dry mass (dried at 105 ^{o}C) to volume at –0.3 kPa. Particle density was measured on disturbed samples using 50 ml water pycnometers and a water bath. The calculated total porosity was estimated as: Total porosity = (Particle density – Bulk density) / Particle density.

The organic matter content was estimated as loss in mass on ignition at 550 ^{o}C. Saturated hydraulic conductivity was measured at sites nos. 1, 2, 4, 9 and 11 of dataset 1 using a constant-head permeameter and cylinder samples (Heiskanen 1993b). Cylinder samples were also collected at sites nos. 1, 6 and 11 of dataset 1 in order to estimate the unsaturated hydraulic conductivity, which was measured using the mean water retention capacity and separate matric potential gradients during drying on duplicate samples by applying the instantaneous-profile method (Hartge and Horn 1989, Heiskanen 1999).

The air-filled porosity at matric potentials of –1, –5 and –10 kPa were estimated as the water content at –0.3 kPa minus the water content at the above-mentioned matric potential (I). In II, the water content and air-filled porosity were estimated from the fitted model by Van Genuchten (1980). The available water content was estimated using the water contents at matric potentials of –10 kPa and –1500 kPa, and using the water contents at matric potential of –100 and –1500 kPa, respectively.

Particle-size distribution was determined using 300 ml samples and mechanical dry sieving with 2, 0.6 and 0.06 mm mesh sizes in dataset 1. Particles over 3–4 cm in diameter were excluded from the particle-size analysis (I). In dataset 2, the particle-size distribution was determined by the pipette method (<0.05 or <0.06 mm fractions) and mechanical dry sieving (>0.05 or >0.06 mm fractions) (Elonen 1971). Before pipetting, the organic matter was removed by treatment on a water bath with H_2O_2.

The textural class of the topsoil and parent material (particles <2 mm) was classified according to the International Society of Soil Science scheme using TAL for Windows (version 4.2) software (Teh 2002, Teh and Rashid 2003). The proportion of fine soil particles was determined as the percentage of particles <0.06 mm. In addition, the samples analyzed using 0.05 mm as the upper limit for silt were classified according to the USDA (IV) and Canadian scheme (VI).

3.3.6 Modelling

The function of van Genuchten (1980) was fitted to the water-retention data of each individual core of dataset 2 (not for the pit cores) using either sequential quadratic programming (SPSS 11.0.1) (II) or the RETC program (Van Genuchten et al. 1991) (VI). The water retention at matric potential 0 kPa was estimated on the basis of the total porosity, and added to six measured water content values (II, VI, Al Majou et al. 2008).

The model of van Genuchten (1980) describes the volumetric soil water retention (θ, m^3 m^{-3}) as a function of the matric potential (ψ) (cm) as follows:

$$\theta = \theta_r + \{(\theta_s - \theta_r) / [1+ (\alpha\, |\psi|)^{\,n}]^{\,m}\} \tag{1}$$

Parameters θ_r and θ_s are the residual and saturated water contents (m^3 m^{-3}), respectively, and α (cm^{-1}), n, and m are empirical parameters (van Genuchten 1980, van Genuchten et al. 1991). Parameter m was defined using the Mualem restriction ($m = 1 - 1 / n$). Average values for the water-retention parameters (θ_s, α, n) for the major USDA soil textural groups (Rawls et al. 1982) were used as starting values in parameter optimization.

The van Genuchten function was used to calculate matric potential value for given air-filled porosities in soil, for example for 0.10 m^3 m^{-3} and 0.20 m^3 m^{-3}, and for one half of the total porosity (VI). In addition, the model was also used to calculate water retention and air-filled-porosity curves and matric potential for the soil water contents measured *in situ* in 1993–1996. The parameter α, which is closely related to the air-entry value of soil, and parameter n, which is related to the shape of water-retention curves (van Genuchten et al. 1991), were used as a covariate in VI.

3.3.7 Soil moisture classification

In the soil moisture classification (VI), the soil of a plot was classified as either "suitable" or "unsuitable" for pine reforestation according to the soil water content of the plot, following the limit presented by Sutinen et al. (2002b). The soil was "suitable" when the soil water content was <0.27 m^3 m^{-3}, and "unsuitable" when $\geq$0.27 m^3 m^{-3}. Because of the temporal variation in the soil water content, the risk of false classification was calculated. The 96 plots were first classified into soil water content classes in 0.01 m^3 m^{-3} intervals according to their average soil water content (mean of the eight observations on a plot), and then further classified either into "suitable" or "unsuitable" for pine reforestation. Next, the individual soil water content observations on plots belonging to different soil water content classes (e.g. 0.25 m^3 m^{-3}) were also classified. Finally, the individual observations belonging to a different class of soil moisture classification than the plot mean were interpreted as false classifications. The proportion of false cases (e.g. 6 observations) out of the total number of observations in the soil water content class (e.g. four plots in a class, including 4 x 8 = 24 observations) was calculated and presented as the risk of false classification (e.g. 25%).

If the soil water content was a valid variable for soil classification, it should result in a correct class of soil moisture classification, irrespective of when it was measured during a growing season. There were 96 x 8 = 768 different possible combinations of soil water content observations in the present study. 40 combinations (5.2%) out of 768 were established by randomizing the soil water content among the eight observations separately for each plot. The impact of soil water content and soil moisture classes on survival was tested in each of the 40 cases, and the proportion of statistically significant cases was reported.

3.4 Measurements of seedling and stump variables

The seedlings growing within a circular 200 m^2 plot (containing 50 sown or planted spot) in the middle of each 20 m x 50 m reforestation plot were inventoried annually during the first seven-year period and, after that, every third year until the end of the 16^{th} growing season (V). The survival, mean height and top shoot length of the seedlings were recorded in each inventory. The two most important causes of damage on living seedling were recorded at the end of the 10th, 13th and 16th growing season (V). The containerized seedlings were inventoried in 1996, 1999 and 2001 (VI) and, in addition to survival and mean height, the diameter at breast height (1.3 m) of the saplings was also measured. Basal area per hectare at breast height was calculated for each plot.

The number and diameter of the stumps (>5 cm) of the previous tree generation were measured on each circular plot (I, III). The proportions of pine, spruce and broadleaved tree species were calculated as proportions of the basal area of the stumps (III). The broadleaved species consisted mainly of downy birch.

3.5 Weather conditions

Monthly mean temperatures, precipitation sums, and temperature sums (threshold +5°C) for the studied growing seasons (up to year 1999) were computed using the model of Ojansuu and Henttonen (1983) for the studied sites. Humidity was calculated using the aridity index formula of de Martonne (Tuhkanen 1980). In addition, the long-term data (1924–2003) for the Rovaniemi (Apukka) (66°35’ N, 26°01’E, 106 m a.s.l.) and Sodankylä (67°22’N, 26°39’E, 178 m a.s.l.) weather stations were also calculated. The mean effective temperature sum for the studied period for each site was used in the data analysis.

For the studied period 1975–2001, the mean temperature varied among the eight sites of the dataset 2 from –0.7°C to 0.0°C for the whole year, from –15.1°C to –13.2°C in January, and from 13.1°C to 14.5°C in July. The mean effective temperature sum varied from 670 d.d. to 856 d.d., respectively. The mean temperature for a growing season varied from 9.7°C to 11.1°C. The mean annual precipitation sum was at its lowest 505 mm and at its highest 564 mm. The respective mean June–September sum varied from 236 mm to 252 mm. The mean humidity for June–September varied between 34.1 and 36.0.

At the Sodankylä weather station, for example, the mean June–September temperature was 4%, precipitation sum 5%, humidity 3% and temperature sum 7% lower during the studied period (1975–2001) than for the 80-year period (1924–2003). The June–September precipitation sum in 1992 (456 mm) was the highest and in 1997 (155 mm) the second lowest in 80 years (Fig. 3).

The mean June–September temperatures in 1993 at Rovaniemi (9.9°C) and at Sodankylä (9.0°C) were the second lowest in 80 years, being about 15% lower than the average of the last 30-year period (1961–1990). The June–September precipitation and evaporation sums were about 30–40% lower than the 30-year means. The temperature and precipitation conditions during the SWC measuring summers (1995 and 1996) were close to the long-term average values.

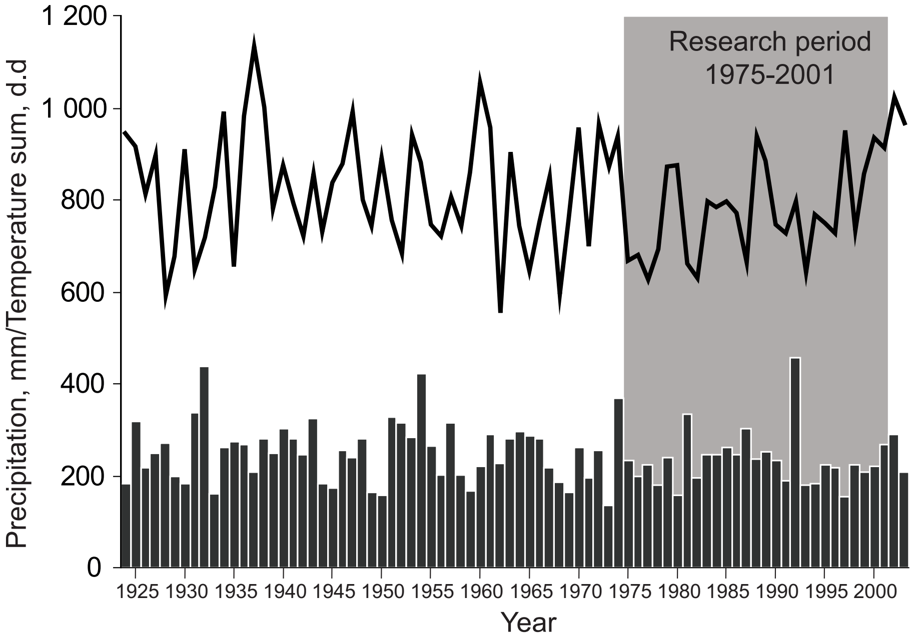

Figure 3. The yearly June–September precipitation sums (bars, mm) and the effective temperature sums (threshold 5°C) (lines, d.d.) at the Sodankylä weather station (67°22'N, 26°39'E, 178 m a.s.l.) during 1924–2003.

3.6 Statistical analyses

In article I, potential linear relationships among the variables were analysed using correlation and regression analyses. Differences in the water retention capacity between the sites were analyzed by multivariate ANOVA (MANOVA), and contrasts using matric potential levels as the repeated factor (–0.3 to –100 kPa). Differences in the water content at separate matric potentials and in the other variables among the sites (transect excluded) were analyzed with ANOVA and the Tukey's test. Differences between the pine and spruce sites were tested by the *t*-test using site means as observations. Spatial variability in the soil along the Vaalolehto transect was analyzed using semi-variograms, in which the model curves were fitted by optimizing the indicative goodness of fit (Pannatier 1996). Semi-variograms were also calculated for the grid data, but their validity was only indicative due to the relatively low sample number and the large minimum sampling distance (20 m).

In article II, two different split-plot based models were used to analyse the data, one for the intermediate areas and one for the comparison of ploughed ridges and adjacent intermediate areas. Site preparation, measurement location and a number of different covariates were used as fixed effects, and all the other terms as random effects. As the primary interest is on the fixed effects, the results of the analysis concerning the random effects are not given here. To observe the effect of the covariates, the data were analysed without covariates and also with the one most significant covariate that was not affected by the treatment. The analysis was performed using the MIXED procedure of SAS statistical software (SAS OnlineDoc, version 8, http://v8doc.sas.com/sashtml/).

The ANOVA models for split-plot-designs in randomised blocks were used to analyse the data in article III. The original experimental layout of the reforestation study (V), including the reforestation year, was maintained as the basis for the statistical analysis in order to control the effect of the planted pine saplings of different age and size on SWC. Site type (pine and spruce site) was the main treatment, site preparation the sub-treatment (under site type), and the reforestation year the sub-sub-treatment (under site preparation). Site type and site preparation were used as fixed factors, the basal area of the planted saplings as a covariate, and the experimental site (= block) and reforestation year as random factors in the model. The ANOVA models were analysed using the GLM procedure associated with SAS statistical software (Version 6.12). For multiple comparisons, Tukey's studentized range test was used (*p*-level: 0.05). The Spearman rank correlation (r_s) and partial rank correlation (r_{sp}) coefficients were computed in order to study the relationships between the different variables.

In article IV, two different split-plot based models were used to analyze the data, one for the intact intermediate areas of the four site preparation methods and one for the micro-sites of the ploughed plots (intact intermediate areas and ploughed ridges). Water content at field capacity (–10 kPa), topographic wetness index and basal area of the seedlings growing on a plot were used as covariates in the analysis of the site preparation methods. The analysis was performed using the MIXED procedure of SAS statistical software (SAS OnlineDoc, version 8, http://v8doc.sas.com/sashtml/).

The differences in the survival, height and top shoot length between the treatments, as well as their interactions, were analysed using an ANOVA model for split-plot-designs in randomized blocks in article V. Site preparation was a main treatment and the reforestation method a sub-treatment under site preparation. Reforestation year was subordinated to the reforestation methods. Site preparation and reforestation method were fixed and the experimental site (block) and reforestation year were random factors in the model. When significant interactions were found, variance analysis was computed separately for the treatment levels. The ANOVA models were constructed using the GLM procedure associated with the SAS statistical software (SAS OnlineDoc, version 8, http://v8doc.sas.com/sashtml/). For multiple comparisons, Tukey's studentized range test was used (p-level: <0.05).

The first dependent variable in article VI, survival (the observed ratio of surviving seedlings on a plot), was binomially distributed. The independent information was measured at different levels and, in order to prevent pseudo-replication, the experimental factors were taken into account as random factors in the model. The repeated nested factorial experiment was analyzed with GLMM with the SAS/GLIMMIXED procedure, in which the correlation caused by the design was taken into account with compound symmetry structure within the site and year (SAS OnlineDoc, version 8, http://v8doc.sas.com/sashtml/). The models were constructed separately for the combined data, and pine sites and spruce sites. Because the second dependent variable, the mean height of the seedlings on a plot, was normally distributed, the modelling was performed with a linear mixed model in which site and year were random factors. The models were made separately for the combined data, and pine and spruce sites. The estimations were produced with the SAS/MIXED procedure, which uses the REML estimation method.

For soil water content *in situ*, the mean, and minimum and maximum values were calculated for each site (Table 2 in VI). In addition, the coefficient of variation (CV) of the soil water content was calculated for each of the eight measurements in 1995–1996 on each site in order to study the spatial variation, and the minimum and maximum values of CV on each site were reported. The minimum and maximum plot-wise ranges of the soil water content in 1995–1996 were also calculated. The Spearman correlation coefficients were calculated for the soil variables used as covariates in the models (Table 3 in VI).

The basal area (at breast height, 1.3 m) of the planted saplings growing on the plots was assumed to correlate with the needle area and, therefore, with the transpiration and rainfall-interception capacity of the saplings (Alavi and Jansson 1995, Alavi 2002). The water content and air-filled porosity *in situ* were used as covariates for survival in article VI, both with and without the effect of transpiration and canopy interception of trees, i.e. with and without basal area in the models (cf. Sutinen et al. 2002b).

4 RESULTS

4.1 Soil hydrological and related physical properties (I, II, VI)

4.1.1 Soil properties in untreated soil

Significant differences (p <0.05) were found among the study sites in the water-retention characteristics of the untreated forest topsoil in dataset 1 (I). The MANOVA also showed highly significant differences in the water-retention characteristics at depths of 3, 7.5, 20, and 50 cm below the organic horizon (I), and among the eight sites of dataset 2 (Fig. 4). In both datasets, the largest differences among the sites were found in the water content and air-filled porosity at matric potentials of –5 and –10 kPa, i.e. near field capacity. For example, ANOVA showed highly significant differences among the sites for water content and air-filled porosity in topsoil at a matric potential of –10 kPa (I).

In dataset 1, the water content at a matric potential of –10 kPa ranged between 0.08–0.44 $m^3\,m^{-3}$, and the air-filled porosity between 0.04–0.39 $m^3\,m^{-3}$. In dataset 2, the respective ranges were 0.11–0.50 $m^3\,m^{-3}$ and 0.05–0.40 $m^3\,m^{-3}$ (I). The modelled water content at a matric potential of –10 kPa was between 0.08–0.53 $m^3\,m^{-3}$, and the air-filled porosity between 0.0015–0.40 $m^3\,m^{-3}$ (II).

The organic matter content ranged between 1.3–15.7 mass% in dataset 1 and 0.5–13.9 mass% in dataset 2, and the proportion of fine soil particle fraction (<0.06 mm in diameter) between 0.3–29.7 mass% and 5.1–52.1 mass%, respectively. Soil particle density and bulk density were within 2.42–2.87 and 0.69–1.65 g cm^{-3} in dataset 1, and within 2.49–2.88 and 0.73–1.65 g cm^{-3} in dataset 2. The saturated hydraulic conductivity ranged between 0.001 and 0.124 cm min^{-1} in dataset 1 (I).

In dataset 2, the van Genuchten parameter θ_s (saturated water content) varied from 0.39 to 0.69 $m^3\,m^{-3}$, α from 0.0008 to 0.9436 cm^{-1} and n from 1.17 to 3.13. The available water content at a matric potential of –10 kPa ranged between 0.04–0.43 $m^3\,m^{-3}$ and at –100 kPa between 0.01–0.34 $m^3\,m^{-3}$. The matric potential for the air-filled porosity of 0.20 $m^3\,m^{-3}$ varied from –198.6 to –0.8 kPa (VI).

The sum of the proportion of fine particles and the organic matter content correlated best (r >0) with the water contents at matric potentials of $\geq$–10 kPa, while the organic matter content correlated best (r > 0) with the water contents at lower matric potentials (Tables 2 and 3 in I). The saturated hydraulic conductivity in the topsoil was the lower, the higher was the proportion of fine particles (I). In dataset 2, the proportion of fine soil particles correlated significantly with all the other soil variables studied, and the organic matter content with all the variables except air-filled porosity *in situ* (VI). For example, α, n and the matric potential for air-filled porosity of 0.20 $m^3\,m^{-3}$ decreased and the available water content at a matric potential of –100 kPa increased when the proportion of fine soil particles or organic matter content increased.

On toe-slopes the proportion of fine particles (54.0 mass%) and the organic matter content (9.6 mass%) were significantly higher (MIXED) than in the four other topographic classes (30.3–35.1 and 3.0–4.5 mass%) in dataset 2. Consequently, the water content at a matric potential of –10 kPa was also significantly higher on toe-slopes (0.40 $m^3 m^{-3}$) compared with the other classes (0.24–0.27 $m^3 m^{-3}$). In addition, the proportion of fine particles, organic matter content and water content at a matric potential of –10 kPa increased, and the respective air-filled porosity decreased significantly when the topographic wetness index increased.

According to semivariogram analysis of the grid data, the soil physical properties showed a spatial dependence within sites that was most commonly below 60 m in dataset 1 (I). However, because of the large minimum sampling distance (20 m), the grid data showed a poorer fit in the semivariograms than the transect data. In the transect data, spatial influence ranges of about 44 and 100 m were found for the water content at a matric potential of –10 kpa and the respective air-filled porosity (I). The mean water content at a matric potential of –10 kPa was 0.33 $m^3 m^{-3}$ and the air-filled porosity 0.11 $m^3 m^{-3}$ along the transect. The coefficient of variation (CV) was 8 and 40%, respectively. All the other variables showed ranges below 40 m.

4.1.2 Differences in soil properties between the pine and spruce sites

There were significant differences between the pine and spruce sites in the water retention characteristics (MANOVA) and in other measured variables in untreated soil (*t*-test) in dataset 1 (I). Compared with the spruce sites, the pine sites had significantly thinner genetic soil horizons, lower organic matter content, higher particle density and lower water retention capacity (at matric potential ≤–5 kPa). For example, the average soil water content and air-filled porosity at a matric potential of –10 kPa were 0.23 $m^3 m^{-3}$ and 0.26 $m^3 m^{-3}$ on the pine sites, and 0.33 $m^3 m^{-3}$ and 0.16 $m^3 m^{-3}$ on the spruce sites. The saturated hydraulic conductivity was higher on the pine sites (0.061 cm min^{-1}) than on the spruce sites (0.028 cm min^{-1}), but the difference was not statistically significant. Neither was the difference in the proportion of fine particles significant.

Although the average water retention capacity was lower on the pine sites than on the spruce sites, according to MANOVA there were no statistically significant differences in the water retention characteristics in dataset 2 (I). In general, the differences between the pine and spruce sites in the various hydrological and related physical properties of the topsoil were not statistically significant in dataset 2 (I). The difference in the air-filled porosity at a matric potential of –10 kPa was close to significant (*t*-test, $p = 0.059$). However, when topographic class or wetness index was used as a covariate in MIXED, significant differences were found ($p = 0.04$). The air-filled porosity was higher on the pine sites (0.25 $m^3 m^{-3}$) than on the spruce sites (0.20 $m^3 m^{-3}$).

The reasons for the non-significant differences in dataset 2 become apparent when the average water retention curves of the eight sites are compared (Fig. 4a). The curve of spruce site no. 4 was close to that of pine site no. 8, with a similar soil texture and organic matter content. The water retention capacity on site no. 4 was clearly lower than on the other pine sites. The air-filled porosity curves (Fig. 4b) showed that the soil on the pine sites and spruce site no. 4 reaches an air-filled porosity of 0.10 $m^3 m^{-3}$ at higher matric potentials (≥–1 kPa) than that of spruce sites nos. 1, 2 and 3 (–2–4 kPa). The same was found for 0.20 $m^3 m^{-3}$ (–2–4 kPa vs. –10–15 kPa) and for 0.25 $m^3 m^{-3}$ (–5–8 kPa vs. –20–34 kPa, respectively).

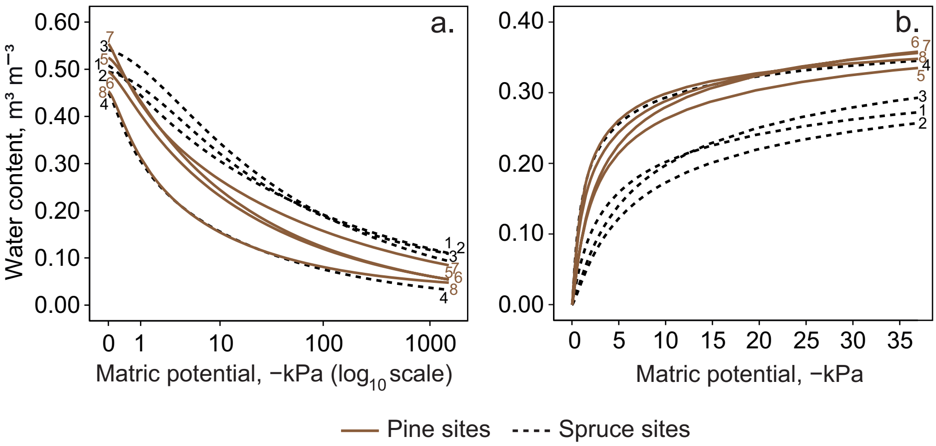

Figure 4. The modelled soil water content (m^3 m^{-3}) (a) and respective air-filled porosity as a function of the matric potential (–kPa) (b) for the pine sites and spruce sites. The numbers inside the figure refer to the sites of dataset 2.

On the average, the difference in the air-filled porosity at a matric potential of –10 kPa was >0.05 m^3 m^{-3} larger below the organic horizon on the pine than on the spruce sites (Fig. 10 in I). The most significant vertical differences in the air-filled porosity and water retention capacity between the soils of the pine and spruce sites were found at depths of 3 and 50 cm below the organic horizon. On the other hand, the differences in the total porosity, and in the water content at matric potentials of –0.3 and –1500 kPa were negligible.

The water content and air-filled porosity at a matric potential of –10 kPa showed significant correlations with the proportion of pine (of basal area) in the former stands (I). The water content was the lower and the air-filled porosity the higher, the higher the proportion of pine had been in the forest before clear-cutting. The mean water content at a matric potential of –10 kPa was <0.30 m^3 m^{-3} and the respective air-filled porosity >0.20 m^3 m^{-3} at about 80% of the sampling points on the pine sites, while on the spruce sites values of >0.30 and <0.20 m^3 m^{-3} occurred at a corresponding number of points (Fig. 5).

4.1.3 Effect of site preparation on soil properties

Total porosity, water content at saturation, available water content at –10 kPa and air-filled porosity at a matric potential of –1–10 kPa were significantly higher and the bulk density lower in the soil of the ploughed ridges than in the soil of the untreated intermediate areas (Table 2, II, IV). The water content at a matric potential of –10 kPa was slightly higher in the ridges, but the difference was not significant. No differences were found in the water retention characteristics among the untreated intermediate areas of the patch-scarified, disk-trenched and ploughed plots (scarified by a bulldozer) and prescribed-burned plots (scarified manually) (II).

The effect of ploughing on soil aeration was different on sites with different soil texture. For example, on pine site no. 8 with a coarse-textured soil and low organic matter content, the air-filled porosity of 0.10 m^3 m^{-3} was reached at a matric potential of >–1 kPa in both micro-sites, and that of 0.20 m^3 m^{-3} at –3 kPa in the soil of intact intermediate areas and at >–1 kPa in the soil of ploughed ridges (Fig. 6a). On spruce site no. 2 with a finer-textured

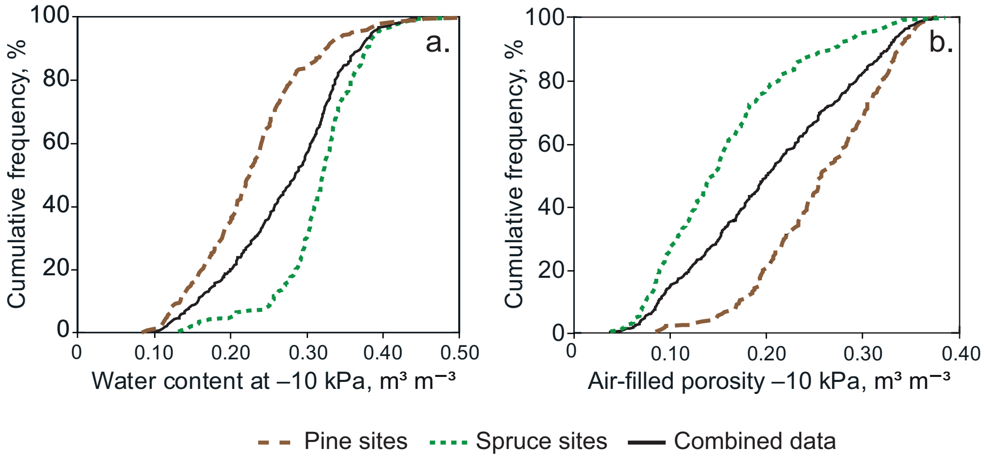

Figure 5. Cumulative frequency distributions of water content ($m^3\ m^{-3}$) (a) and of air-filled porosity ($m^3\ m^{-3}$) (b) at matric potential of –10 kPa (data sets 1–2 combined for the uppermost mineral soil layer).

soil and higher organic matter content, the air-filled porosity of 0.10 $m^3\ m^{-3}$ was reached at a matric potential of –3 kPa in the intermediate areas and at –1 kPa in the ploughed ridges (Fig. 6b). For the air-filled porosity of 0.20 $m^3\ m^{-3}$, a matric potential of –15 kPa was needed in the intermediate areas and – 4 kPa in the ploughed ridges.

4.2 Soil water content and air-filled porosity *in situ* (III, IV, VI)

4.2.1 Soil conditions in the untreated soil

The mean volumetric soil water content and air-filled porosity *in situ* showed a high variation among and within the experimental sites in the intermediate areas of dataset 2 (Fig. 7, III, IV, VI). In the mineral topsoil (2.5–15.0 cm layer) of the untreated intermediate areas, the soil water content varied among the plots from 0.08 to 0.33 $m^3\ m^{-3}$ in August 1993 and from 0.07 to 0.40 $m^3\ m^{-3}$ in October 1993. During the summers of 1995–96, the soil water content in the mineral topsoil (0–15 cm) ranged between 0.04–0.55 $m^3 m^{-3}$. In general, the water content increased slightly with increasing depth, being on the average 0.03 $m^3\ m^{-3}$ higher at the depth of 25.0–27.5 cm than at 2.5–5.0 cm (III).

The air-filled porosity in the mineral topsoil was between 0.07–0.53 $m^3\ m^{-3}$ in August 1993, between 0.15–0.53 $m^3\ m^{-3}$ in October 1993 and between 0.00–0.49 $m^3\ m^{-3}$ in 1995–1996 (III, IV). On five sites out of eight, the air-filled porosity was lower than 0.10 $m^3\ m^{-3}$ at least once during the summers of 1995–1996. On three sites (nos. 2, 4 and 7), a low air-filled porosity occurred during most of the eight measuring rounds (IV).

Because the soil water content was not measured at the same time on the study sites, the water content and air-filled porosity results are fully comparable only within but not among the sites (Fig. 7, IV). For example, high water contents following the snowmelt peak in June 1996 (measurement 4 in IV) were detectable on most of the sites, except on two sites with rather coarse-textured soil (site nos. 6 and 8). The peak in the water content curves in July 1996 (measurement 6) was caused by a heavy rainfall episode (66 mm during 10–14th of July,

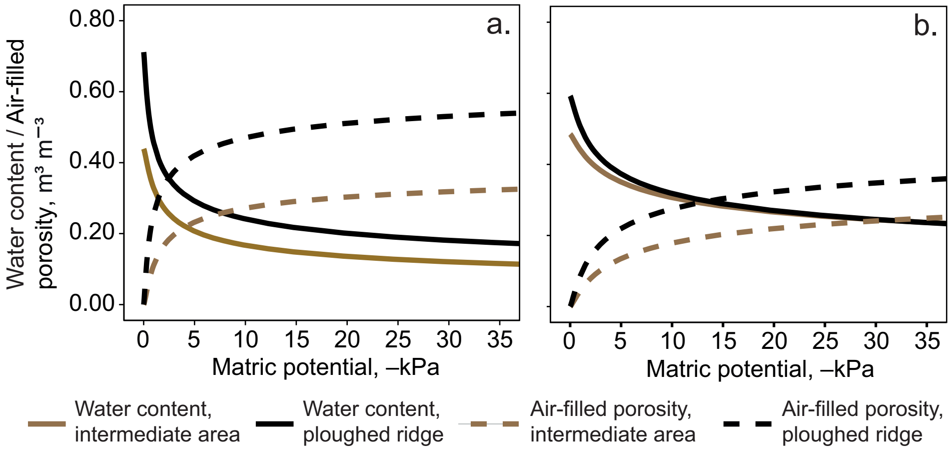

Figure 6. The modelled soil water content (m^3 m^{-3}) and respective air-filled porosity as a function of the matric potential (–kPa) in the intermediate areas and ploughed ridges on coarse-textured pine site no. 8 (a) and on fine-textured spruce site no. 2 (b) in dataset 2.

measured at the Sodankylä weather station). However, this was not noticeable at all on sites no. 1 and no. 2 because measurement 6 was made there before this period, and on site no. 6 it was made four days after.

The organic matter content (III) and water content at a matric potential of –10 kPa (IV) showed a significantly increasing effect on the soil water content. Soil texture also had a significant effect. An increasing proportion of fine particles or clay content increased the soil water content, whereas the effect of the proportion of coarse sand was the opposite (III). Topographic variables also significantly affected the soil water content, which was the lowest on summits, and the highest on toe-slopes (III) and with high values of the topographic wetness index (IV).

The spatial variability in soil water content was studied along a transect on site no. 11 in dataset 1 (I). The dielectric constant values showed a spatial influence range of about 37 m, and a CV of the dielectric constant of 26% on this fine-textured spruce site. The spatial variation pattern found in dataset 2 was, however, relatively different among the eight sites and among the eight measurements in 1995–1996 (VI). For example, on coarse-textured spruce site no. 4, CV was at a minimum of 11.4% in September 1995 and at a maximum of 50.1% in September 1996. However, on fine-textured spruce sites nos. 1 and 3, the CV was <11% at all the eight measuring rounds in 1995–1996.

The basal area (at breast height 1.3 m) of the planted saplings growing on the plots in 1996 showed a significant relationship with the soil water content at depths of 5–10 cm below the O horizon (III). The water content was the lower the higher was the basal area. In the 1995–1996 data, however, the influence of basal area on the water content in the 0–15 cm layer was non-significant (IV).

4.2.2 Differences in soil conditions between the pine and spruce sites

The soil water content in the untreated soil was slightly higher on the spruce sites than on the pine sites (Fig 7a). The mean difference in the soil water content between the two site types in August 1993 was 0.01–0.02 m^3 m^{-3} in the topsoil and 0.04–0.05 m^{3}m^{-3} at the depths of ≥15 cm

(III). However, the difference was not statistically significant until the depth of 27.5–30.0 cm. The difference in the upper soil layers was not significant ($p = 0.20$) in the 1995–1996 data.

The air-filled porosity was higher on the pine sites than on the spruce sites (Fig. 7b). The average air-filled porosity was significantly higher ($p = 0.038$) on the pine sites (0.26 $m^3 m^{-3}$) than on the spruce sites (0.19 $m^3 m^{-3}$) when the effect of topography (topographic class) was used as a covariate in the model (MIXED).

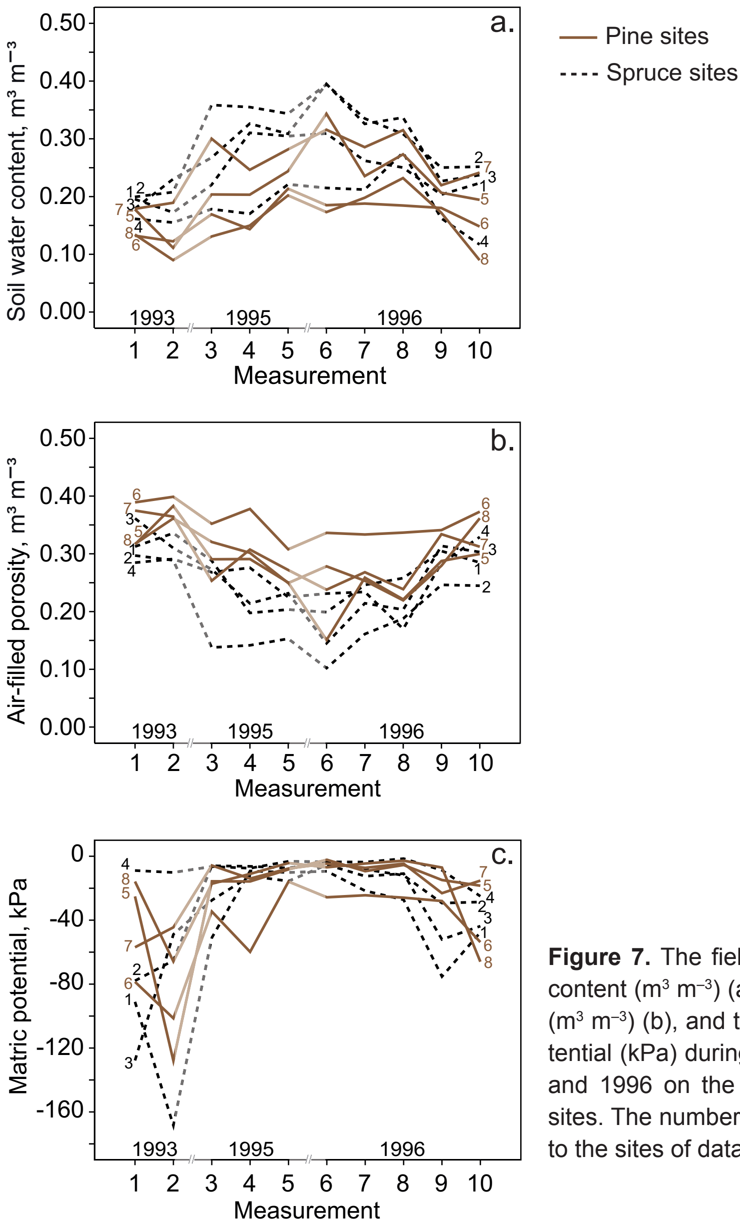

Figure 7. The field measured soil water content ($m^3 m^{-3}$) (a) and air-filled porosity ($m^3 m^{-3}$) (b), and the modelled matric potential (kPa) during summers 1993, 1995 and 1996 on the pine sites and spruce sites. The numbers inside the figure refer to the sites of dataset 2.

The modelled mean matric potential varied between –41 and –90 kPa on the pine sites and between –10 and –130 kPa on the spruce sites in 1993. In 1995–1996, it varied between –10 and –33 kPa on the pine sites, and between –7 and –24 kPa on the spruce sites (Fig. 7c).

The proportion of pine and spruce in the previous tree generation showed significant correlations with the soil water content (III). It was the lower, the higher was the proportion of pine (III) or the higher was the proportion of spruce in the forest before clear-cutting.

4.2.3 Effect of site preparation on soil conditions

In ploughed ridges, the soil water content varied from 0.09 to 0.23 $m^3 m^{-3}$ in August 1993 and from 0.05 to 0.46 $m^3 m^{-3}$ in 1995–1996. The air-filled porosity ranged between 0.28–0.79 $m^3 m^{-3}$ in August 1993 and between 0.11–0.78 $m^3 m^{-3}$ in 1995–1996.

The soil in and under the ploughed ridges was significantly drier down to a depth of 17.5 cm than the soil at the same depth in the adjacent untreated intermediate areas in August 1993 (Table 2, III). The highest statistical significance was found in the 10.0–12.5 cm layer, i.e. at the depth of the double organic layer in the ridges, and the difference decreased with increasing depth. On an average, the ridges were 0.02–0.08 $m^3 m^{-3}$ drier than the untreated soil in the intermediate areas close to the ridges (III).

In 1995–1996, the difference in soil water content in the topsoil between the two micro-sites was also highly significant (Table 2, IV). Consequently, the air-filled porosity in the topsoil was significantly higher in the ridges in 1993–1996 (Table 2). The difference between the micro-sites varied between 0.04–0.07 $m^3 m^{-3}$ in the soil water content, and between 0.14–0.18 $m^3 m^{-3}$ in the air-filled porosity. The air-filled porosity in the ploughed ridges occasionally decreased below 0.20 $m^3 m^{-3}$ at three sites, but it did not reach the critical limit for root growth, i.e. 0.10 $m^3 m^{-3}$ (IV). In June 1996, soon after snowmelt, the soil water content in the ridges was 0.03–0.10 $m^3 m^{-3}$ lower and the air-filled porosity 0.04–0.34 $m^3 m^{-3}$ higher than in the adjacent intermediate areas. The soil water content in the untreated intermediate areas had a strong positive relationship with that in the ridges (III). The same result was obtained in the top 15-cm mineral soil layer in 1995–1996 (IV).

In August 1993, the thickness of the ridges, mineral soil or double organic layer in the ridges did not show any significant correlation with the soil water content of the top 15 cm soil layer of the ridges (III). The mean total height of the ridges two decades after site preparation, measured from the surface of the mineral soil in the intermediate areas, was 12.6 cm, and consisted of a 3.2 cm-thick double organic layer with an overlying 9.4 cm-thick mineral soil layer.

In the intermediate areas, no significant differences were found in the soil water content or air-filled porosity among the site preparation methods in any of the measurements carried out in 1993–1996 in the topsoil or at any other measurement depth (III, IV).

4.3 Performance of the planted Scots pine (V, VI)

4.3.1 Height growth in the combined data

At the end of the 16th growing season, both the reforestation and site preparation method had statistically significant effects on the mean height of the Scots pine saplings in the combined data (Table 3). Height growth followed the same pattern observed in the initial height (V). The mean height of the sown seedlings (178 cm) was significantly lower than that of the con-

Table 2. Model-estimated means of different soil properties and conditions for the intermediate areas and ploughed ridges, their standard errors (SE, the same value for both micro-sites) and the significance (p) of the difference between the micro-sites.

Variable	Intermediate area	Ploughed ridge	SE	p
Organic matter content, mass%	4.2	11.1	3.1	0.059
Bulk density, g cm^{-3}	1.32	1.02	0.08	<0.001
Total porosity, m^3 m^{-3}	0.51	0.62	0.03	<0.001
Water content at a matric potential				
–0.3 kPa, m^3 m^{-3}	0.49	0.59	0.03	<0.001
–1 kPa, m^3 m^{-3}	0.41	0.46	0.03	0.019
–5 kPa, m^3 m^{-3}	0.33	0.35	0.03	0.12
–10 kPa, m^3 m^{-3}	0.27	0.30	0.03	0.14
–100 kPa, m^3 m^{-3}	0.17	0.21	0.02	0.036
–1500 kPa, m^3 m^{-3}	0.07	0.06	0.01	0.23
Air-filled porosity at matric potential				
–1 kPa, m^3 m^{-3}	0.09	0.16	0.02	0.004
–5 kPa, m^3 m^{-3}	0.18	0.27	0.03	0.002
–10 kPa, m^3 m^{-3}	0.23	0.32	0.03	0.002
Available water content at matric potential				
–10 kPa, m^3 m^{-3}	0.21	0.24	0.03	0.028
–100 kPa, m^3 m^{-3}	0.10	0.15	0.02	0.067
Matric potential for air-filled porosity				
0.10 m^3 m^{-3}, kPa	– 6.17	–1.86	2.92	0.26
0.20 m^3 m^{-3}, kPa	–15.78	–5.85	5.80	0.19
Van Genuchten parameters				
θ_s, m^3 m^{-3}	0.51	0.62	0.03	<0.001
α, cm^{-1}	0.11	0.20	0.04	0.10
n	1.51	1.38	0.06	0.11
Water content *in situ,* m^3 m^{-3}				
August 1993	0.18	0.14	0.01	<0.001
1995–1996	0.26	0.21	0.03	<0.001
Air-filled porosity *in situ,* m^3 m^{-3}				
August 1993	0.33	0.47	0.02	<0.001
1995–1996	0.25	0.41	0.03	<0.001

Table 3. Summary of the effects of site preparation and reforestation methods, effective temperature sum, and differnet terrain and soil variables on the mean height and survival of planted Scots pine saplings. Abbreviations: H = mean height, S = survival, *α* and *n* = van Genuchten parameters, * = statistically significant effect ($p < 0.05$), ns = statistically non-significant effect, ↑ = increasing effect, ↓ = decreasing effect.

Variable	Combined data		Pine sites		Spruce sites	
	H	S	H	S	H	S
16 growing seasons						
Site preparation	*	ns	*	ns	*	*
Reforestation method	*	ns	*	*	*	ns
Site preparation X Reforestation m.	ns	ns	ns	ns	ns	ns
25–27 growing seasons						
Site preparation	*	*	*	ns	ns	*
Effective temperature sum, d.d.	ns	*↑	*↓	ns	ns	ns
Slope gradient, %	ns	ns	ns	ns	ns	ns
Topographic wetness index	ns	ns	ns	ns	ns	ns
Topographic class	ns	ns	ns	ns	ns	ns
Stoniness, %	*↑	ns	ns	ns	ns	ns
Fine soil particle fraction, mass%	ns	ns	ns	ns	ns	ns
Organic matter content, mass%	ns	ns	ns	ns	ns	ns
Bulk density, g cm^{-3}	ns	ns	ns	ns	ns	ns
α, cm^{-1}	ns	ns	ns	ns	ns	*↑
n	ns	ns	ns	ns	*↑	ns
Water content at matric potential						
–1 kPa, $m^3 m^{-3}$	ns	ns	ns	ns	ns	*↓
–10 kPa, $m^3 m^{-3}$	ns	ns	ns	ns	ns	ns
–100 kPa, $m^3 m^{-3}$	ns	ns	ns	ns	*↓	ns
Air-filled porosity at matric potential						
–1 kPa, $m^3 m^{-3}$	ns	ns	ns	ns	ns	*↑
–10 kPa, $m^3 m^{-3}$	ns	ns	ns	ns	*↑	ns
Available water content at matric potential						
–10 kPa, $m^3 m^{-3}$	*↓	ns	ns	ns	ns	*↓
–100 kPa, $m^3 m^{-3}$	*↓	ns	ns	*↑	*↓	*↓
Matric potential for air-filled porosity						
0.10 $m^3 m^{-3}$, kPa	ns	ns	ns	ns	ns	ns
0.20 $m^3 m^{-3}$, kPa	ns	ns	ns	ns	*↑	ns
Water content *in situ,* $m^3 m^{-3}$	*↓	ns	ns	*↑	*↓	*↓
Air-filled porosity *in situ,* $m^3 m^{-3}$	*↑	ns	ns	ns	*↑	ns

tainerized (261 cm) seedlings and bare-rooted transplants (300 cm). The difference between the containerized seedlings and bare-rooted transplants was not significant. On the average, the bare-rooted transplants attained the ecologically important mean height of 100 cm (i.e. the average height of the snow cover) 1 year earlier than the containerized seedlings and 4 years earlier than the sown seedlings. Saplings growing on the burnt (264 cm) and ploughed (265 cm) plots were significantly taller than those growing on the disk-trenched (217 cm) plots at the end of the 16th growing season (V).

The same pattern was found in 2001, when the containerized seedlings had been growing for 25–27 growing seasons in the field. Site preparation significantly affected the mean height of the containerized seedlings (Table 3). The height growth on the burnt plots (626 cm) had been slightly faster than on the ploughed plots (612 cm) (VI). The shortest saplings were found on the disk-trenched plots (575 cm). The mean height of the pines on the patch-scarified plots (589 cm) was close to that of the disk-trenched ones. The height increment in 10 years was 352 cm (128%) for the burnt, 331 cm (128%) for the patch-scarified, 337 cm (142%) for the disk-trenched and 347 cm (126%) for the ploughed plots.

The highest CV values for mean height occurred on the plots reforested by sowing (V). According to the results at the end of the 16th growing season, the best combination of site preparation and reforestation methods was planting bare-rooted transplants on ploughed areas (324 cm). Consequently, the shortest saplings (on average 151 cm) occurred when the seeds were sown on the disk-trenched tracks.

The air-filled porosity *in situ* was a significant covariate in the mean height model of the combined data (VI). Mean height increased by almost one meter when the air-filled porosity increased from 0.05 to 0.45 $m^3 m^{-3}$ (VI). The soil water content *in situ* had a significant negative effect on mean height. The positive effect of the air-filled porosity at field capacity was close to significant ($p = 0.077$). The effects of effective temperature sum, altitude, the topographic wetness index, and various soil variables were not significant.

The air-filled porosity ($p = 0.016$) and water content ($p < 0.001$) *in situ* were significant covariates also in the mean height models that included the basal area of the saplings as a covariate. The basal area had a highly significant effect ($p < 0.001$) on the mean height in the models.

4.3.2 Survival in the combined data

Neither the site preparation nor the reforestation method had any statistically significant influence on the survival of the Scots pine seedlings at the end of the 16th growing season. The interaction between the site preparation and reforestation method was also non-significant (Table 3). However, the reforestation year had a significant interaction with both the site preparation and the reforestation method. When the results were analysed on a yearly basis, some significant differences were found (V). Survival was the highest on the plots regenerated immediately after site preparation. However, the differences among the reforestation years were not statistically significant.

The variation in the results was high, and the CV values varied between 42% and 77% among the method combinations (V). The best combination was planting containerized seedlings on ploughed areas (survival 0.57, CV 42%). The lowest survival (0.28) and highest variation in survival (CV 77%) was found on the plots treated with the disk trencher and reforested by sowing.

Ten years later in 2001, i.e. 25–27 years after reforestation, site preparation significantly affected the survival of the containerized seedlings (Table 3). Survival on the ploughed plots was significantly higher than on the plots treated with lighter site preparation methods (VI). The mortality was at its highest in the 1980s, but was negligible during the last 10 years (V, VI). The causes of dieback were not studied in 2001. However, fungal diseases such as *Phacidium infestans* (P. Karst.) (snow blight) and *Gremmeniella abietina* ((Lagerb.) Morelet) (Scleroderris canker) were the most common damaging agents on living saplings in earlier inventories (V).

The effective temperature sum and van Genuchten parameter α had significant effects on the survival of the containerized seedlings in 2001 (VI). The predicted survival tripled when the effective temperature sum increased from 650 d.d. to 850 d.d. The increase in survival was about 0.25 when α increased from 0.05 to 0.8 cm^{-1}. The other variables, such as the proportion of fine particles or the topographic wetness index had no statistically significant influence on survival.

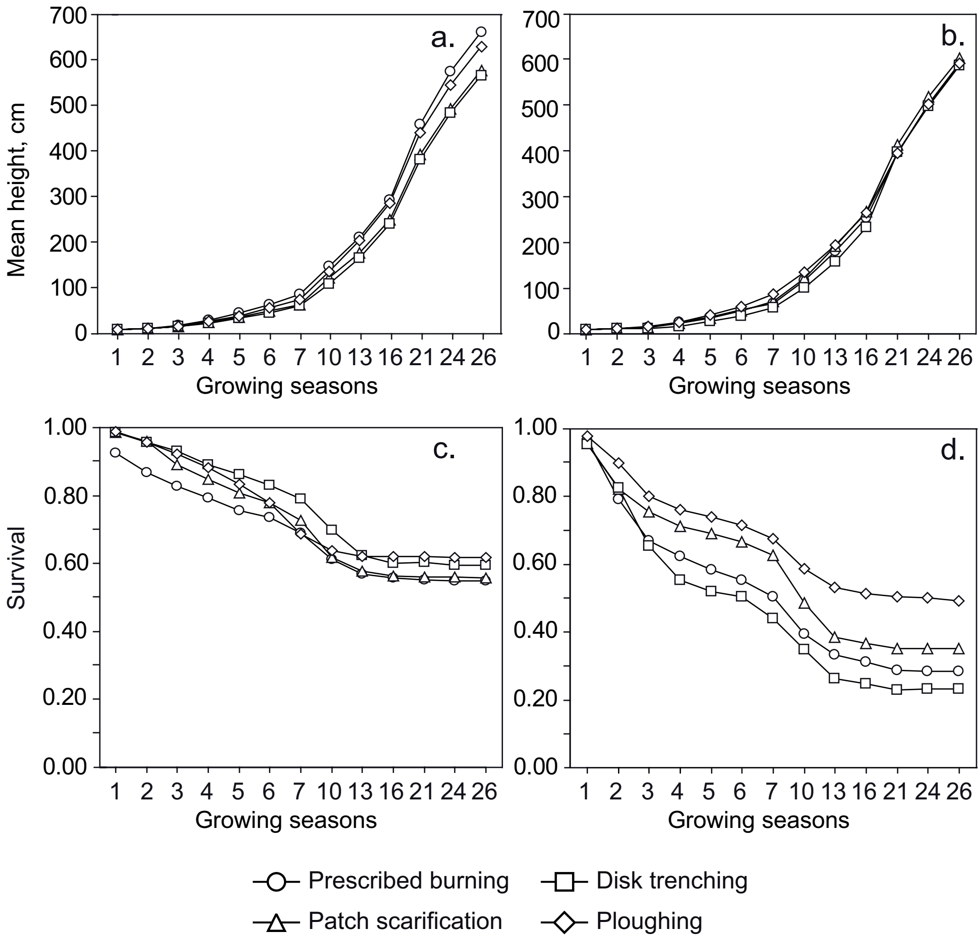

Figure 8. Development of the mean height (cm) of the planted Scots pine on the pine (a) and spruce sites (b), and the development of survival on the pine (c) and spruce sites (d) during the study period 1975–2001.

4.3.3 Height growth on the pine and spruce sites

Site preparation significantly affected the mean height on both the pine and spruce sites after 16 growing seasons, when all three reforestation methods were analysed together (Table 3). On the pine sites, containerized seedlings had grown significantly faster on the burnt (293 cm) and ploughed (286 cm) plots than on the patch-scarified (249 cm) and disk-trenched (242 cm) plots. After 25–27 growing seasons, the respective mean heights were 662, 630, 577 and 565 cm (Fig. 8a). The effect of prescribed burning differed significantly from that of patch scarification and of disk trenching (VI).

On the spruce sites, there were no significant differences among the four site preparations after either 16 (mean heights 234–267 cm) or 25–27 growing seasons (582–605 cm) on the plots reforested with containerized seedlings (Fig. 8b, VI). The significant differences among the site preparation methods at the end of the 16th growing season (Table 3) were mainly due the superior height growth of the sown saplings on the ploughed plots (208 cm) compared with the saplings on the disk trenching (128 cm) and patch scarification (159 cm) plots. These differences were, however, not significant in the later inventories (data not shown).

However, when the plots of containerized seedlings were "thinned" artificially to the same sapling density in all the site preparations, keeping the lowest number of survived saplings as the target density in every regeneration year, the result changed. MIXED showed a significant difference ($p = 0.03$) between ploughing (696 cm) and disk trenching (605 cm) after 25–27 growing seasons. The mean height on the ploughed plots did not differ significantly from that on the burnt (646 cm) or patch-scarified (662 cm) plots. "Thinning" was carried out by leaving only the tallest saplings on a plot.

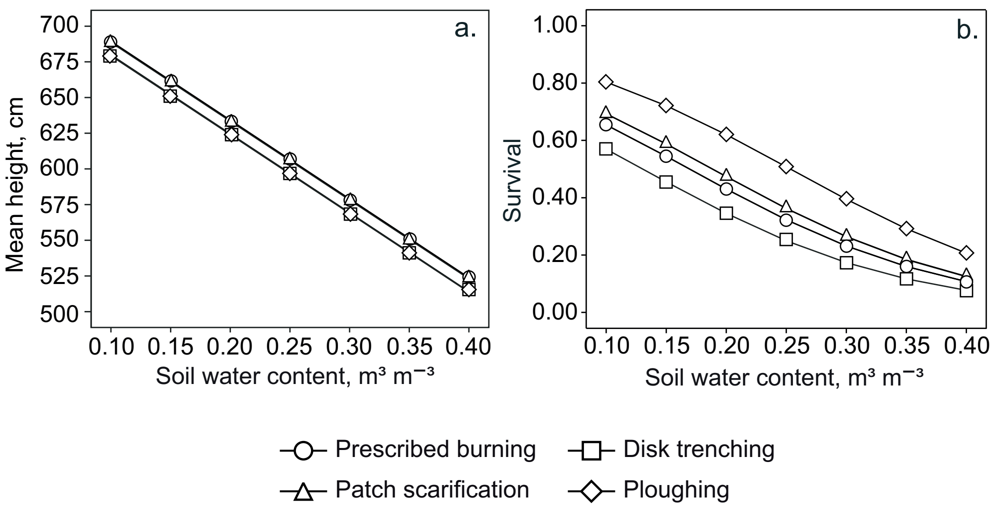

Figure 9. The predicted mean height (cm) of the planted Scots pine (a), and survival (b) of the planted Scots pine as a function of the soil water content in situ ($m^3\ m^{-3}$) for different site preparation methods on the spruce sites in dataset 2.

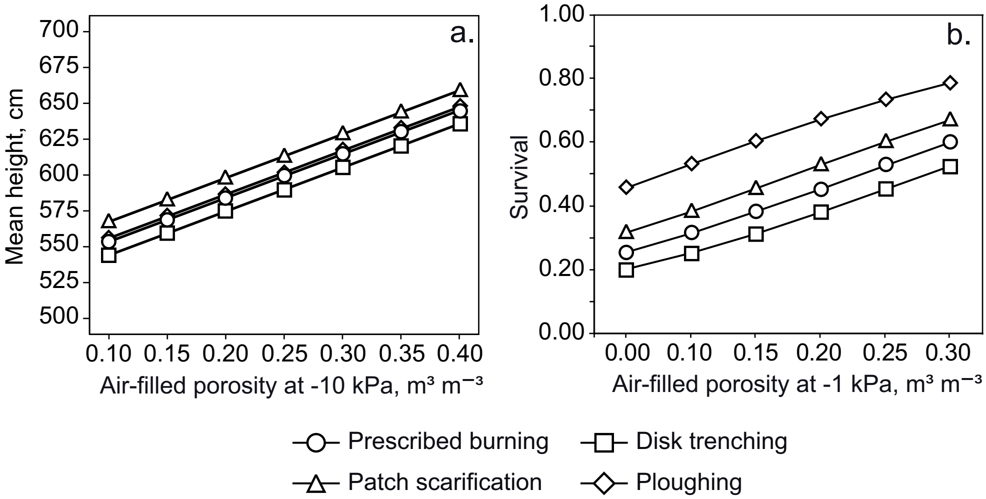

Figure 10. The predicted mean height (cm) of the planted Scots pine as a function of the air-filled porosity at a matric potential of –10 kPa (m^3 m^{-3}) (a), and survival as a function of the air-filled porosity at a matric potential of –1 kPa (m^3 m^{-3}) (b) for different site preparation methods on the spruce sites in dataset 2.

The proportion of pine or spruce in the previous tree generation had no effect on the mean height in the combined data (VI). The mean height was relatively similar on the pine (248 cm) and spruce (245 cm) sites already at the end of the 16th growing season (V). For the containerized seedlings, the corresponding heights were 267 cm and 255 cm, respectively. During the next 10 years, the growth rate was similar on both site types, and the absolute difference in the mean height increased by 4 cm (Fig. 8).

In general, the soil physical properties and conditions had significant effects on the height growth of pine on the spruce sites, but not on the pine sites (Table 3). An increase in the soil water content and a decrease in the air-filled porosity *in situ* resulted in a decrease in the mean height on the spruce sites (Fig. 9a). In addition, the mean height also significantly increased when the air-filled porosity at a matric potential of –10 kPa (Fig. 10a) or the matric potential for the air-filled porosity of 0.20 m^3 m^{-3} increased (Fig. 11a). The more detailed study showed that the highest statistical significance ($p = 0.0128$) was reached with the matric potential for the air-filled porosity of 0.21–0.22 m^3 m^{-3} (Fig. 11b). Significant p-values ($p < 0.05$) were obtained for the matric potentials representing air-filled porosities of between 0.13–0.25 m^3 m^{-3}. The mean height also increased significantly when the parameter n in the topsoil (Van Genuchten 1980) increased (Fig. 12a).

The impact of the air-filled porosity in situ on the mean height was positive in the models where basal area was a covariate. The effect was, however, only marginally significant (p = 0.054) on the spruce sites. The soil water content in situ had a significant negative effect on the mean height for the spruce sites ($p = 0.037$), and a marginally significant negative effect on the pine sites ($p = 0.50$). The basal area had a highly significant effect ($p < 0.001$) on the mean height in all the models.

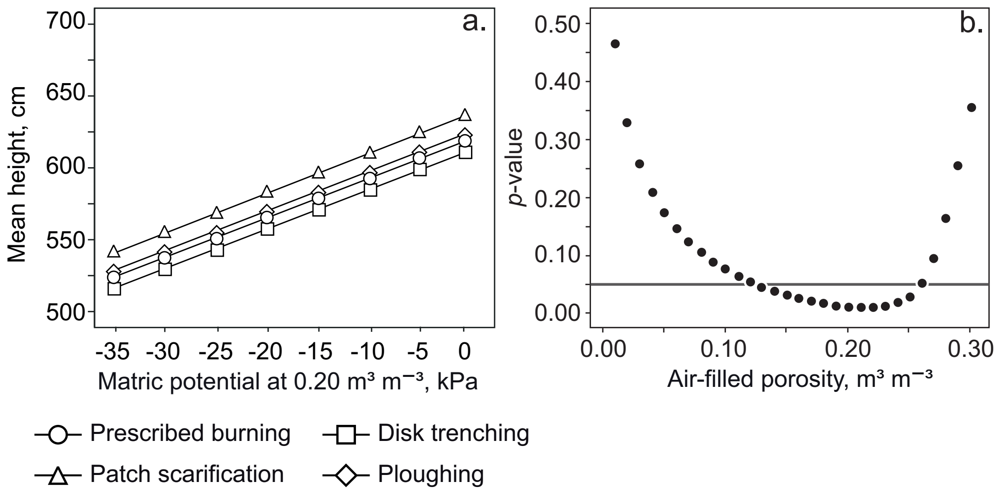

Figure 11. The predicted mean height (cm) of the planted Scots pine on spruce sites as a function of the matric potential at the soil-air-filled porosity of 0.20 m^3 m^{-3} for different site preparation methods (a), and the p-values (b) for different air-filled porosities (m^3 m^{-3}) in the model, in which mean height was explained by the matric potential calculated separately for each air-filled porosity value (<0.30 m^3 m^{-3}) in each plot on the spruce sites. The horizontal line represents the 0.05-significance level.

4.3.4 Survival on the pine and spruce sites

The mortality pattern was different on the pine and on the spruce sites (Fig. 8). Reforestation method had a significant effect on survival on the pine sites but not on the spruce sites at the end of the 16th growing season (Table 3). The containerized seedlings had a significantly higher survival than the sown ones (V). Site preparation affected the survival only on the spruce sites. The seedlings had survived the best on the ploughed plots (survival 0.44), which differed significantly from the disk-trenched plots (0.23).

On the pine sites, survival was almost equal among the site preparation methods (Fig. 8c), 25–27 growing seasons after reforestation. Survival of the containerized seedlings was significantly higher on the ploughed plots (0.49) than on the burnt (0.26) and disk-trenched plots (0.22) on the spruce sites (Fig. 8d).

The overall survival was 0.49 on the pine sites and 0.33 on the spruce sites at the end of the 16th growing season (V). Owing to differences in the altitude and temperature conditions between the site types, the difference in survival was not statistically tested and reported (V). The statistical analysis method used (ANOVA) did not allow the usage of block-wise covariates such as the effective temperature sum or altitude. According to the results after 16 growing seasons, survival seemed to be the higher, the higher was the proportion of pine in the previous tree generation (V).

Analysis of the survival of containerized seedlings 10 years later with a generalized linear mixed model (MIXED) showed that the effective temperature sum had a significant positive effect on survival (Table 3), but altitude no effect. Neither did the proportion of pine or spruce in the previous tree generation have any effect. The difference between the pine (0.58) and

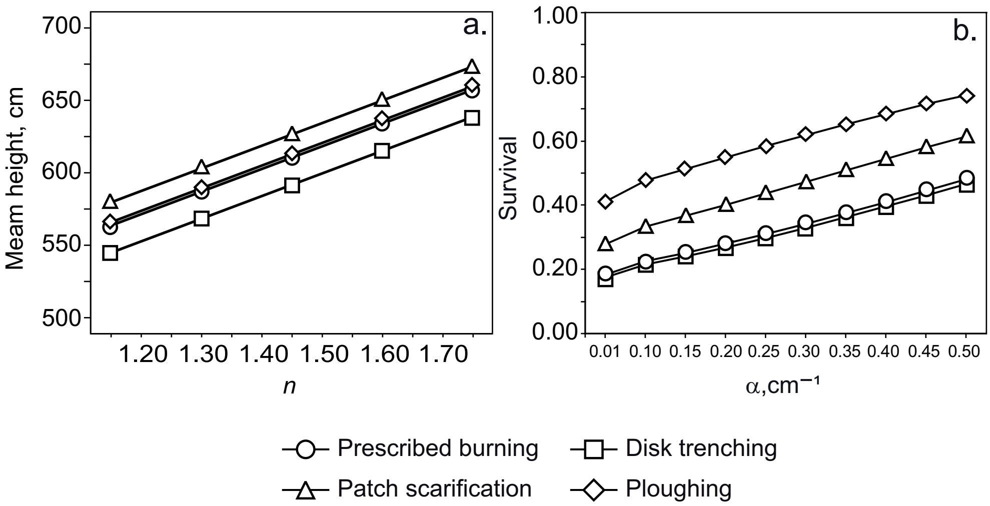

Figure 12. The predicted mean height (cm) of the planted Scots pine as a function of the van Genucten parameter *n* (a), and survival as a function of the van Genucten parameter *α* (cm^{-1}) (b) for different site preparation methods on the spruce sites in dataset 2.

spruce sites (0.34) in the survival of containerized seedlings was not significant after 25–27 growing seasons.

The soil physical properties affecting survival were different from those affecting the mean height. The parameter *α* (Van Genuchten 1980) (Fig. 12b), and the water content and air-filled porosity at a matric potential of –1 kPa (Fig. 10b), which are closely related to the soil aeration near saturation, had a significant impact on survival. Survival was the lower, the higher were *α* and the air-filled porosity, and it was the lower, the higher was the water content. The water content and air-filled porosity at a matric potential of –1 kPa and *α*were highly intercorrelated (VI).

Survival of the planted pines decreased on the spruce sites and increased on the pine sites when the water content *in situ* increased (Table 3, Fig. 9b, VI). When the soil water content of the different measuring rounds were used in modelling, it was found that the pattern and order of the site preparation methods in the models remained relatively constant among the measuring rounds, despite the different soil moisture ranges (Fig. 13).

The available water content at a matric potential of –10 kPa had a significant decreasing effect on the survival on the spruce sites, and that at –100 kPa a significant increasing effect on the pine sites and a decreasing effect on the spruce sites (Table 3).

The basal area of the saplings was a highly significant covariate in the survival models ($p < 0.001$). When it was used in the models, the effect of the soil water content *in situ* was significant only on the spruce sites ($p = 0.039$).

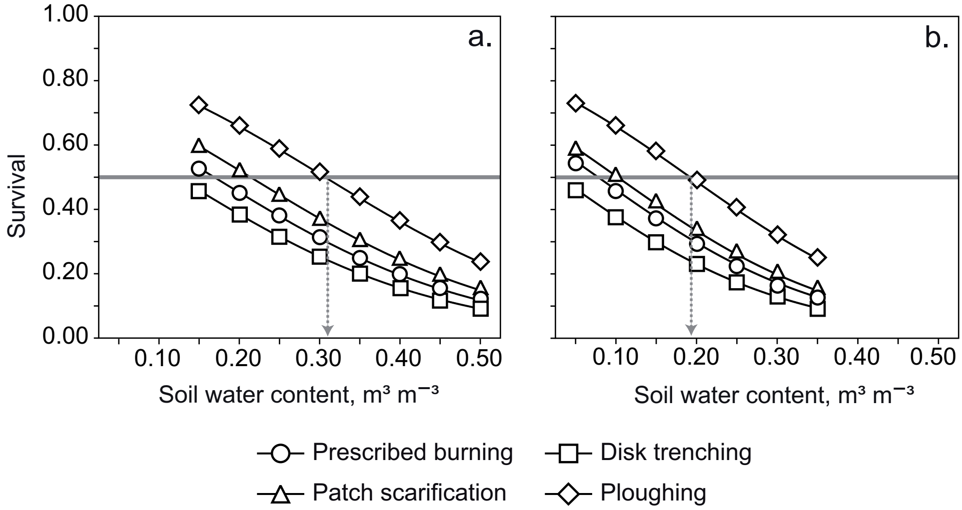

Figure 13. The predicted survival of the planted Scots pine on the spruce sites as a function of the soil water content in situ in June 1996 (a) and in September 1996 (b) for different site preparation methods. The horizontal solid line is the reference line for a survival of 0.50, and the dotted vertical line shows the soil water content for the survival value of 0.50 on the ploughed plots.

4.3.5 Soil moisture classification

When the effects of the continuous soil water content variable and the classified soil water content variable ("suitable" for pine reforestation = soil water content <0.27 $m^3 m^{-3}$, "unsuitable" = ≥0.27 $m^3 m^{-3}$) were analyzed separately for the eight measuring rounds, significant effects were found in seven cases of eight on the pine sites and in all eight cases on the spruce sites for the continuous soil water content (VI). The same was found with the average soil water content (i.e. the mean of the eight observations on a plot), indicating a significant positive impact on the pine sites and a negative impact on the spruce sites. Further analysis of the 40 randomized cases showed that the soil water content in situ had a significant positive influence on survival in 22.5% of the cases on the pine sites, and a significant negative influence on the spruce sites in 50% of the cases. However, the soil water content classified into two classes showed a significant impact on survival only in 2.5% of the cases on the pine sites and in 12.5% of the cases on the spruce sites.

On the spruce sites, survival was significantly ($p < 0.001$) higher on the plots where the average soil water content was classified as suitable (survival 0.46) than on the plots classified as unsuitable for pine reforestation (0.25) (Fig. 14). On the pine sites, however, survival was significantly ($p = 0.014$) higher on the unsuitable plots (0.72) than on the suitable plots (0.56). In the combined data, the difference between the two classes was non-significant.

The analysis of the soil water content data showed that the risk of false classification was less than 5% for the class "suitable" when the average soil water content of a plot was lower than 0.20 $m^3 m^{-3}$, and for the class "unsuitable" when the soil water content was higher than 0.37 $m^3 m^{-3}$ (Fig. 9 in VI). The soil water content was within this range on 57% of the 96 plots studied. The risk was the higher, the closer was the average soil water content of a plot to 0.27 $m^3 m^{-3}$.

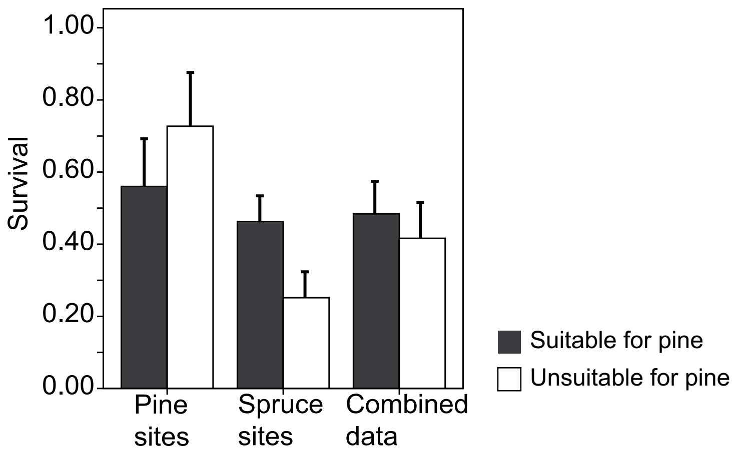

Figure 14. The mean survival (+SE, standard error) of the planted Scots pine in the two soil moisture classes, "suitable" for pine reforestation (soil water content in situ <0.27 $m^3 m^{-3}$) and "unsuitable" for pine reforestation (>0.27 $m^3 m^{-3}$) on the pine sites, spruce sites and all sites (combined data) in dataset 2, at the end of the study period. The differences in survival between the classes were statistically significant on the pine sites ($p = 0.014$) and spruce sites ($p < 0.001$).

5 DISCUSSION

5.1 Variation in soil hydrological properties and conditions

There was considerable variation in the soil physical properties and conditions both among and within the 20 mesic and sub-xeric heath forest sites. The values of the soil physical properties such as water retention characteristics, total porosity and bulk density were, however, mostly within the ranges reported earlier for till soils in Fennoscandia (Andersson and Wiklert 1972, Lähde and Mutka 1974, Lähde 1978, Lundin 1982, Heiskanen 1988, Nordén 1989, Høstmark et al. 1990, Jacobsen and Jensen 1990, Tamminen and Starr 1994, Nyberg 1995, Wall and Heiskanen 2003). This was also the case for the *in situ* measured soil water content and air-filled porosity (Siren 1955, Lähde and Mutka 1974, Kauppila and Lähde 1975, Mutka ja Lähde 1977, Lähde 1978, Ritari ja Lähde 1978, Sepponen et al. 1979, Ritari 1985, Magnusson 1992, III).

The water retention characteristics of till soils in Fennoscandia vary according to their texture, organic matter content and structure, and are normally between 0.22–0.55 $m^3 m^{-3}$ at a matric potential of –10 kPa i.e. at field capacity, and between 0.01–0.20 $m^3 m^{-3}$ at –1500 kPa, i.e. at wilting point (Heiskanen 1988, Nordén 1989, Høstmark et al. 1990, Jacobsen and Jensen 1990, Nyberg 1995). The results of this study verify the important contribution of soil organic matter and texture to the variation in soil water retention characteristics. In forest soils in Finnish Lapland, the water content near to field capacity has also earlier been found to correlate well with the above-mentioned variables (Sepponen 1981, Sepponen et al. 1979). These relationships are widely accepted (e.g. Lundmark 1986), and soil texture, or texture and organic matter content together, are commonly used in models predicting water retention characteristics (e.g. Gupta and Larson 1979, Rawls et al. 1982, De Jong et al. 1983, Saxton et al. 1986, Kern 1995, Kolev et al. 1996, Rajkai et al. 1996). Correspondingly, it was not a surprise that the *in situ* measured soil water content was strongly affected by the soil texture and organic matter content in this study.

The ranges of the spatial variation in the physical properties and conditions measured in this study were within those reported earlier for the *in situ* soil water content (Nyberg 1996, Hänninen 1997, Penttinen 2000). The location of individual trees, i.e. the internal structure of the stand, may cause spatial variability in soil properties and conditions (Liski 1995, Elliott et al. 1998). The water content measured in inter-canopy locations in 1993 was the lower, the higher was the basal area (at breast height of 1.3 m) of the planted Scots pines growing on the plot. Trees affect the soil water content and its spatial variation both through canopy transpiration (Kellomäki and Wang 2000) and the canopy interception of rainfall (Päivänen 1966). Thus, the effect of trees depends on the weather conditions during the growing season and on the point where the soil water content is measured. In this study, the influence of basal area was statistically significant in the dry late summer of 1993, but non-significant in the summers of 1995–1996, which represented average weather conditions. The strongest effect was found in the top 10-cm soil layer, where most of the fine roots of Scots pine are to be found (Kalela 1949, Persson 1980).

Temporal variation in the soil water content was clearly detected, even though the monitoring was carried out at intervals of 2 weeks at least. The temporal variation in the soil water content varied according to the soil texture, and was within the range of variation reported earlier in Finnish Lapland (Lähde and Mutka 1974, Kauppila and Lähde 1975, Mutka ja Lähde 1977, Lähde 1978, Ritari ja Lähde 1978, Ritari 1985, Hänninen 1997, Table 7 in III). Recently, Sutinen et al. (2007b) found that the dielectric constant (soil water content) in till soil on a flat spruce site in Finnish Lapland was temporally stable. They concluded that pines planted in wet soil spots are subjected to water saturation during snowmelt and excess water contents throughout their lifespan. Intra-seasonal wetting and drying did not alter the spatial pattern of the soil water content in their study. The spatial variation expressed as the CV of the soil water content *in situ* varied, however, considerably among the eight water content measurements and eight experimental sites in this study. The results indicate that the spatial patterns in soil moisture may not always be consistent over time, especially on sites with topographic variation. However, these results should be considered preliminary, and the subject needs further investigation.

The topographic variation in the terrain affects both the spatial and temporal variation in soil physical properties and conditions (Soulsby 1993). Yeakley et al. (1998) suggested that topography and soil physical properties are the two main geophysiographic factors regulating the soil water content on forested hill slopes. Topographic factors primarily control the variation in soil water content during drier periods as drainage progresses, while the variation in soil water storage properties is more important during wetter periods. According to Nyberg (1996), macro-topography causes a high proportion of the variability in the soil water content in forests. The soil water content in the present study was the highest with high topographic wetness index values and on toe-slopes, and the lowest on summits. Differences in soil water content among topographic classes may be explained by e.g. differences in drainage and in the depth to the water table (Beldring et al. 1999). However, the water retention capacity was higher with high topographic wetness index values, and also higher on toe-slopes compared with the other classes, and this may have partly caused the differences in soil water content.

In general, the water content increased with increasing depth. When the total porosity decreases with increasing depth (Høstmark et al. 1990, I), then the soil air-filled porosity and matric potential *in situ* most probably also decreases more rapidly than the water content increases. The air-filled porosity at a matric potential of –10 kPa, i.e. at field capacity, decreased with soil depth and was >0.40 $m^3 m^{-3}$ in the organic horizon and <0.15 $m^3 m^{-3}$ at the depth of 50 cm. Total porosity was lower and the bulk density higher with greater soil depth, which could imply a lower hydraulic conductivity at greater soil depths (Espeby 1989, Lind and Lundin 1990). Thus, in fine-textured soils with a low saturated hydraulic conductivity and high water content at field capacity, this may further prolong saturation in the root zone after snowmelt and heavy rainfall events. In coarse-textured soils with the lower water content at field capacity, dense or impermeable layers such as hardpan layers (site no. 4 in dataset 2) or the presence of bedrock close to the soil surface (patch-scarified plots on site no. 8 in dataset 2) may cause the same kind of effect (Ritari and Ojanperä 1984).

Significant differences in soil texture, organic matter content and water-retention characteristics were found between the pine and spruce sites in dataset 1, which represented almost pure pine- and spruce-dominated stands where the proportion of the other conifer species was low or it was totally missing. In several recent studies, soil water content has also been found to be higher on the spruce sites than on the pine sites (Sepponen et al. 1979, Hänninen 1997, Penttinen 2000, Salmela et al. 2001, Sutinen et al. 2002a). However, the differences in most of the hydrological and related physical properties, as well as in the soil water content *in situ*, between the pine and spruce sites were statistically non-significant in dataset 2, which also included mixed stands. It was also evident that there is a strong relationship between the proportion of pine (or spruce) in the previous tree generation and both the soil physical properties and conditions. These results are in agreement with the earlier findings of Sepponen et al. (1979), who reported significant differences in the soil texture, organic matter content and soil water content *in situ* in the topsoil between the pine and spruce stands, but not between the pure stands and mixed stands.

The soil aeration properties and conditions differed significantly between the pine and spruce sites. On the spruce sites, the air-filled porosity at field capacity in the topsoil was, in about 80% of the cases, lower than 0.20 $m^3 m^{-3}$, i.e. lower than the air space limit for good root growth of conifers. Similarly, in about 25% of the cases it was lower than 0.10 $m^3 m^{-3}$, i.e. lower than the minimum for root growth and lower than the lowest limit for gaseous diffusion in soil (Wesseling and Wijk 1957, Vocomil and Flocker 1961, Heiskanen 1993a). The results suggest that, under soil moisture conditions corresponding to field capacity, planted Scots pines presumably suffer from excess soil water content and poor soil aeration on most spruce sites, but not on pines sites, in Finnish Lapland. This is even more obvious under the wetter conditions prevailing after snowmelt and heavy rain events.

5.2 Effect of site preparation on soil hydrological properties and conditions

Bulk density was significantly lower, and total porosity and air-filled porosity at field capacity significantly higher in the ploughed ridges than in the intact intermediate areas. The results indicated that the modified soil physical properties and water-retention characteristics in the ploughed ridges could last and affect the soil water regime for more than two decades. De Chantal et al. (2003) found no significant differences among site preparation treatments in soil water retention and air-filled porosity in forest soils in southern Finland, immediately after and one year after site preparation. Compared with the present study, the lack of any differences in their study may be partly explained by the different sampling depth and different organic matter content.

On the average, there were no significant differences in the van Genuchten function parameters other than in the saturated water content, and the water-retention curves for the two locations had a relatively similarly shape. Modifications in the soil porosity and the pore-size distribution due to site preparation change the water-retention characteristics and hydraulic conductivity. The increase in soil porosity mainly occurs in the larger pore-size range, so that the proportion of this fraction increases (Lindstrom and Onstad 1984, Mapa et al. 1986, Ahuja et al. 1998). Consequently, a change in water retention occurs at high water potentials, when the changes that mainly take place in the macro-pores affect the air-filled porosity and, through this, also the availability of soil air and water to the planted tree seedlings (Dickerson 1976, Mannerkoski and Möttönen 1990, Heiskanen 1993).

The minimum soil air-filled porosity value for root growth (0.10 $m^3 m^{-3}$) and the value for good root growth (0.20 $m^3 m^{-3}$) were reached at higher matric potential values in the ploughed ridges than in the intermediate areas. These differences between the two micro-sites may cause some differences in the root growth of pine, especially on the former spruce sites with fine-textured soils after snowmelt and rainy periods, when waterlogged conditions can occasionally prevail. The results suggested that, while sufficient soil aeration for good root growth is reached in untreated soil under soil moisture conditions drier than field capacity on most of the spruce sites, it is already reached under moisture conditions close to saturation in the ploughed ridges. The soil aeration properties in the ploughed ridges on the fine-textured sites seem to be relatively similar to the properties in the untreated topsoil on the coarse-textured sites.

Site preparation had no effect on the soil physical properties and conditions in the untreated soil in the intermediate areas. For example, the bulk density and saturated water content values were almost the same, and the small differences among the site preparation methods could be explained totally on the basis of the differences in soil organic matter content. Hence, the use of heavy pulling machines with all the site preparation methods, except for prescribed burning, either did not cause any noticeable soil compaction or the soils had recovered during the past twenty years due to soil freezing and thawing (Chamberlain and Gow 1979, Miller 1980). The soil water content and air-filled porosity *in situ* in the intermediate areas were not affected by site preparation. Thus, compared to the lighter site preparation methods, the ploughed furrows seemed to have had no detectable lateral drainage effect in the intermediate areas. This has also been found earlier in the study of Mannerkoski and Möttönen (1990).

In boreal forests, the matric potential in the uppermost mineral soil layers is commonly close to field capacity, i.e. close to –10 kPa, but wilting point (c. –1500 kPa) may occasionally be reached (Lähde 1978, Heiskanen 1988, Norden 1989, Alavi and Jansson 1995, Alavi 1996). Although the water contents were very low at the end of the dry growing season of 1993, the wilting point was not reached in either the ridges or in the intermediate areas.

The soil water content *in situ* was significantly lower and the respective air-filled porosity higher in the ridges than in the intermediate areas 20–23 years after site preparation. The results concur with those of earlier studies performed 2–7 years after site preparation, which reported a significant difference in the soil water content between untreated soil (or patch) and ridge (or mound) (Mutka and Lähde 1977, Ritari and Lähde 1978, Lähde et al. 1981, Örlander et al. 1990a, Nohrstedt 2000). Recently, Sutinen et al. (2006) reported the same kind of results for 8 to 23-year-old ridges in Finnish Lapland. Lähde (1978) found a significant difference in both the total and air-filled porosity between ridges and untreated areas in the 0–10 cm layer, while the respective differences in deeper layers, and the difference in the soil water content in all layers, were not significant. The results of Mannerkoski and Möttönen (1990) showed a statistical difference in soil water content between ridges and unprepared intermediate areas only on a paludified site, while the difference in the soil matric potential was significant on all the sites.

The difference in soil water content between the intermediate areas and the ridges varied during summer and among the years, and it was dependent e.g. on soil texture. According to Lähde (1978), the respective difference in the 0–10 cm layer was 0.04–0.06 $m^3 m^{-3}$ on a coarse-textured site and 0.15–0.27 $m^3 m^{-3}$ on a fine-textured site, in the late summers of 1972–1976, i.e. 2–6 years after site preparation. The soil water content in the ridges had a strong positive relationship with the soil water content in the intermediate areas, i.e. the soil water content in the ridges on fine-textured sites was higher than that of the coarse-textured sites in this study. This emphasizes the effect of the fine fraction content on soil water retention characteristics and water content. The relationship has been recently confirmed in the study of Sutinen et al. (2006).

In addition to the differences in soil properties, there are probably also several explanations for the differences in the water content *in situ* between the two micro-sites. In most cases, the measurements were made in the ridges under the sapling canopies, while in the intermediate areas they were performed between the canopies. Thus, rainfall interception by the saplings planted on the ridges, which at its maximum close to the stem can be 50–75% (Päivänen 1966), may have lowered the water content in the ridges compared to that in the intermediate areas. In addition, the slight difference in elevation between the micro-sites may have caused a slight difference in the magnitude of the kPa value. It is also possible that the capillary rise of water in the ridges is still lower than that in the intermediate areas due to the artificially layered structure of the soil in the ridges (Mannerkoski and Möttönen 1990).

The distribution of roots was not studied in the present study, and the contribution of water uptake by the roots to differences in the water content remained somewhat unclear. Rusanen (1986) found that 80% of the pine roots in ridges were located in the mineral soil under the ridges, and that the horizontal distribution of Scots pine roots was relatively even on ploughed areas, including also the intermediate areas. However, Tanskanen and Ilvesniemi (2007) recently showed that the fine root biomass of planted Norway spruce in southern Finland was the highest in the ridges and the lowest in the intact intermediate areas and furrows, 20–33 years after site preparation.

The differences between the ridges and untreated intermediate areas may also be partly due to e.g. the lack of an organic layer on the ridges, and differences in the dominance and species composition of vegetation (Ferm and Sepponen 1981). As a result of these differences, evaporation from the soil may be higher in the ridges than in the intermediate areas, which may lead to a lower soil water content in the ridges. In addition, the snow cover during the winter is clearly thinner and it melts earlier on the ridges than on the untreated intermediate areas (Kubin and Poikolainen 1982). During summer, the difference in temperature between the ridges and intermediate areas (Leikola 1974, Lähde 1978, Ritari and Lähde 1978, Kubin and Kemppainen 1994) enhances the differences in evaporation and soil water content. No significant correlation was found between the height of the ridges and the soil water content in any of the layers in the ridges. The results are in agreement with those of Lähde et al. (1981), who found no statistically significant relationship between the height of the mound and the soil water content in the topsoil of the mound.

The mean heightof the ridges 19 years after ploughing was almost the same as the value of 13 cm reported by Rusanen (1986) 10 years after ploughing. Ferm and Pohtila (1977) reported that the height of the ridges was 14–29 cm (mean 21.9 cm) 2 years and 14–30 cm (mean 21.5 cm) 5 years after site preparation. Lähde et al. (1981) found a ridge thickness of 20 cm 7 years after ploughing. Unfortunately, no data were available about the original height of the ridges when the experiments were established. In earlier studies, the height of the ridges immediately after preparation has varied from 25 cm in shoulder ploughing (Ritari and Lähde 1978) to 30–40 cm in ridge ploughing (e.g. Kauppila and Lähde 1975, Ritari and Lähde 1978, Kellomäki 1972, Lähde et al. 1981).

In Finnish Lapland, the ploughing of clear-cut forest soils has been found to disturb, on the average, 64% of the total treated area (Ferm and Pohtila 1977). The ploughed track levels off vertically by a few centimeters and widens by a couple of tens of centimeters during the first years after site preparation. Ferm and Sepponen (1981) found 20% levelling of the original 46-cm distance between ridge and ditch bottom in 8 years, and most part of the levelling was considered to be due to compression of ridges. On more fertile and finer soils in Lapland, Kellomäki (1972) found that the difference in height between the ploughed ridges and the bottom of the furrow decreased by as much as one half within 15 years due to erosion, compression of the mineral soil, and decomposition and compression of the double organic layer. About 70% of the settling can occur within the 5 first years. In Canada, the height of mounds has been found to decrease by 50–75% within ten years after mounding, depending on the mounding equipment and composition of the soil in the mounds (Heinemann 1999). In general, the bulk density of the soil can recover to approximately its original value after varying periods of time, ranging from almost immediately after and up to 20 years after logging and site preparation, depending on the parent material (Corns 1988).

In this study, about 60% of the ploughed sites consisted of the treated area and 40% of the untreated intermediate area (Pohtila and Pohjola 1985). The ca. 1.0 m-wide ridges covered approximately 50–60 % of the treated area, i.e. 30–36% of the whole area of the site. If the ridges were about 30 cm high immediately after site preparation, it can be roughly calculated that there was a volume of ca. 1 000 m^3 ha^{-1} (100 litre m^2) of well-aerated soil available for the pine sapling roots. In two decades the volume has decreased to ca. 400 m^3 ha^{-1} (40 litre m^2). Because the shape of the ridges is convex, then these figures may be slight overestimates, especially immediately after ploughing. The ploughed tracks also included furrows on approximately 40–50% of the treated area, i.e. 24–30% of the total area. The aeration properties and conditions in the soil in the furrows are clearly unfavourable compared with those in the ridges, and even with those in the untreated areas, due to the lower total porosity and lower air-filled porosity at field capacity (I), and the higher water content *in situ* (Sutinen et al. 2006). These features have to be taken into account when the long-term effects of ploughing on soil properties and tree growth are elucidated.

5.3 Effect of site preparation and reforestation method on the performance of Scots pine

Site preparation significantly affected the height growth. The results indicated that the positive effect of burning on Scots pine growth on the former pine sites may last for over 25 years. The nutrient status of the soil remains satisfactory for a long time after burning (Viro 1974), which may explain the long-term favourable effect. Ploughing had an almost equally as strong effect on height growth as burning. In a number of studies, the height growth of conifers in the early post-preparation years has been reported to be the fastest on sites subjected to intensive site preparation treatments such as ploughing, mounding or inverting (e.g. Örlander et al. 1990a, 1998, Mattsson and Bergsten 2003, Hallsby and Örlander 2004, Saksa et al. 2005). In this study, disk trenching had the weakest effect on height growth.

The impact of site preparation on the pine-dominated sub-xeric heath forest sites was clear. The good height growth on the burnt sites was in conflict with the results reported by Örlander et al. (1990b, 1996). Their study indicated that burning decreases wood production compared to ploughing and the untreated control. This may be partly due to the drier and less fertile sites and more complete burning of the organic layer in their studies. The results of this study do not support the hypothesis of site productivity degenerating on ploughed sites. The long-term results obtained on dry lichen-type heath forest sites in northern Sweden (Örlander et al. 1990b, 1996, Mattsson and Bergsten 2003) coincided with this study. The height growth of the seedlings on the ploughed sites was clearly greater than that on the untreated sites.

Presumably the positive influence of both prescribed burning and ploughing on the pine-dominated sub-xeric heath forest sites is due to the increase in nutrient availability compared to the situation with the other two methods. Nitrogen often limits tree growth in boreal forests, and nutrient uptake seems to be a critical factor for the performance of conifer plantations after the establishment period (Örlander et al. 1990a). As discussed earlier, poor soil aeration is not a problem on the pine-dominated sites in Finnish Lapland. The results also suggested that the positive impact might last for a longer period of time on the burnt than on the ploughed areas. The difference in the mean height of pines between burning and ploughing has increased during the last 10 years (Fig. 7). The beneficial effect of ploughing on nutrient availability in the soil is mainly based on the higher temperature and enhanced microbial activity in the ridges, in contrast to the conditions in the untreated intermediate areas (Leikola 1974, Voss-Lagerlund 1976, Lähde 1978, Ritari and Lähde 1978). It is possible that these beneficial effects will decrease more rapidly than the effects of burning. However, the difference between burning and ploughing was not statistically significant after 25–27 growing seasons, and more research is needed on this subject.

Mattsson and Bergsten (2003) suggested that site preparation might affect the growth of contorta pine to a greater extent on poor sites than on sites of intermediate fertility. The results of this study with Scots pine are partly in agreement with these assumptions. However, because most of the spruce sites in this study presumably suffered from the poor soil aeration conditions, the effect of site fertility was not reflected in the results. The mean height of the Scots pines was even slightly higher on the pine-dominated sub-xeric heath forest sites than on the potentially more fertile spruce-dominated mesic heath forest sites. Unlike the pine sites, site preparation had no effects at all on the mean sapling height on the spruce sites. The results indicate that soil nutrient status is not a critical factor for the height growth of Scots pine on the spruce sites in Finnish Lapland, but that soil aeration presumably is.

Ploughing did not result in significantly better height growth on the spruce sites than the lighter methods after 25–27 growing seasons, which conflicts with the results of earlier studies (e.g. Örlander et al. 1990a). The results could be interpreted to mean that ploughing is not capable of ensuring adequate soil aeration for pine roots in the long run, despite the favourable aeration properties in the ploughed ridges found in this study. The roots also tend to spread out of the ridges into the soil of the surrounding intermediate areas and furrows (Rusanen 1986). As discussed earlier, ploughing does not seem to have any beneficial lateral effects on soil aeration in the untreated intermediate areas, and soil aeration in the furrows is even poorer than that in the intermediate areas.

Survival was clearly higher on the ploughed plots than on the other plots on the spruce sites. However, it is possible that saplings survived on the ploughed plots in spots with aeration conditions under which saplings died on the plots treated by other methods. The height growth of these saplings has presumably been relatively slow, thus decreasing the mean height on the ploughed plots. This conclusion gained support when the survival was artificially equalized and only the tallest saplings on a plot were included in the data: the mean height was significantly higher on the ploughed plots than on the disc-trenched plots in this dataset on the spruce sites.

The reforestation method had a significant influence on height growth. The mean height of the sown saplings was significantly lower than that of the planted saplings. Thus, in this study, height growth seemed to follow the pattern observed already in the initial height of the saplings (Ruha et al. 1997).

The results confirmed the low average survival in Scots pine plantations, reported in earlier studies in northern Finland (e.g. Pohtila and Pohjola 1983, Pohtila and Valkonen 1985, Valkonen 1992, Valtanen and Tasanen 1996). The wide variation in seedling survival observed in this study is in agreement with the results of Pohtila and Pohjola (1983). In an inventory study, Hallikainen et al. (2004) found 1 500 sown and 1 300 planted living pines on ploughed areas, 1 350 sown and 1 200 planted pines on disk-trenched areas, and 1 050 planted pines per hectare on mounded areas, 6–17 years after reforestation in Finnish Lapland. In this study, to the corresponding number of trees per hectare is: 900 sown and 1 425 planted pines on the ploughed areas, and 700 sown and 1 050 planted pines on the disk-trenched areas, 16 years after reforestation. Sowing especially was more successful in the study of Hallikainen et al. (2004) than in this study. However, comparing the results of inventories and of field trials is relatively problematic (Saksa 1992, Saksa et al. 2005, Miina and Saksa 2008). For instance, the number of reforestation spots may differ among the methods, reforestation years and tree species. During the 2000s, the recommended number of spots has been 2 500 for planting and 4 000 for sowing Scots pine in Finnish Lapland (Hyppönen et al. 2001).

At the end of 16th growing season, there were no statistically significant differences in the survival of Scots pine in the combined data among either site preparation or reforestation methods due to the high variation in survival. However, Pohtila and Pohjola (1985) reported highly significant differences among the reforestation methods ten years earlier on the plots of this study. The interaction between the site preparation and reforestation methods was also non-significant in this study, in contrary to the earlier results (Pohtila and Pohjola 1985, de Chantal et al. 2003). In the data of Pohtila and Pohjola (1985), for example, sowing had the best survival on the burnt and the worst on the ploughed plots, while the two planting methods showed opposite results.

According to the results of this study, there was high mortality in the Scots pine plantations as late as 10–16 years after reforestation. The mortality pattern was relatively similar to that reported in northern Sweden (Fries 1991, Persson and Ståhl 1990, 1993, Hansson and Karlman 1997). Hansson and Karlman (1997) suggested that more than 20 years are required in harsh boreal conditions before reliable results can be obtained about the outcome of reforestation. The relatively late mortality may result in sparse sapling stands, and cause volume increment losses if the contribution of natural regeneration is inadequate. The results of supplementary planting in northern Finland have been rather poor, and the mortality rate of these fill-in seedlings of Scots pine has been found to increase as the time interval between the original and supplementary planting increases (Saarenmaa and Leppälä 1995).

It has been earlier suggested that the mortality of pine seedlings is highest when the seedlings reach a height equalling the thickness of the snow cover (Lähde 1974, Olsson 1982, Hansson and Karlman 1997). The results of this study indicated that there is no specific critical height, but that mortality is more or less dependent on the occurrence of epidemics of fungal pathogens. These outbreaks most probably take place following cold, wet summers, which occur, on the average, at least once every ten years in Lapland. Thus, pine seedlings are exposed to these attacks at least once before they reach the mean height of 1.0–1.5 m (Jalkanen 1989).

The results also indicated that those seedlings with a height clearly below the top of the snow cover are especially susceptible. These results agree well with findings from northern Sweden, where decreasing mortality with increasing height was found: saplings below 0.5 m in height had the highest mortality and no saplings higher than 2.0 m had died (Fries 1991, Persson 1994a, 1994b). In northern Sweden, this height corresponds approximately to an age of 12–16 years (Persson and Ståhl 1990, 1993). Persson (2006) suggested that the reduced mortality of Scots pine associated with tree height and age may be partially explained by selection. Thus, most of the trees with a low tolerance to cold temperatures die at a young age. However, the reduced mortality of Scots pine may also be due to the fact that the sensitivity to environmental disturbances decreases with increasing tree size, e.g. to night frost near the ground surface (Persson 2006).

The highest mortality in the 1980s occurred on the sown plots. The mean height of the sown seedlings remained below the top of the snow cower for three to four years longer than the height of the other seedlings, and the main part of the canopy of the sown seedlings was exposed to snow blight damage. In addition, the dense groups of seedlings on the sown plots encourage infection and the spread of snow blight. The seedlings were exposed to snow blight for a longer period on the high altitude spruce sites than on the corresponding pine sites because of the greater thickness and longer retention of the snow cover. A thick snow cover has been found to favour the growth of *Gremmeniella abietina* (Marosy et al. 1989), and seedlings weakened by severe *Phacidium infestans* attacks can be later killed by *Gremmeniella abietina* (Karlman 1986, Roll-Hansen et al. 1992). Seedling mortality was the highest on the disk-trenched plots, where the mean height of the seedlings was the lowest in the 1980s. The thinner snow cover, and the higher growing position and the more rapid early height growth of seedlings on the ridges may partly explain the lower seedling mortality on the ploughed plots (Kubin and Poikolainen 1982, Roll-Hansen et al. 1992, Hansson and Karlman 1997).

Severe *Gremmeniella abietina* epidemics occurred in the 1980s in sapling stands of pine in northern Finland (Kaitera 1997) and in northern Sweden (Karlman et al. 1994). The period of high mortality recorded in this study coincides with the severe epidemic of Scleroderris canker on large trees in 1982–1986, reported by Kaitera and Jalkanen (1992). The damage in Scots pine plantations was the most severe on the spruce sites and on high-altitude sites with low effective temperature sums (Uotila and Jalkanen 1982, Karlman et al. 1994). Witzell and Karlman (2000) found that Scots pines planted on former spruce sites were more severely infected by *Gremmeniella abietina* than pines planted on former pine sites. Similar epidemics and a high mortality of Scots pine seedlings were also observed in the 1960s (Norokorpi 1971), 1970s (Heikkilä 1981) and in the 1990s (Kaitera 1997) following rainy and cool growing seasons. The wide variation in weather conditions is typical of northern Finland, and it causes a lot of problems in forest regeneration (Pohtila 1978).

The development of survival was different on the pine and on the spruce sites. In general, the results suggested that the reforestation of spruce sites with Scots pine appears to include a high risk of failure in Finnish Lapland. Varmola et al. (2007) have earlier reported total failures of Scots pine reforestation on fine-textured, spruce sites. Disk trenching and prescribed burning have proved to be unsuitable site preparation methods for spruce sites, but ploughing has a long-term, beneficial effect on survival. Intensive site treatment methods like ploughing and mounding have also been found to be superior in terms of survival on formerly spruce-dominated sites (e.g. Fries 1991, Örlander et al. 1996, Valtanen and Tasanen 1996, Hansson and Karlman 1997).

On the pine sites, the influence of site preparation on the survival of Scots pine was negligible. Thus, the results also indicated that excessive drying of the ploughed ridges has evidently not been a serious problem for survival even on sites with coarse-textured, till soil (cf. Kauppila and Lähde 1975, Ritari and Lähde 1978, Örlander et al. 1990a).

5.4 Effect of soil hydrological properties and conditions on the performance of Scots pine

The soil condition variables, soil water content and air-filled porosity *in situ*, and the laboratory-measured air-filled porosity at field capacity, all of which were determined on the soil in the untreated intermediate areas, affected the mean height of the containerized seedlings after 25–27 growing seasons. Mean height was the higher, the lower was the water content and the higher was the air-filled porosity. The results indicate that soil physical properties and conditions, and especially soil aeration, play an important role in the height growth of Scots pine in till soils in Lapland. It has earlier been shown in Finnish Lapland that soil water content and bulk density in the planting spot correlate negatively, and the air-filled porosity positively, with the early height growth of Scots pine seedlings (Lähde 1978, Ritari 1985, cf. Lähde et al. 1981). In Southern Finland, Levula et al. (2004) found that an increase in the soil water content decreased both the height and diameter growth of Scots pine saplings. However, when the pine and spruce sites were analyzed separately in this study, the impact of the above-mentioned variables on mean height was evident only on the spruce sites with relatively fine-textured soils. The effect of soil water retention characteristics can even be the opposite on sorted, coarser-textured soils, where soil drought may occasionally restrict pine growth (Viro 1962).

The mean height of the saplings was the better, the higher was the soil matric potential, when the air-filled porosity of 0.20 $m^3 m^{-3}$ was reached, or the higher was the van Genuchten (1980) parameter *n*. The water content in soils with high *n* values decreases faster with decreasing matric potential than in soils with low *n* values. Coarse-textured soils typically have high *n,* and fine-textured soils low *n* values. The results indicate that the growth of Scots pine is better, the sooner the soil dries to optimum aeration conditions for root growth after snowmelt and heavy rain events. These conclusions are supported by earlier studies on the optimum air-filled porosities for root growth (Heiskanen 1993a, Zou et al. 2001, Wall and Heiskanen 2003). Zou et al. (2001) found that the root growth rate of radiata pine was close to zero when the air-filled porosity was <0.05 $m^3 m^{-3}$, and reached 90% of its maximum value at 0.15 $m^3 m^{-3}$. All of these relationships were independent of the soil texture. Wall and Heiskanen (2003) showed that both the root dry mass and shoot height growth of Norway spruce seedlings, growing in mineral soil with low organic matter content, were at their highest at an air-filled porosity of 0.20 $m^3 m^{-3}$.

The proportion of soil fine particles (<0.06 mm) did not significantly affect survival, contradicting the earlier studies in Finnish Lapland. Lähde and Siltanen (1973) found that, on sites with over 100-cm-tall pine saplings in good condition, the proportion of fine particles in the soil was considerably smaller than that on sites with dead saplings. Lähde (1974) concluded that good results in establishing Scots pine on scarified sites in northern Finland can be expected on sites with a proportion of fine particles of less than 25%. He found a statistical difference in soil texture between condition classes (good, poor and dead) for saplings taller than 70 cm.

The reasons for the contradiction between the results of this and earlier studies remained somewhat unclear. The proportion of fine particles correlated significantly with the soil water content *in situ*. If the unfavourable effect of a high proportion of fine particles in a soil on seedling performance was due to a high soil water content and poor aeration in the above-mentioned studies, then the relationship between pine performance and the proportion of fine particles should have been similar also in this study. However, we found that topographic factors significantly affected the soil water content. Thus, it is possible that the data of Lähde and Siltanen (1973) and Lähde (1974) were collected from sites with a flatter topography, where the proportion of fine particles may have a stronger effect on survival. The different results may also be due to differences in the laboratory methods used in determining the proportion of the fine fraction (<0.06 mm). Different upper size limits, e.g. 20 or 2 mm in diameter, can be used for the soil samples. In the present study, the proportion used in statistical analysis was determined from the sample including particles <2 mm in diameter on each plot. The procedure used in the two studies cited above has not been reported in detail.

The higher the α parameter of the soil, the higher was the survival of the pine saplings. The α parameter of the Van Genuchten model for water retention is an empirical parameter, the inverse of which is often referred to as the air-entry value ($h \sim \alpha^{1}$) or bubbling pressure (Van Genuchten 1980, Van Genuchten et al. 1991). The air-entry value corresponds to the soil matric potential at which air truly enters the soil after some drainage has occurred (Van Genuchten et al. 1991, Nemati et al. 2002). According to Grip and Rodhe (1994, cited by Beldring et al. 1999), the air entry value in till soils is generally in the range of –0.1–0.2 m, i.e. ca. –1–2 kPa. The result obtained in this study suggested that the higher survival on the plots with high α values is related to better aeration conditions, while plots with low α values may be subjected to prolonged soil saturation after snowmelt and heavy precipitation episodes.

However, when the data were split into pine and spruce sites, α had a significant influence on survival only at the “wet end” of the sites, i.e. on the spruce sites. On these sites, the effect of near-saturated soil moisture conditions on survival was even more strongly supported by the laboratory-measured water content and air-filled porosity near saturation. The higher were the water content and the lower the air-filled porosity at a matric potential of –1 kPa on a plot, the lower was the survival after 25–27 growing seasons. The models also showed differences among the site preparation methods. For instance, planting pines on spruce sites in soil that reached the critical air-filled porosity for root growth of 0.10 $m^3\ m^{-3}$ close to saturation at –1 kPa, resulted in a long-term survival of 0.53 in the ploughed areas but only 0.25 in the disk-trenched areas. The more favourable aeration and temperature conditions in the ploughed ridges compared to the soil in the lighter site preparation methods presumably enhanced pine survival on the ploughed plots.

The soil water content *in situ* was not a significant covariate for survival in the combined data of this study. However, a statistically significant interaction between the soil water content and the proportion of pine before clear-cutting was found. The survival of the planted Scots pines decreased when the soil water content increased on the spruce sites, which is in agreement with the results of Sutinen et al. (2002b). In eastern Finland, Saksa (1992) found a significant negative correlation between the proportion of paludified plots and reforestation success on disk-trenched sites.

There may in fact be a number of reasons for the increase in mortality with increasing soil water content, and the causes may be different at different stages of seedling growth. For example, two periods of high seedling mortality were found on spruce site no. 2 in dataset 2.

The first period occurred during the first three growing seasons, and the second one during the five growing seasons in the middle of the 1980s (Fig. 5 in V). Abiotic factors, such as low soil temperature, high soil moisture and poor soil aeration in the patches, frost heaving on all the scarified spots, and the desiccation of seedlings on ploughed ridges and mounds, have been suggested as the main causes of pine seedling mortality in northern Finland during the first years after planting or sowing (Pohtila 1977, Heikkilä 1981, Mäkitalo 1983). All of these factors are closely related to soil texture and water content. Frost heaving damage is rather common, especially on sites with fine-textured soil (Goulet 1995, de Chantal et al. 2006). In a laboratory study carried out on soil samples from the sites of dataset 2, Liwata (1999) found the highest maximum frost heaving value (8 cm) for the soil of spruce site no. 2. The values for spruce sites no. 1 (6 cm) and no. 3 (6.5 cm) were also relatively high. No frost heaving at all was found in the soil from sites with coarser-textured soil, i.e. spruce site no.4 and pine sites no. 6 and no. 8. However, in addition to abiotic factors, insects such as the pine weevil (*Hylobius abietis*) (Sundkvist 1994, Örlander and Nilsson 1999), and mammals such as voles or moose (Rousi 1983a, 1983b), may cause severe damage to Scots pine plantations during the early growing seasons after reforestation.

The role of abiotic damaging agents has been found to decrease and the role of fungal diseases to increase with time in Scots pine plantations (Heikkilä 1981). However, long periods of poor soil aeration (Ritari and Lähde 1978, Lähde 1978) can predispose the seedlings to fungal pathogens also at later stages of seedling development, especially on spruce sites with fine-textured soils (Nevalainen and Uotila 1984, Uotila 1988). Saarenmaa and Leppälä (1995) found a clustered pattern in the mortality of Scots pine seedlings on ploughed and disk-trenched reforestation sites in northern Finland. The gaps in plantations were usually caused by unfavourable environmental conditions, e.g. waterlogged sites.

The most severe damage by *Gremmeniella abietina* on Scots pines has occurred in topographic depressions, where an unfavourable microclimate and high soil moisture may weaken the trees (Uotila 1988, Witzell and Karlman 2000). Fine-textured forest soils tend to have high organic matter contents. Both the proportion of the fine fraction and the organic matter content correlate well with site fertility (Westman 1990), which, in turn, correlates positively with the occurrence of *Gremmeniella abietina* (Witzell and Karlman 2000). Recently, Sutinen et al. (2000) suggested that a high shoot/root ratio predisposes fast growing Scots pine seedlings to dieback on spruce sites with fine-textured soils with a high water and nutrient content.

Besides the high soil fertility, high soil water content and poor aeration of fine-textured soils, the temperature regime of these soils may be unfavourable for root growth. Because of the high soil water content, fine-textured soils warm up slowly in the beginning of the growing season and cool down slowly in autumn (Ritari and Lähde 1978). During mild winters, and especially when snow falls on the unfrozen soil surface with a thick mor layer, the temperature in the root zone may remain above over zero throughout the winter (Schaetzl and Tomczak 2001). The wintertime soil conditions may have effects on the physiological condition of the planted seedlings, and thus predispose the seedlings to damage.

The soil water content had a significant positive effect on survival on the pine sites in this study. Because the survival was also significantly higher, the higher was the available water content at a matric potential of –100 kPa, it can be concluded that the planted Scots pine saplings may have suffered from drought stress on the driest pine sites during dry growing seasons. Consequently, the pine saplings may have been weakened, and thus become susceptible to damaging agents. *Phacidium infestans* and *Gremmeniella abietina* damage were also found on the pine sites in this study, as well as in the earlier studies carried out on similar sites (e.g. Witzell and Karlman 2000).

Although there seems to be a relationship between the soil water content and survival of planted Scots pine in Finnish Lapland, the effect of the trees themselves on the soil water content, the variation in the soil water content during and among growing seasons, and the different moisture regime on different sites and in different topographic positions, suggests that soil water content may have a poor explanatory value as a condition variable for survival. Therefore, utmost caution should be taken in using a fixed soil water content threshold (e.g. 0.27 $m^3\,m^{-3}$) as the sole criterion for sustainable pine plantation performance, especially when the fixed soil water content criterion is based on a single measurement on a site, instead of monitoring it for several growing periods (cf. Sutinen et al. 2002b). The results of Levula et al. (2004) support this conclusion.

If soil water content is to be a valid variable for soil classification and tree species selection, then it should result in a correct soil moisture class irrespective of when it is measured during the growing season. The analysis of randomly chosen cases showed only a few instances of statistically significant effect for the two-class soil moisture classification, but the relation between the soil water content and survival was more often significant on both site types. However, the significant effects found in the data from separate measuring rounds indicate that the results are better if the soil matric potential on the plots is as similar as possible. Thus, measuring the matric potential together with soil water content (e.g. Baumgartner et al. 1994, Noborio et al. 1999) might increase the reliability of the soil moisture classification. However, the results of this study indicated that the use of soil water content for site classification gives reasonable results only in the “wet end” of the upland forest sites in Finnish Lapland.

5.5 Material validity and methodological aspects

The data used in this study were considered to represent rather well the actual distribution of forest sites in Finnish Lapland where artificial regeneration with Scots pine is practised. The data consisted of 20 forest sites classified into either sub-xeric or mesic upland heath forest sites. Apart from one site with sorted coarse-textured soil, the sites were all located on till soils. According to the inventory data of Tomppo et al. (2005), the total area of sub-xeric and mesic heath forests is 92% of the area of the total productive forest land area in Finnish Lapland, and 85% of these forests are located on till soils.

The reforestation and site preparation methods used in this study were relatively similar to those used throughout the 1980s, 1990s and 2000s. In the 1970s, however, most of the containerized seedlings were paper-pot seedlings, planted together with the paper container. Thus, deformation of the root systems (Rautiainen & Kubin 1997) may have influenced the performance of the containerized seedlings in this study. However, the survival of the containerized seedlings was higher than that of the other reforestation methods, thus indicating that root problems have presumably been relatively minimal. Because ploughed ridges can be regarded as corresponding to linear mounds (Sutton 1993), the results for ploughing obtained in this study can also be generalized to apply to mounding with an inverted organic layer, which is nowadays used more frequently than ploughing.

Site preparation does not alter the soil water content (Mannerkoski and Möttönen 1990, III, IV) or the water retention characteristics, including the van Genuchten model parameters (II), in the intact intermediate areas. Consequently, it can be concluded that the soil physical properties in the intermediate areas represent the "original site properties" before clear-cutting and site preparation, and thus can be used as independent variables in the models (Spruill et al. 1993). However, because of the sampling approach used in this study, the effect of soil physical properties in the planting spots was included in the site preparation effect in the models. The effects were evident in the ploughed ridges (II, IV), but have elsewhere been considered negligible on plots prepared with lighter site preparation methods (e.g. Lähde 1978, Ritari and Lähde 1978, Sutinen et al. 2007b).

One possible explanation for the differences in soil condition variables between the micro-sites, ploughed ridges and intermediate areas, could be of a technical nature. The conversion function of Topp et al. (1980) used in this study for converting the measured dielectric constant to volumetric water content may give a slight underestimate of the soil water content in ridges with high total porosity and low bulk density (Noborio 2001, Robinson et al. 2003, II). For example, the conversion function of Malicki et al. (1996), which needs either soil bulk density or total porosity data, gives, on the average, a 0.05 $m^3\,m^{-3}$ higher soil water content for ridges (total porosity 0.62 $m^3\,m^{-3}$) than that of Topp et al. (1980). However, it also gives 0.03 $m^3\,m^{-3}$ higher values for the intermediate areas (total porosity 0.51 $m^3\,m^{-3}$) in this study. It is possible that the use of a different conversion function would have also affected the results in paper III, where the soil water content was measured at different depths with different porosities (I) (Alavi 2002). The effect of TDR conversion functions on the interpretation of soil moisture data should be studied in more detail in the future. The use of two different methods (capacitance method in III and TDR in IV and VI) for determining dielectric permittivity was not considered to cause any problems. According to Robinson et al. (1999), the measurement results for the capacitance and TDR methods are fully comparable.

Trees have an effect on soil moisture through transpiration and canopy interception (Kozlowski et al. 1991). As in the study of Sutinen et al. (2002b), who measured soil water content under the canopy of trees aged from 2 to 41 years, this was not taken into account in all of the models presented in this study. However, the use of sapling basal area to reduce the effect of the saplings on soil water content was tested in this study. Because of the even-aged, single-species planted stands with a relatively similar mean diameter in the present study, the basal area was also very closely linked ($p < 0.001$) to the dependent variable survival i.e. the number of saplings. This makes basal area a relatively problematic covariate when used together with soil water content in survival models. The use of the leaf area index (LAI) instead of basal area might be a better way to control the effect of trees on soil moisture (Alavi 2002).

6 CONCLUSIONS

The results obtained in the thesis showed that Scots pine- and Norway spruce-dominated upland forest sites in Finnish Lapland differ significantly in their soil hydrological properties and conditions. Under field capacity or wetter soil moisture conditions, planted pines presumably suffer from excessive soil water and poor soil aeration on most of the originally spruce sites, but not on the pine sites. The soil water retention characteristics and water content in situ had significant correlations with topography, the soil organic matter content and the proportion of fine particles, and the proportion of pine and spruce in the previous tree generation. The results indicated that site hydrology might be decisive for the natural tree species composition of sites in Finnish Lapland.

The results also suggested that the changes found in the soil physical properties and organic matter content caused by site preparation may affect the soil water regime and, through this, the prerequisites for forest growth for more than two decades after site preparation. The better soil aeration in ploughed ridges was verified on the basis of soil water content and air-filled porosity measurements *in situ.* However, the volume of well-aerated soil in ridges decreases due to soil erosion and compression, and the root systems of the planted pines tend to extend over time into the surrounding soil. In addition, because fungal pathogens that kill pine shoots and needles under the snow cover seem to be a common cause of pine seedling mortality in Finnish Lapland, a part of the beneficial effect of ploughing may be due to the thinner snow cover on ridges, and to the higher planting positions and faster early height growth of seedlings planted on ridges compared with those planted in the tracks formed by lighter site preparation methods. Therefore, the direct effect of good soil aeration in ridges on the survival of planted Scots pine, a decade or more after establishment of plantations, remained unclear.

High variation was found in the long-term survival and mean height of the planted pines. Survival, but not mean height, could be enhanced on the spruce sites, which usually have relatively fine-textured soils, by employing intensive site preparation methods like ploughing instead of lighter site preparation methods. On ploughed areas, the average survival of planted pines was close to that on the former pine sites. Disk trenching and prescribed burning proved to be unsuitable for spruce sites. From the point of view of the survival of planted pine, there seems to be a relatively broad assortment of site preparation methods suitable for pine sites with coarser-textured soils. The results of this thesis indicated, however, that site preparation methods that affect the nutrient status of the soil, such as ploughing and especially prescribed burning, may enhance the height growth of pine over several decades after reforestation on formerly pine-dominated sites in Finnish Lapland.

The results of the thesis suggested that, on formerly spruce-dominated sites, the survival of planted pines is the lowest on sites that dry out slowly after snowmelt and rainfall events, and that height growth is the fastest on soils that reach favourable aeration conditions for root growth soon after soil saturation, and/or where the average soil air-filled porosity near field capacity is large enough for good root growth. The results also indicated that, on formerly pine-dominated sites, the survival is the lowest on sites where the average soil water content and/or the available water content at low matric potentials is low, which may cause drought stress to seedlings during dry growing seasons.

Soil hydrological properties and conditions, as well as topographical variation, should be taken into account when Scots pine is reforested in Finnish Lapland. Intensive site preparation does not appear to ensure adequate performance of pine plantations on wet spruce sites. The use of soil water content measured *in situ* as the sole criterion for sites suitable for pine reforestation was tested in this thesis and found to be a relatively uncertain approach. However, the thesis identified new potential soil variables, such as water retention characteristics near saturation, the water retention curve parameters α and n (Van Genuchten 1980), and matric potentials for optimal soil aeration, that affect either the long-term survival or height growth of planted Scots pine. The use of these variables as criteria for sites suitable for pine should be tested using other data in the future.

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