Dissertationes Forestales 14

Soil water-retention characteristics and fertility of afforested arable land

Antti Wall

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

Academic dissertation

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in the hall of Vanha ruokala of the Hyytiälä Forestry Field Station, Hyytiäläntie 124, Korkeakoski, on December 16th 2005, at 12 o'clock noon.

Soil water-retention characteristics and fertility of afforested arable land

Antti Wall

Dissertationes Forestales 14

Thesis supervisors:

Prof. Carl Johan Westman, Department of Forest Ecology, University of Helsinki

Dr. Jyrki Hytönen, Finnish Forest Research Institute

Pre-examiners:

Prof. Martti Esala, Environmental Research, Agrifood Research Finland
Prof. Hannu Mannerkoski, Faculty of Forestry, University of Joensuu

Opponent:

Prof. Markku Yli-Halla, Department of Applied Chemistry and Microbiology, University of Helsinki

ISSN 1795-7389
ISBN 951-651-116-3 (PDF)

Paper copy printed:
Yliopistopaino, Helsinki, 2005

Publishers:
The Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
Faculty of Forestry of the University of Joensuu

Editorial Office:
The Finnish Society of Forest Science
Unioninkatu 40A, 00170 Helsinki,Finland
http://www.metla.fi.dissertationes

Wall, Antti 2005. Soil water-retention characteristics and fertility of afforested arable land. University of Helsinki, Department of Forest Ecology

ABSTRACT

From the standpoint of evaluating site quality for growing forest trees, the soil chemical and physical properties of cultivated arable land are poorly known. Therefore, soil matrix, water-retention characteristics and fertility of afforested arable land were studied. Subsequently, the implications of these soil characteristics for productivity of tree stands were assessed.

The results indicated that the soil properties of afforested arable land differ markedly from those of forest soils. The changes in the composition of the soil matrix due to former agricultural land use manifested as increased organic matter content in mineral soils and, in contrast, as increased mineral matter content in peat soils. In general, afforested arable lands were characterized by soils having high contents of nutrients, high content of organic matter, high pH, and low air-filled porosity at field capacity, which resulted from the predominance of small pores. In all investigated soils, the air-filled porosity was less than 20% in the topmost soil layer and decreased significantly with increasing soil depth. The results suggested that soils of afforested arable land commonly have critically low aeration for tree growth.

It appears that due to management history, afforested arable lands have a higher level of soil fertility compared to their inherent soil fertility. The high soil fertility of former arable land was, however, also attributed to the inherent properties of fine-grained soils. Consequently, based on of densities of Ca, P, silt and pH in the 0-10 cm soil depth, derived discriminant functions classified all sites from afforested arable land into forest site types of high productivity. Among these soils, those with high clay and silt content were the most fertile. The changes in the physical and chemical properties of soils due to former agricultural land use seem to be significant and long lasting to such a degree that afforested arable land is very unlikely to regain its inherent soil fertility even over an extended period of time.

Keywords: afforestation, agricultural land, nutrient availability, soil aeration, soil properties

ACKNOWLEDGEMENTS

This study was carried out at Kannus Research Station of the Finnish Forest Research Institute as part of the research project on afforestation of agricultural land. The study was financed by the Academy of Finland (project no. 209691), the Finnish Cultural Foundation, the Kemira Foundation, the Ministry of Agriculture and Forestry, the Niemi Foundation and the Nordic Forest Research Co-Operation Committee.

I thank the personnel of the Kannus Research Station for invaluable help and for their contribution to the outcome of this dissertation over the years. In particular, I thank Dr. Jyrki Hytönen for being a supervisor and co-author as well as for helping to find financing for my work. I am also deeply grateful to Prof. Carl Johan Westman for being a supervisor and co-author. I also thank Dr. Juha Heiskanen for being a co-author and Dr. Pekka Tamminen for scientific discussions and advice over the years. I thank Dr. Joann v. Weissenberg for revising the English language of this dissertation and some of the other papers. I also thank Prof. Hannu Mannerkoski and Prof. Martti Esala for critical reviews of this dissertation.

Kannus, November 2005

Antti Wall

LIST OF ORIGINAL ARTICLES

This thesis is based on the following original papers listed below, which are referred to in the text by their Roman numerals. These papers are reproduced with the permission of the journals in question.

I Wall, A. & Heiskanen, J. 1998. Physical properties of afforested former agricultural peat soils in western Finland. Suo 49: 1-12.

II Wall, A. & Heiskanen, J. 2003. Water-retention characteristics and related physical properties of soil on afforested agricultural land in Finland. Forest Ecology and Management 186: 21-32.

III Wall, A. & Hytönen, J. 1996. Painomaan vaikutus metsitetyn turvepellon ravinnemääriin. Summary: Effect of mineral soil admixture on the nutrient amounts of afforested peat fields. Suo 47: 73-83.

IV Hytönen, J. & Wall, A. 1997. Metsitettyjen turvepeltojen ja viereisten suometsien ravinnemäärät. Summary: Nutrient amounts of afforested peat fields and neighbouring peatland forests. Suo 48: 33-42.

V Wall, A. & Hytönen, J. 2005. Soil fertility of afforested arable land compared with continuously forested sites. Plant and Soil 275: 247-260.

VI Wall, A. & Westman, C.J. 2005. Site classification of afforested arable land based on soil properties for forest production. Submitted manuscript.

Antti Wall participated in planning the research together with his co-authors, was responsible for data collection, data analysis and writing of the first drafts of all papers, which were put into final form together with the co-authors.

TABLE OF CONTENTS

1 INTRODUCTION

In recent decades, afforestation of agricultural land has been an important land use change both in Finland and in other European Union countries. The general concern about surpluses of agricultural products has promoted forestry as an alternative land use to agriculture. In Finland, large-scale afforestation, aiming at reducing the area under cultivation, began in the late 1960s. At present, over 240 000 ha of arable land, i.e. some 11% of the total area of arable land (corresponding to 1% of the area of forest land), has been afforested (Finnish Statistical… 2003).

In Finland, arable lands are mostly mineral soils, and organic soils account for only 14% of the total area of arable land (Myllys and Sinkkonen 2004). Arable mineral soils are mainly fine-textured, sorted soils except in the eastern part of the country, where the prevailing soil type is till (Kähäri et al. 1987). In Finnish arable soils, as classified according to the FAO/Unesco system, Cambisols are most frequent; but Podzols, Regosols, Gleysols, Arenosols and Histosols have also been identified (Yli-Halla et al. 2000).

Ploughing and tilling results in mixing of the topsoil, decreased soil bulk density and increased total porosity (Lindstrom and Onstad 1984). Changes in porosity occur mainly in the larger pore-size range (Lindstrom and Onstad 1984, Mapa et al. 1986, Ahuja et al. 1998). These changes diminish gradually with time due to reconsolidation of soil caused by the impact of water drops and by wetting and drying of the soil (Cassel 1983, Onstad et al. 1984, Rousseva et al. 1988, Makeschin 1994). As opposed to ploughing, vehicular traffic compacts the soil and reduces aeration (Domżał et al. 1993, Czyż 2004). On mineral soils, cultivation commonly decreases the organic matter content of the soil by reducing inputs of plant litter and enhancing decomposition of organic matter due to elevated soil temperature and physical mixing (Mann 1986, Johnson 1992). On cultivated peatlands, drainage profoundly changes the hydrology of the site and results in reduced water content, increased bulk density and reduced organic matter content of soil (McLay et al. 1992). Furthermore, in cultivated peatlands the addition of mineral soil as a soil- improving agent results in an additional increase in bulk density as well as an increase in ash content (Pessi 1961a, 1961b).

In Finland, the application of lime and fertilizers in agriculture has increased considerably from the 1950s to the 1980s. This has led to a marked increase in soil pH and plant-available amounts of P, Ca, K and Mg in Finnish cultivated soils (Urvas 1985, Kähäri et al. 1987, Erviö et al. 1990). Under other conditions, various effects of previous agricultural land use on chemical properties of soil have been reported, for example, increased (Koerner et al. 1997, Compton and Boone 2000, Richter et al. 2000) or decreased N content of mineral soil (Ellert and Gregorich 1996), increased (Ellert and Gregorich 1996, Koerner et al. 1997, Compton and Boone 2000) or lowered (Kalisz 1986) P content, increased K (Goovaerts et al. 1990), Ca (Kalisz 1986) and Mg (Goovaerts et al. 1990) contents, and higher pH (Kalisz 1986, Goovaerts et al. 1990, Koerner et al. 1997). Moreover, agricultural land use has long-term effects on the structure of the microbial community (Buckley and Schmidt 2001), which in turn affect decomposition of organic matter, nutrient cycling and nutrient availability. These findings and those of other studies consistently suggest that former agricultural land use may have a significant effect on soil properties, lasting at least several decades or even centuries (Sandor and Eash 1995, Entwistle et al. 1998, Richter et al. 2000, Dupouey et al. 2002).

Site productivity is a result of the combined effects of physical, chemical and biological site factors and prevailing climate. For plant growth, in addition to sufficient supply of light and heat, the availability of nutrients, oxygen and water from the soil must be adequate. Commonly used indicators of soil fertility, which is defined as the ability of the soil to supply and sustain adequate amounts of nutrients for plant growth, are plant-available nutrient content, total nitrogen content, pH and organic matter content of soil (Schoenholtz et al. 2000). The supply of nutrients in the soil at any point in time is the net balance between additions and removals of nutrients in the available pool, the course of which are both natural and influenced by human activity. Nutrients are added through mobilization processes such as weathering of soil minerals, decomposition of organic matter, fixation of nitrogen and atmospheric deposition. In addition, nutrients are added through land use practices such as liming and fertilization. Nutrients are lost from the rooting zone through leaching and nutrient uptake of plants and become unavailable for plant uptake due to immobilization, i.e. chemical reactions including precipitation, adsorption reactions and ionic fixation.

Soils of varying texture generally differ in their mineral composition and consequently, in their nutrient contents. The contents of mica, chlorite, vermiculite, smectite and amorphous materials in soil decrease with increasing particle size, while the contents of feldspars and quartz increase (Sippola 1974). In Finnish agricultural soils, the contents of total K and Mg are higher in the clay fraction than in coarser fractions, while the total content of Ca is lower (Kaila and Ryti 1968). Furthermore, the contents of exchangeable K, Ca and Mg increase with an increase in clay content while the content of soluble P decreases (Lakanen and Hyvärinen 1971, Kaila 1972, Sippola and Tares 1978, Urvas et al. 1978). Thus, soil mineralogy and texture are inter-correlated and in an interacted way control the availability of nutrients from mineral soil. Depending on organic matter content, soils differ in their contents of nutrients. In general, the pH and contents of exchangeable cations (K, Ca, Mg) are lower in peat soils than in mineral soils (Sippola and Tares 1978). In peat soils, peat types having different botanical compositions differ in their chemical composition (Bohlin et al. 1989). Consequently, the contents of exchangeable of cations are higher in *Carex* peat than in *Sphagnum* peat (Sippola and Tares 1978).

Soil water-retention characteristics (retention curves) are important soil properties as soil pore-size distribution directly determines the amount of water that can be retained by the soil at a given matric potential, and inversely the air-filled porosity (Hillel 1982). Soil water content between fixed matric potentials is commonly used as a measure of water availability. Matric potentials used as the upper limit of plant-available water content (field capacity) have been reported to vary from -5 kPa to -33 kPa, while matric potential used as the lower limit (permanent wilting point) has commonly been -1500 kPa (McKeague et al. 1984). Available water content has been related to easily measurable physical properties of soil such as bulk density, organic matter content and particle-size distribution; but the relationship between available water content and these soil properties varies among textural classes and horizons (Salter and Williams 1967, Shaykewich and Zwarich 1968, Rivers and Shipp 1972, Reeve et al. 1973, Hudson 1994).

Availability of oxygen to roots depends on the rate of gaseous exchange (i.e. diffusion of oxygen into and diffusive removal of excess carbon dioxide from the soil) between the atmosphere and the growth medium. This soil aeration is positively related to air-filled porosity and negatively related to water content (Glinski and Stepniewski 1985). For mineral soils, an air-filled porosity of 10% is usually given as the minimum limit for gaseous diffusion and 10-15% for root respiration and growth, although *in situ* these values may actually vary from 5 to 30% (Wesseling and Wijk 1957, Vomocil and Flocker 1961, Magnusson 1992, Xu et al. 1992, Zou et al. 2001). In organic soils, such as peat, optimum air-filled porosity for tree seedlings may even be over 40% (Puustjärvi 1977, Lähde and Savonen 1983, Heiskanen 1995). In general, air-filled porosity is larger in coarse-textured mineral soils than in fine-textured soils and decreases with increasing bulk density (Heinonen 1954, Archer and Smith 1972, Reeve et al. 1973).

In Finland, over the past century the production potential of a forest site is estimated on the basis of its floristic properties (Cajander 1909, Cajander 1926, Cajander 1949). In Cajander's system of classification for mineral soils, site types are arranged into a floristic-ecological continuum that, presuming sufficient soil water is available, indicates that the Ca pool in the soil is the primary factor determining site productivity (Valmari 1921, Cajander 1926, Urvas and Erviö 1974). This site type classification system is broadly related to particle-size distribution of soil as it is typical that classes of lesser productivity potential appear on sites having coarse-grained and, most often, sorted soils (Aaltonen 1941, Urvas and Erviö 1974). However, site types indicating high productivity may also appear on coarse-grained soils as a result of auxiliary water supply, although site types of high productivity are more common on soils rich in fine-grained material. In peat soils drained for forestry, pools of N, P, K and Ca indicate the site productivity (Kaunisto and Paavilainen 1988, Westman and Laiho 2003). The importance of pH and N, especially the supply of mineral N, in characterizing soil nutrient regimes and site productivity has been reported elsewhere (Wang 1997, Giesler et al. 1998, Wilson et al. 2001).

Upon afforestation of agricultural land, to meet the objectives of forest management, information on soil chemical and physical properties and their effects on site productivity are needed to formulate site-specific management recommendations and policies. Such objectives may include wood production, preservation of biodiversity, preservation of recreational values, protection of groundwater quality and sequestration of atmospheric carbon. From the standpoint of silviculture, however, the chemical and physical properties of soil on arable land are poorly known. Furthermore, land-use change from agriculture to forestry induces a special problem for estimation of site productivity. The site productivity of forest land, which is defined as the ability of a site to produce wood biomass per unit area over a given time, is estimated based on site properties, stand properties or a combination of the two (Hägglund 1981). Methods of site classification for forest soils that are based on ground vegetation or stand properties are not feasible due to the absence of floristic properties inherent to forest ecosystems and to the absence of trees. Depending on management history, planted tree species and site fertility, such non-forest floristic properties may prevail in a plant species community for decades, centuries or even indefinitely (Bråkenhielm 1977, Peterken 1993, Dupouey et al. 2002). Thus, prior to afforestation, estimation of the site productivity of former arable land for forest production must be based on soil properties. Site productivity cannot be measured directly from soil properties, but must be inferred from those soil properties that serve as indicators of productivity.

1.1 Objectives

The main objectives of this thesis were to study the soil water-retention characteristics and fertility of afforested arable land and to assess the potential implications of these soil

characteristics for site productivity. In order to achieve this aim, the following specific objectives were set:
1) to characterize soil matrix by bulk density, densities of mineral matter and organic matter, and particle-size distribution (I, II, III, VI);
2) to examine soil water-retention characteristics, plant-available water content and air-filled porosity and to determine the effect of soil depth, organic matter content and particle-size distribution on these soil properties (I, II);
3) to examine soil fertility characterized by pH, density of total N and densities of extractable nutrients and to determine the effect of soil depth, organic matter content and particle-size distribution on these soil properties (III, VI);
4) to examine changes in soil fertility caused by agriculture (IV, V);
5) to estimate the site productivity of afforested arable land based on soil properties (VI).

2 MATERIAL AND METHODS

2.1 Approach

Afforested arable lands were randomly sampled in order to study their soil matrix, soil water-retention characteristics and soil fertility (I, II, III, VI). Soil fertility, availability of water and soil aeration were used as measures of quality of the soil as a growth medium for forest trees from the standpoint of timber production. Instead of directly measuring nutrient, water and aeration conditions in soil, nutrient and water availability and aeration were inferred from measured soil properties. This approach was chosen because physical and chemical conditions are transient states in soil and their measurement in the field is difficult, time consuming, costly and impractical due to the high degree of spatial and temporal variability (e.g. Rawls et al. 1991, van den Berg et al. 1997). Soil fertility was measured as levels of pH, density of total N and densities of nutrients that are extractable with acid ammonium acetate. Air-filled porosity was used as an indicator of soil aeration and was measured as the volume fraction of air-filled pores at matric potential -10 kPa (field capacity). Water content retained between -10 kPa and -1500 kPa matric potentials was used as an indicator of water availability. To examine changes in soil fertility caused by agriculture, the soil fertility of afforested arable lands was compared to that of adjoining continuously forested sites (IV, V). To estimate the site productivity of afforested arable land based on soil properties, the key components of soil fertility discriminating among site types of continuously forested sites, expressed as in the forest site type classification system (Cajander 1949), were identified and site productivity was estimated from soil properties using discriminant functions derived from continuously forested sites (VI). In this study, soil samples from the upper horizon of mineral soil were used to represent the current level of site productivity and soil samples from the deeper C-horizon to represent the original soil fertility that prevailed before agricultural land use altered the upper soil horizon.

2.2 Study sites

The material used to study the soil matrix, soil water-retention characteristics and soil fertility of afforested arable land consisted of 38 sites chosen randomly among arable lands afforested with Scots pine (*Pinus sylvestris* L.) in 1973-1974 and 1981-1982 (Table 1, I, II, III, VI). Thus, at the time the sample plots were established, the ages of the plantations were 11-12 or 19-20 years. The sites are located in western Finland and scattered over an area of 5500 km^2 (Figure 1). The mean effective temperature sum (threshold 5 °C) of the region is 1000 degree days and the mean annual total precipitation is 577 mm, while the mean accumulated precipitation from May to September is 280 mm. The elevation of the sampled sites varies from 65 to 122 m above sea level. The plantations were all situated on level ground. This study region started to emerge from the sea some 7000 years ago. The soils in this region are thus geologically young, less weathered and less leached than average soils in Finland (Aaltonen 1941). This material was supplemented with 22 fields on peat soil afforested with Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* (L.) Karst.) situated in North Savo, central Finland (III). The criterion used for selecting these study sites was that the sites had a peat layer more than 40 cm thick.

At each site, as a rule two circular sample plots 100 m^2 in area were delimited. However, if the area of the site was small, only one sample plot was established. The material of this data set included a total of 73 sample plots plus 35 plots from the supplemented material. The soils of the sample plots were classified into mineral soils, mull soils and peat soils according organic matter concentration: mineral soils had a concentration of organic matter less than 15% in the 0-20 cm soil layer, mull soils had a concentration of organic matter that was 15-40% and peat soils had a concentration of organic matter that was 40% or more (Aaltonen et al. 1949). The peat soils were divided into two classes according to the depth of the peat layer: deep peat soils where the peat layer was over 30 cm thick and shallow peat soils where the peat layer was less than 30 cm. The mineral soils of this data set are mostly Mollic Gleysols, but there are also soils having the features of Haplic Podzols, Eutric Regosols and Humic Cambisols (FAO 1988). On each sample plot, separate sets of soil samples were taken for analyses of nutrients and for analyses of water-retention characteristics. For analyses of water-retention characteristics, volumetric soil samples (162 cm^3) were collected using open-ended metal cubes (I, II). One sample per soil depth (5-10 cm, 15-20 cm, 25-30 cm, 35-40 cm) was collected from each sample plot. For nutrient analyses, the soil samples were taken from five soil pits of which one was dug in the centre and the other four were dug at even distances along the circumference of the plot (III, VI). Volumetric soil samples were taken with a soil corer at soil depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm. If the soil layer to be sampled consisted of clearly different soil horizons, sub-samples were taken from a given horizon and the horizon thickness was measured. The soil samples were bulked into one composite sample for each sample plot and soil depth.

To examine changes in soil fertility due to agricultural land use, pairs of afforested arable land and adjoining continuously forested sites located in central and southern Finland were chosen (IV, V). On peat soils, the six pairs were chosen using the criteria that (i) the afforested peat field was originally cleared from the adjoining peatland and (ii) the peat layer was at least 40 cm thick (IV). At each location, two circular sample plots 100 m^2 in area were placed on both afforested arable land and on the adjoining forest, except at one location, where six sample plots were placed on both afforested arable land and on the adjoining forest. The sample plots were situated at distances of 10 m and 30 m from either side of the ditch separating the arable land from forest. On each sample plot, the soil samples were taken from three locations, of which one was in the centre and the other two were opposite each other on the circumference of the plot. Volumetric soil samples were collected from 0-5 cm, 5-10 cm, 10-20 cm, 20-30 cm and 30-40 cm soil depth and bulked into one composite sample for each sample plot and soil depth. On mineral soils, the twelve pairs were selected using the criteria that (i) Norway spruce (*Picea abies* (L.) Karst.) was the dominant tree species on both the afforested arable and its adjoining forest, (ii) the adjoining site had been continuously forested and (iii) the afforested arable land and its adjoining forest had similar soil texture (V). At six locations the afforested arable lands had been afforested in 1990, and at another six locations they had been afforested in the 1930s. Thus, at the time the sample plots were established, plantations were 10 or 60-70 years old. At each location, three circular sample plots, each 100 m^2 in area, were randomly placed 10–30 m from each other both on the afforested fields and on their adjoining forests, except in one location where only four sample plots were placed. Volumetric soil samples were collected from the organic soil layer and from mineral soil at soil depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm.

To identify the key properties of soil fertility that discriminate among site types of forests, 30 sites located in central Finland were sampled (VI). These sites represent a fertility gradient in which site fertility varies from the dry and less productive *Calluna* site type to the moist and highly productive *Oxalis-Myrtillus* site type. From each stand, core samples were collected by horizon from three soil pits: the humus layer (O), the leached E horizon (E), the upper B horizon (B1), the lower B horizon (B2), and the parent soil material (C horizon). Prior to analyses, the three sub-samples were combined by horizon into one composite sample.

To estimate site productivity of afforested arable land based on soil properties, randomly chosen sites on mineral soils located in western Finland were used (VI). The material of this data set includes 40 sample plots situated on 24 sites. On each sample plot, the soil samples were taken from five soil pits, of which one was dug in the centre and the other four were dug at even distances along the circumference of the plot. Volumetric soil samples were taken with a soil corer at soil depths of 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm. The soil samples were bulked into one composite sample for each site and soil depth.

2.3 Soil analyses

Water-retention characteristics of the soil samples were measured at matric potentials of -1, -5, -10, -100 and -1500 kPa (I, II). The air-filled porosity and the plant-available water content were calculated from the measured water retention values. The total porosity of the soil samples was calculated from the bulk density and the density of solids. The bulk density was estimated as the ratio of dry mass to the total soil volume determined after saturation. The organic matter content was determined as a percentage of the loss of mass after ignition at 550 °C. The density of solids was measured on 63 randomly chosen samples using a pycnometer with water as filling liquid, and heating in a water bath (Heiskanen 1992). Soil colour was determined either with a tristimulus colour analyser or visually with Munsell colour charts. After organic matter was removed from the samples with H_2O_2, the particle-size distribution was determined by dry-sieving and sedimentation method (Elonen 1971).

Prior to nutrient analysis, soil samples were sieved through a 2 mm mesh sieve, roots were removed, and the samples were air-dried and stored at room temperature. After HCl extraction of ignition residue, soil samples from peat soils were analyzed for total P, K, Ca, Mg, Fe, Mn and Zn concentrations (III, IV). The total N concentrations of all soil samples were determined by the Kjeldahl method (Halonen et al. 1983) (III, IV, V, VI). After extraction with 0.5 M NH_4OAc (pH 4.65) (Halonen et al. 1983), concentrations of extractable P, K, Ca, Mg, Mn, Fe and Zn were determined either with inductively coupled plasma emission spectrometry (ICP) or with an atomic absorption spectrophotometer, and P concentration by colorimeter using the molybdenum blue method (III, IV, V, VI). After H_3PO_4-H_2SO_4 extraction of ignition residue or digestion of the soil samples with HNO_3-H_2O_2 in a microwave oven, the concentration of extractable B was determined (III, IV, V). Soil pH was measured in distilled-deionized water from dried soil samples using a 1:2.5 soil - solution suspension (III, IV, V) or in a 0.01 M $CaCl_2$ suspension (VI).

Amounts of nutrients at different soil depths were calculated on the basis of oven-dry (105 °C) weight of the soil samples using bulk densities and expressed on an area basis for the sampling depth (kg ha^{-1}) (III, IV, V). The amount of organic matter for each soil depth was calculated by multiplying the concentration of organic matter by the bulk density and was expressed on an area basis for sampling depth. Nutrient values were also expressed as densities of nutrients in soil (mg cm^{-3}) at different soil depths and were calculated on the basis of nutrient concentrations and oven-dry (105 °C) weight of the soil samples using bulk densities (VI).

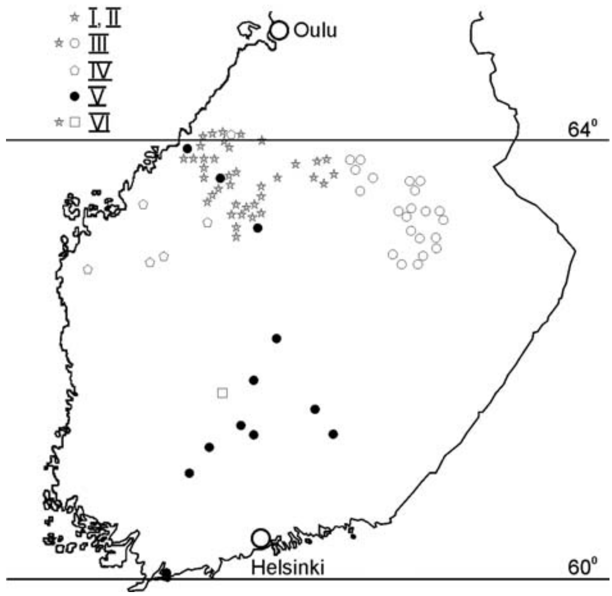

Figure 1. Location of the study sites.

Table 1. Summary of the study material and the measured soil properties.

Paper	Number of sites	Number of sample plots	Number of soil samples	Analyses
I	21	31	111	Water-retention characteristics Bulk density Particle density Organic matter content Colour
II	23	38	138	Water-retention characteristics Bulk density Particle density Organic matter content Colour Particle-size distribution
III	36	54	214	Total nutrient content (N, P, K, Ca, Mg, Mn, Fe, Zn) Extractable nutrient content (P, K, Ca, Mg, Mn, Fe, Zn, B) pH Bulk density Organic matter content Particle-size distribution
IV	12	32	160	Total nutrient content (N, P, K, Ca, Mg, Mn, Fe, Zn) Extractable nutrient content (P, K, Ca, Mg, Mn, Fe, Zn, B) pH Bulk density Organic matter content
V	24	70	344	Total nutrient content (N) Extractable nutrient content (P, K, Ca, Mg, Zn, B) pH Bulk density Organic matter content Particle-size distribution
VI	54	70	276	Total nutrient content (N) Extractable nutrient content (P, K, Ca, Mg) pH Bulk density Organic matter content Particle-size distribution

2.4 Statistical analyses

In peat soils, to determine the effect of soil depth and organic matter content on the water-retention characteristics, repeated measures analyses of variance was used (I). In mineral and mull soils, the effect of soil depth, organic matter content and particle-size distribution on water content at selected matric potentials, air-filled porosity and plant-available water content was tested with mixed linear models (II). To estimate the potential linear relationships between the soil properties, correlation and regression analyses were used.

To determine the effect of soil depth and organic matter content on pH and on amounts of nutrients in peat soils, repeated measures analyses of variance was used (III). To determine the effect of soil depth, organic matter content and particle-size distribution in mineral soils on pH, density of total N and densities of extractable nutrients, mixed linear models were used (VI).

To examine changes in soil fertility of peat soils due to agriculture, differences in soil properties between former arable lands and continuously forested sites were tested with a *t* test for paired samples (IV). In mineral soils, differences were tested separately for each soil depth with ANOVA (MIXED) as a multilocation trial (V). In the data analyses, the focus was on land-use effects averaged over entire populations represented by the various locations.

In order to identify the soil properties that best reveal the differences among site types, soil properties from the E horizon of forest soils were subjected to discriminant analysis (SAS 1989) using stepwise selection (VI). Canonical discriminant analysis was then used to classify sites from forest soils into site types. Next, the derived discriminant functions were applied to classify 24 sites from afforested arable land situated on mineral soil into forest site types using soil properties from the 0-10 cm soil layer. The same above- mentioned discriminant analysis was repeated for the C horizon of forest soils and for the 30-40 cm soil layer of afforested arable land. Finally, cluster analysis was used to group soils from the 0-10 cm soil layer of arable land into clusters with similar soil properties.

3 RESULTS AND DISCUSSION

3.1 Soil matrix

Use of machines in agricultural operations can result in increased soil compaction, bulk density and, consequently, physical degradation of the soil (Soane et al. 1981, Domżał et al. 1993, Alakukku 1999). Soil compaction, in turn, may result in mechanical resistance and reduced root growth (Siegel-Issem et al. 2005). The results of this study showed no indication of soil compaction in afforested mineral soils. On the contrary, the bulk density of soil on afforested arable land was lower than that in soils from continuously forested sites (V). In contrast to this finding, it has been reported that the bulk density of soil is lower in mineral soils under forests than in soils under field crops (Rolfe and Boggess 1973, Messing et al. 1997, Compton et al. 1998). The lower bulk density of mineral soil in afforested arable land found here, compared to forest soils, is probably a legacy of agriculture because tillage decreases the bulk density of soil and increases the total porosity (Lindstrom and Onstad 1984). Furthermore, the increased organic matter content of soil in

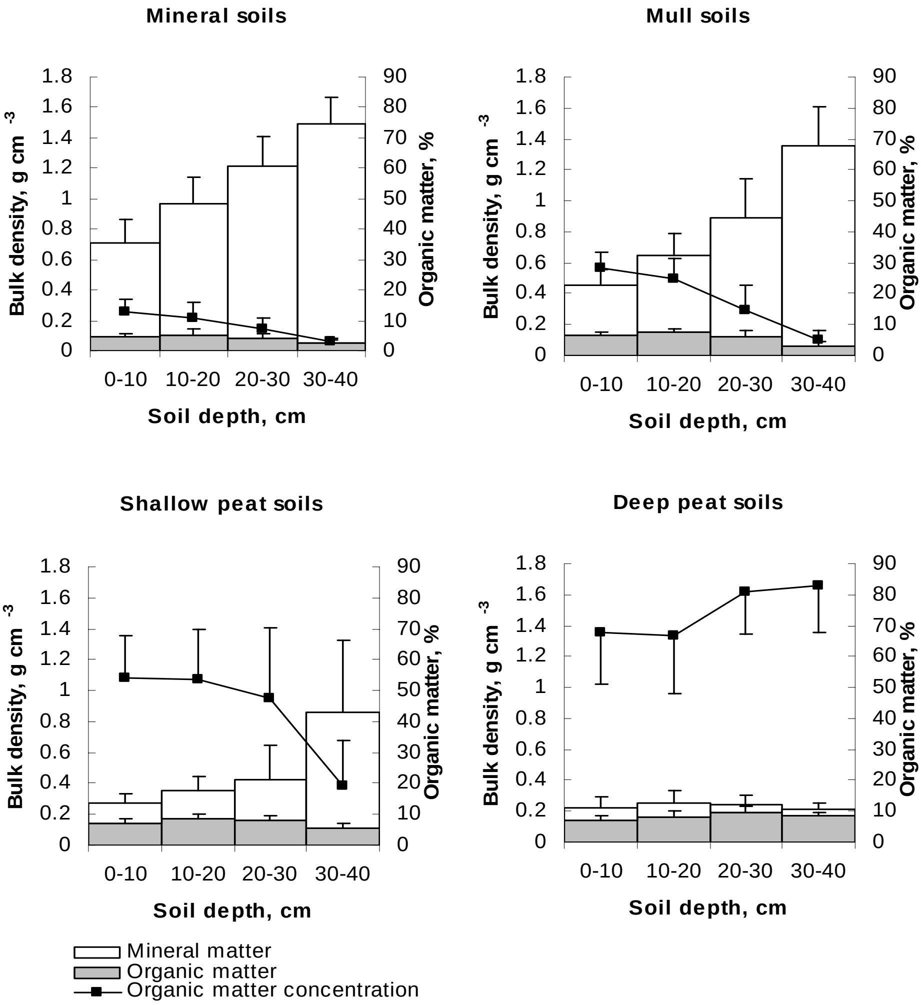

Figure 2. Mean bulk density of soil and its distribution into mineral matter and organic matter and the organic matter concentration of soil on afforested arable land by soil types and soil depths. Bars show plus or minus standard deviation.

former arable land also results in decreased bulk density due to the inverse relationship between organic matter content and bulk density (Adams 1973, Federer et al. 1993).

In mineral and mull soils, the organic matter content decreased markedly lower down in the soil profile and the bulk density increased (Figure 2). The mineral soils of the afforested arable land contained more organic matter in the 0-20 cm soil depth than in adjacent continuously forested sites (V, VI). This indicates that agricultural land use increased the organic matter content of soil, which is in contrast to the view that in most cases cultivation results in loss of organic C from the soil compared to the original C content (Mann 1986, Davidson and Ackerman 1993). The increase in organic matter content in the afforested arable lands studied here is, in addition to boreal climate, a result of the use of organic amendments and incorporation of residues and below-ground litter from agricultural crops into the soil. Furthermore, liming of fields during the agricultural period may have had a stabilising effect on the organic matter, thus contributing to its accumulation (Oades 1988).

In contrast to mineral soils, peat soils of afforested arable land had higher bulk density in soil at the depth of 0-20 cm than did peatlands drained for forestry (I, III, IV). This is in accordance with the results of other studies (Kaunisto 1991, Hynönen and Makkonen 1999). High bulk density of soil was due mainly to the use of mineral soil as a soil ameliorant or to mixing mineral soil during ploughing from the mineral soil underlying a shallow peat layer. In western Finland, the amount of added mineral soil was found to be, on average, 230 m^3 ha^{-1}, while in central Finland the corresponding amount was 630 m^3 ha^{-1} (III). Most of the added mineral soil was still located in the uppermost soil layers (0-20 cm depth) while minor amounts had been transported to deeper soil layers (III), as has been found in other studies (Kaunisto 1991, Hynönen and Makkonen 1999). In addition, soil compaction and more advanced decay of the peat due to enhanced decomposition probably have also had an effect on bulk density and ash content.

In terms of densities of mineral and organic matter, mull soils are a soil class intermediate between mineral soils and peat soils (Figure 2). It is likely that mull soils have originated from peatlands with a shallow peat layer, which during decades of cultivation has decomposed (Valmari 1983, Myllys and Sinkkonen 2004). Accordingly, in mull soils, in most cases peat remnants mixed with mineral soil were still recognisable (II).

Mineral and mull soils were commonly located on fine-textured clay and silt soils and thus had finer texture than forest soils in general (II). In Finland, some 80% of mineral forest soils are till soils in which the prevailing particle fraction is fine sand (Ilvessalo 1933, Aaltonen 1941, Tamminen 1991). In contrast to forest soils, agricultural mineral soils are clearly more fine-textured, sorted soils, except in the eastern part of the country where the prevailing soil type is till (Kähäri et al. 1987). In eastern Finland afforested arable lands are also more commonly located on silty or sandy till (Hynönen and Saksa 1997).

3.2 Soil water-retention characteristics

In afforested mull soils, total porosity and water retention were generally higher than in mineral soils in the entire profile but lower than in peat soils (I, II). In afforested peat soils, the total porosity was lower than that of a natural *Sphagnum* bog peat (Päivänen 1973) and commercial peat growth media (Heiskanen 1993b); nevertheless, water retention at low matric potentials was considerably higher. In mineral soils and mull soils, total porosity and water retention capacity were highest at a soil depth of 5-10 cm and decreased with increasing depth in the profile (Figure 3, II). In deep peat soils, the relation to depth in soil was the opposite: total porosity and water retention capacity were lower at a depth of 5-10 cm than deeper in the soil (I).

In all four soil classes and at all sampling depths, most water was retained within the matric potential range -100 kPa to -1500 kPa, indicating that small pores (diameter 0.2- 3.0 μm) made up the predominate pore size class (I, II). In mineral soils, the predominance of small pores may be attributed to the fine texture of the soils. In mull soils, in addition to fine-grained mineral material, decomposed peat material also contributes to the abundance of small pores. Apparently, cultivated peat soils have lost their original structure due to compaction and decomposition of peat. In cultivated peat soils, water retention is predominantly characterized by micro-pore formation caused by biochemical transformations of plant constituents in decomposition (Flaig 1986). In forest soils, the

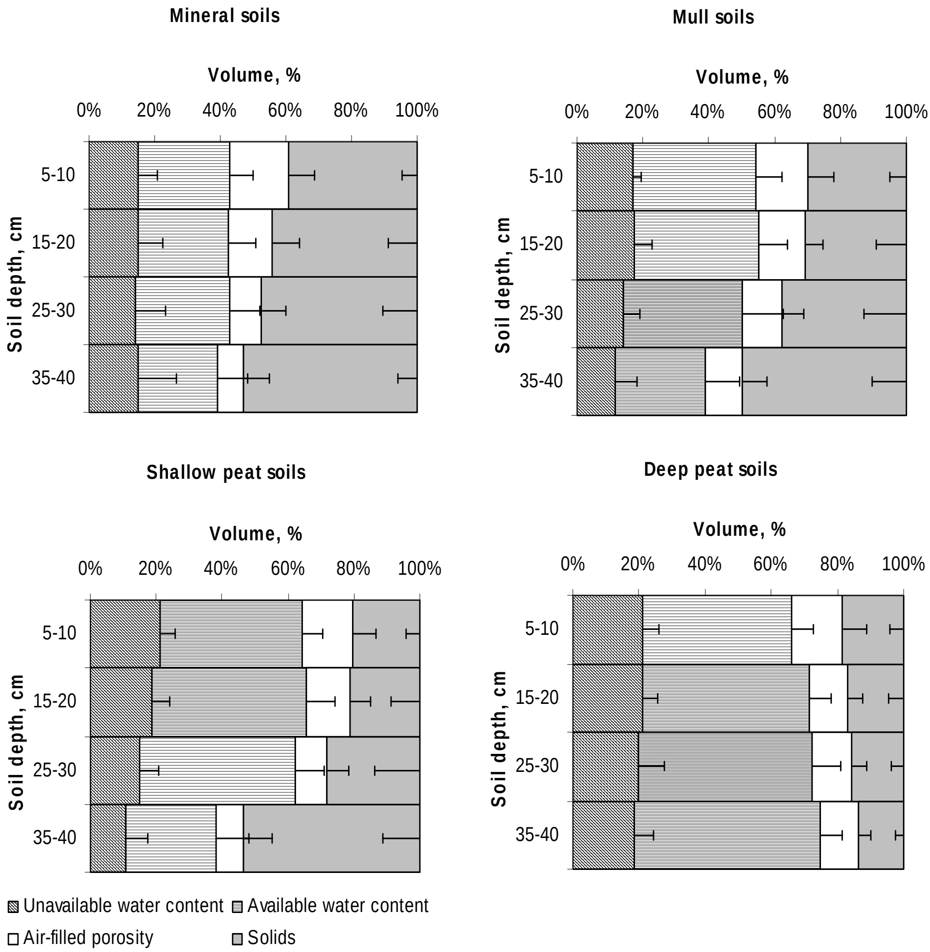

Figure 3. Mean volume of unavailable water (at -1500 kPa), available water (water content between -10 kPa and -1500 kPa), air-filled porosity (at -10 kPa) and solids of soil on afforested arable land by soil types and soil depths. Bars show plus or minus standard deviation.

occurrence of lignified roots and abundance of empty root channels resulting from the decomposition of dead roots may give these soils a greater volume of macro-pores compared to agricultural soils (Messing et al. 1997). Therefore, it can be assumed that in soils of afforested arable land, the root channels will increase the volume of macro-pores in soil over time. However, in this study, the effect of trees on the pore-size distribution of the studied soils was minor due to the young age of the sampled plantations.

In all soils, in general, the air-filled porosity was less than 20% in the topmost soil layer and decreased significantly with increasing soil depth (I, II). Among the mineral soils investigated in this study, with a median particle size of <0.02 mm (clay and silt soils), the air-filled porosity was significantly lower than that in the coarser textured soils, as was previously found in agricultural soils (Heinonen 1954). In mull soils, texture did not affect air-filled porosity. Air-filled porosity decreased with increasing bulk density, however, which is consistent with the findings of other studies (Archer and Smith 1972, Reeve et al. 1973).

In mineral soils in general, the plant available-water content of soil increases with an increase in silt content (Salter et al. 1966, Petersen et al. 1968, Shaykewich and Zwarich 1968). Accordingly, in Finnish cultivated mineral soils, the available-water content is highest in silty soils (Heinonen 1954). In this study, however, there was no difference in the available-water content between soils having different textures (II). Here, due to the wide range of variation in organic matter content, the available-water content was dependent on organic matter content. Similar results have been reported also earlier (Hollis et al. 1977, Hudson 1994). On the other hand, water content at -1500 kPa matric potential (i.e. the lower limit for the available-water content) was positively correlated with clay content, which is consistent with the findings of Kivisaari (1971) and Manrique et al. (1991).

Air-filled porosity and available-water content are crude measures of potential aeration and water availability; and they may not describe accurately the actual water and aeration conditions under different management regimes, growth media and plant growth phases (Ritchie 1981, Heiskanen 1993a). However, air-filled porosity and available water content are useful for measuring relative differences within and among soils. The present results on soil water-retention characteristics suggest that, considering the adequacy of aeration and water availability for forest growth, the soils of afforested arable land are generally rather unfavourable. On fine-grained mineral soils and in peat soils, when an air-filled porosity value of 20% is attained, the soil matric potential would be lower than -100 kPa and water availability would be less than optimum. On the other hand, when the soil matric potential is >-100 kPa and water availability is within the favourable range, the air-filled porosity value would be less than optimum. Therefore, the results suggest that in fine-textured mineral soils and in peat soils the favourable range for water and aeration conditions is rather narrow and would thus be difficult to reach. In all soils, the air-filled porosity below soil depths of 10 cm was commonly so low that root penetration may be inhibited and the formation of superficial root systems promoted (Paavilainen 1967). High water-retention capacity in soil may lead to high water content and low air-filled porosity, which can cause water logging and hypoxia (Lotocki 1977, Heiskanen 1995). Consequently, among afforested arable soils, in mull soils and also in many mineral soils, gleyic properties were frequently typical for soil layers below 20 cm soil depth. Indeed, this finding suggests prolonged periods of water saturation and reducing conditions during the year.

3.3 Soil fertility

According to the present results, the soils of afforested arable land had high pH value and high concentrations and amounts of nutrients in the topsoil compared to those of continuously forested sites (IV, V, VI). Similar nutrient levels in soils of afforested arable land have also been reported previously (Hynönen 1992, Kinnunen and Aro 1996, Hynönen and Makkonen 1999, Hynönen 2000, Hytönen 2003). The former agricultural land use has apparently increased the nutrient pools in the soil due to use of organic amendments and inorganic fertilizers. Furthermore, liming has increased the Ca and Mg contents of the soil, and consequently raised the soil pH. In addition, fine-textured mineral soils have differing mineralogy compared to coarse-textured soils; and thus the contents of exchangeable K, Ca and Mg tend to increase from sand soils to clay soils while soluble content of P is highest in coarse textured soils (Kaila 1972, Sippola 1974, Urvas et al. 1978). Thus, in the mineral soils of the afforested arable land studied here, the high levels of nutrients in the soil are also partly an inherent property of these fine-grained soils. On afforested peat soils, mineral soil matter added as ameliorative to the organic soil also increased the amounts of most nutrients. Nitrogen and boron are, however, not influenced by such additions (III, IV). The results of the present study for 60- to70-year-old afforestations support the view that agricultural land use has a long-term effect on the chemical properties of soil (Goovaerts et al. 1990, Sandor and Eash 1995, Koerner et al. 1997, Compton and Boone 2000, Richter et al. 2000).

In addition to differences in the densities of nutrients, the afforested fields studied here differed from forest soils in terms of distribution of nutrients within the soil profile (IV, V). On mineral forest soils, the organic O horizon on top of the soil is the layer that has the highest concentrations of plant-available nutrients (Urvas and Erviö 1974). The O horizon is therefore a main source of nutrients for plants. In the afforested arable lands studied here, the mass of the newly formed O horizon was still low compared to continuously forested sites, even 60-70 years after afforestation (V). On such sites, the thin organic layer contained relatively small amounts of nutrients, despite high concentrations of nutrients. In afforested arable land, the formerly cultivated layer (0-20 cm top soil) was richer in nutrients than the underlying non-broken parent matter soil and would therefore be the main source of nutrients for the developing forest (Figure 4).

The mean nutrient densities of soil and pH of afforested arable land were lower than those of soils under cultivation (Table 2). This may result from lower inherent soil fertility of afforested sites, as arable land of low fertility is more likely to be afforested than are productive lands of high fertility (Selby 1980). It is also possible that afforested arable lands have received less lime during the former cultivation period than arable land still under cultivation or that the effect of liming has decreased since afforestation. Nevertheless, the mean densities of extractable K, Ca and Mg and pH value in topsoil of afforested arable land were substantially higher than those in the most fertile forest soils (Table 2).

Table 2. Comparison of densities of ammonium acetate-extractable nutrients (mg dm^{-3}) and pH of soil between different land-use types.

Land use type	P	K	Ca	Mg	pH
			Mineral soils		
Forest[1)]	2.9	45	319	60	4.5
Arable land[2)]	11.5	152	1273	171	5.9
Afforested arable land[3)]	7.6	106	729	169	4.9
			Peat soils		
Forest[4)]	11.1	23	167	-	-
Arable land[2)]	11.7	58	1870	233	5.2
Afforested arable land[3)]	6.2	45	802	127	4.4

[1)]Data for forest soils is from 0-30 cm soil depth of the most fertile forest sites (Tamminen 1991). [2)]Data for mineral soils of arable land is from plough layer of finer fine sand soils and for peat soils from *Ligno carex* peat (Kähäri et al. 1987). [3)]Data for afforested arable land is from 0-10 cm soil depth of this study. [4)] Data for forested peat soils is from 0-10 cm soil depth of fertile spruce mires (Kaunisto and Paavilainen 1988).

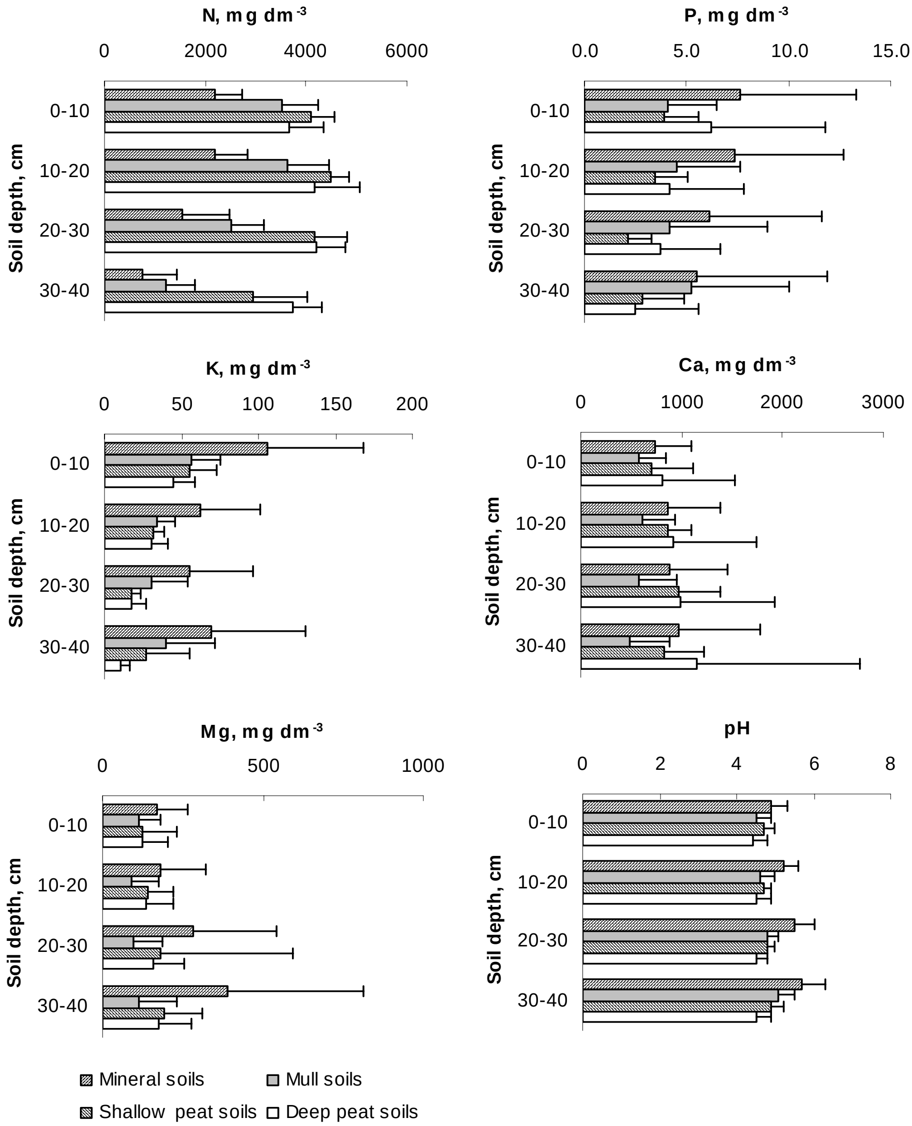

Figure 4. Mean amounts of total nitrogen, extractable nutrients and pH of soil on afforested arable land by soil types and soil depths. Bars show positive standard deviation.

In the mineral soils of afforested arable land studied here, throughout the entire profile, the density of total N was lower and densities of extractable P, K and Mg were higher than in the organic soils (Figure 4). In all soils, however, the density of extractable Ca in the topsoil was the same. Among mineral and mull soils, clayey and silty rich soils separated from more coarse-textured soils owing to their inherently higher content of basic elements (VI). This means that despite the equalizing effect of fertilization and liming on formerly cultivated soil, texture still controls pools of nutrients available for plant uptake (Lakanen et al. 1970, Lakanen and Hyvärinen 1971). Among peat and mull soils, nutrient densities in the topsoil were rather similar, except for P density, which was highest in deep peat soils. This is somewhat in contrast to findings in Finnish agricultural soils, in which the contents of exchangeable cations in mull soils are higher than those in peat soils (Sippola and Tares 1978). In contrast, as found in this study, soluble P is highest in peat soils. Evidently, liming, fertilization and use of organic amendments had equalized the difference in nutrient densities between the organic soils studied here. The addition of mineral soil on top of peat soils certainly has also decreased the difference between mull soils and peat soils.

3.4 Estimation of site productivity based on soil properties

Measurement of soil fertility through chemical analysis of soil is problematic due to the fact that the available pools of nutrients are dynamic, there are a large number of chemical forms of nutrients, uncertainties exist concerning appropriate analytical methods for estimating the pools of available nutrients and about choice of expression of analytical results (Tamm 1964, Schoenholtz et al. 2000). In Finnish forest soils, Ca and N concentrations are soil properties that best distinguish between the site types on mineral soils (Valmari 1921, Cajander 1926, Urvas and Erviö 1974, Tamminen 1991) as well as on peat soils (Starr and Westman 1978, Westman 1981, Westman and Laiho 2003). In this study, discriminant analysis produced similar results (VI). The derived discriminant functions classified all sites from afforested arable land into forest site types of high fertility on the basis of densities of Ca, P, silt and pH in the 0-10 cm soil depth (VI). Based on high nutrient densities of soils on afforested arable land, the site productivity would be even higher than that of OMT sites. In this study, the site-type continuum used for comparison did not include the most fertile sites of forests, which have cambic mull soils and herb-rich vegetation. Such soils are rare and cover less than 1% of the forest area in Finland, and it is uncertain whether soils from arable land are of such a fertility level.

The results, however, suggest that afforested arable lands have higher soil fertility and hence higher capacity for tree production than do the most common Finnish forested sites. This finding is supported by the large volume of stems on sites afforested 60-70 years ago (V). In Sweden, trees growing on former farmland have also been reported to have a high production capacity (Johansson 1996, Karlsson et al. 1997). In general, site productivity of afforested arable land measured using the site index has, however, varied from being a VT site of poor fertility to exceeding that of OMaT sites, which is the most fertile site type among forest sites (Vuokila 1980, Oikarinen 1983, Kinnunen and Aro 1996, Saramäki and Hytönen 2004). This suggests that the material of this study did not cover the whole range of soils on arable land or that in some cases estimation of site productivity based on soil properties yields overestimates. In this study, such overestimates of site productivity may result from factors that limit tree production, which were not included in the discriminant functions. The results of this study indicated that such a factor is the low air-filled porosity in a large proportion of soils on afforested arable land (I, II). Other adverse factors reported on afforested arable land, which may limit tree production capacity, are nutrient-based growth disturbances (Carlyle et al. 1989, Birk 1991, Hytönen and Ekola 1993, Hynönen and Makkonen 1999, Zas and Zerrada 2003), acute N deficiency (Richter et al. 2000) and vigorous growth of weeds (Gilmore and Boggess 1963, Ferm et al. 1994).

Validity of the use of soil properties as a basis for estimation of the site productivity of former arable land for forest production land may be limited in time because changes in the chemical properties of the soil, such as decrease in soil pH, exchangeable K, Ca and Mg content, may occur within a few decades after afforestation (Binkley et al. 1989). In such a case, estimation of site productivity prior to or at the outset of afforestation would be valid only for a short period of time. Thus, to remedy the potential risk for change in soil properties over time in estimation of site productivity, in addition to estimation of current site productivity, the inherent site productivity could be estimated from the properties of soil at a depth of 30-40 cm (VI). Soil at this depth is little affected by agricultural use (Kaunisto 1991). The inherent soil fertility of afforested arable land can also be inferred from the site type of continuously forested sites adjacent to afforested arable land (Hynönen 2000).

4 CONCLUSIONS

The results of this research indicated that the soil properties of afforested arable land differ markedly from those of forest soils. The changes in the soil matrix of afforested arable land due to former agricultural land use were manifested as increased organic matter in mineral soils and as increased mineral matter in peat soils. In general, the soils of afforested arable land were characterized by high densities of nutrients, high pH and low air-filled porosity at field capacity (-10 kPa matric potential).

The results suggest that soils of afforested arable land commonly possess critically low aeration for tree growth, which results from the predomination of small pores in the pore space. Therefore to maintain favourable aeration for tree growth, effective drainage and/or mounding of these soils is needed.

Afforested arable lands apparently have higher soil fertility than forests do. Consequently, soils from afforested arable land were classified into forest site types of high productivity. Among these soils, those with high clay and silt content were the most fertile. The high productivity of soils of afforested arable land was attributed to the legacy of former agricultural land use and to the inherent properties of fine-grained soils. The changes in the physical and chemical properties of soil due to former agricultural land use seem to be significant and long lasting to such a degree that the inherent soil fertility of afforested arable land is very unlikely to be regained even over a long period of time.

The change in soil fertility due to former agricultural land use presents a special challenge for sustainable forest management if the desire is to sustain the new human-imposed level of soil fertility and site productivity. On afforested arable land, potential risks for reduced soil fertility over time, such as leaching of nutrients from the soil, immobilization of nutrients in the organic layer and biomass, and acidification of soil, should be studied.

REFERENCES

Aaltonen, V.T. 1941. Metsämaamme valtakunnan metsien toisen arvioinnin tulosten valossa. Communicationes Instituti Forestalis Fenniae 29(5). 71 p.

Aaltonen,V.T., Aarnio, B., Hyyppä, E., Kaitera,P., Keso, L., Kivinen, E., Kokkonen, P., Kotilainen, M.J., Sauramo, M., Tuorila, P., Vuorinen, J. 1949. Maaperäsanaston ja maalajien luokituksen tarkastus v. 1949. Summary: A critical review of soil terminology and soil classification in Finland in the year 1949. Journal of the Scientific Agricultural Society of Finland 21: 37-66.

Adams, W.A. 1973. The effect of organic matter on the bulk and true densities of some uncultivated podzolic soils. Journal of Soil Science 24: 10-17.

Ahuja, L.R., Fiedler, F., Dunn, G.H., Benjamin, J.G. & Garrison, A. 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Science Society of America Journal 62: 1228-1233.

Alakukku, L. 1999. Subsoil compaction due to wheel traffic. Review. Agricultural and Food Science in Finland 8: 333-351.

Archer, J.R. & Smith, P.D. 1972. The relation between bulk density, available water capacity, and air capacity of soils. Journal of Soil Science 34: 475-480.

Binkley, D., Valentine, D., Wells, C. & Valentine, U. 1989. An empirical analysis of the factors contributing to 20-year decrease in soil pH in an old-field plantation of loblolly pine. Biogeochemistry 8: 39-54.

Birk, E.M. 1991. Stem and branch form on 20-year-old radiata pine in relation to previous land use. Australian Forestry 54: 30-39.

Bohlin, E., Hämäläinen, M. & Sunden, T. 1989. Botanical and chemical characterization of peat with multivariate methods. Soil Science 4: 252-263.

Bråkenhielm, S. 1977. Vegetation dynamics of afforested farmland in a district of South-eastern Sweden. Acta Phytogeographica Suecica 63: 1-106.

Buckley, D.H. & Schmidt, T.M. 2001. The structure of microbial communities in soil and the lasting impact of cultivation. Microbial Ecology 42: 11-21.

Cajander, A.K. 1909. Über Waldtypen. Acta Forestalia Fennica 1. 175 p.

— 1926. The theory of forest types. Acta Forestalia Fennica 29(3). 108 p.

— 1949. Forest types and their significance. Acta Forestalia Fennica 56: 71 p.

Carlyle, J.C., Turvey, N.D., Hopmans, P. & Downes, G.M. 1989. Stem deformations in *Pinus radiata* associated with previous land use. Canadian Journal of Forest Research 19: 96-105.

Cassel, D.K. 1983. Spatial and temporal variability of soil physical properties following tillage of Norfolk loamy sand. Soil Science Society of America Journal 47: 196-201.

Compton, J.E. & Boone, R.D. 2000. Long-term impacts of agriculture on soil carbon and nitrogen in New England forests. Ecology 81: 2314-2330.

—, Boone, R.D., Mozkin, G. & Foster, D.R. 1998. Soil carbon and nitrogen in a pine-oak sand plain in central Massachusetts: Role of vegetation and land use history. Oecologia 116: 356-542.

Czyż, E.A. 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil & Tillage Research 79: 153-166.

Davidson, E.A. & Ackerman, I.L. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20: 161-193.

Domżał, H., Hodara, J., Słowińska-Jurkiewicz, A. & Turski, R. 1993. The effects of agricultural use on the structure and physical properties of three soil types. Soil & Tillage Research 27: 365-382.

Dupouey, J.L., Dambrine, J., Laffite, J.D. & Moares, C. 2002. Irreversible impact of past land use on forest soils and biodiversity. Ecology 83: 2978-2984.

Ellert, B.H. & Gregorich, E.G. 1996. Storage of carbon, nitrogen and phosphorus in cultivated and adjacent forested soils of Ontario. Soil Science 161: 587-603.

Elonen, P. 1971. Particle-size analysis of soil. Acta Agralia Fennica 122. 122 p.

Entwistle, J.A., Abrahams, P-W. & Dodgshon, R.A. 1998. Multi-element analysis of soils from Scottish historical sites. Interpreting land-use history through the physical and chemical analysis of soil. Journal of Archaeological Science 25: 53-68.

Erviö, R., Mäkelä-Kurtto, R. & Sippola, J. 1990. Chemical characteristics of Finnish agricultural soils in 1974 and in 1987. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds). Acidification in Finland. Springer-Verlag. p. 217-234.

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

Federer, C.A., Turcotte, D.E. & Smith, C.T. 1993. The organic fraction - bulk density relationship and expression of nutrient content in forest soils. Canadian Journal of Forest Research 23: 1026-1032.

Ferm, A., Hytönen, J., Lilja, S. & Jylhä, P. 1994. Effects of weed control on the early growth of *Betula pendula* seedlings established on an agricultural field. Scandinavian Journal of Forest Research 9: 347-359.

Finnish Statistical Yearbook of Forestry 2003. 2003. SVT. Agriculture, forestry and fishery 2003:45. Finnish Forest Research Institute. 389 p.

Flaig, W. 1986. Some basic principles of water management in peat. In: Fuchsman, C. (ed.). Peat and water. Aspects of water retention and dewatering in peat. Elsevier Applied Science publishers, London and New York. p. 119-132.

Giesler, R., Högberg, M. & Högberg, P. 1998. Soil chemistry and plants in Fennoscandian boreal forest as exemplified by a local gradient. Ecology 79: 119-137.

Gilmore, A.R. & Boggess, W.R. 1963. Effects of past agricultural practices on the survival and growth of planted trees. Soil Science Society of America Proceedings 27(1): 98-102.

Glinski, J. & Stepniewski, W. 1985. Soil aeration and its role for plants. CRC Press, Boca Raton, Fla. 229 p.

Goovaerts, P., Frankart, R. & Gérard, G. 1990. Effet de la succession de différentes affectations sur les propriétés chimiques de pédons en Fagne de Chimay (Belgique). Pédologie 40: 179-194.

Hägglund, B. 1981. Evaluation of forest site productivity. Forestry Abstracts 42: 515-527.

Halonen, O., Tulkki, H. & Derome, J. 1983. Nutrient analysis methods. Metsäntutkimuslaitoksen tiedonantoja 121: 1-28.

Heinonen, R. 1954. Multakerroksen kosteussuhteista Suomen maalajeissa. Summary: Moisture conditions in Finnish topsoils. Agricultural Research Centre. Department of Soil Science. Agrogeological Publications 62. 82 p.

Heiskanen, J. 1993a. Favourable water and aeration conditions for growth media used in containerized tree seedling production: A review. Scandinavian Journal of Forest Research 8: 337-358.

— 1993b. Variation in water retention characteristics of peat growth media used in tree nurseries. Silva Fennica 27: 77-97.

— 1995. Irrigation regime affects water and aeration conditions in peat growth medium and the growth of containerized Scots pine seedlings. New Forests 9: 181-195.

Hillel, D. 1982. Introduction to soil physics. Academic press, San Diego, California. 364 p.

Hollis, J.M., Jones, R.J.A. & Palmer, R.C. 1977. The effects of organic matter and particle size on the water-retention properties of some soils in the west Midlands of England. Geoderma 17: 225-238.

Hudson, B. 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation 49: 189-194.

Hynönen, T. 1992. Maan ominaisuuksien vaikutus turvemaapeltojen metsittämiseen. Tutkielma maatalous- ja metsätieteiden lisensiaatin tutkintoa varten. Helsingin yliopisto, Metsäekologian laitos. 181 p.

— 2000. Pellonmetsitysten onnistuminen Itä-Suomessa. Metsäntutkimuslaitoksen tiedonantoja 765. 90 p.

— & Makkonen, T. 1999. Turvemaapeltojen maan ominaisuudet ja niiden vaikutus hieskoivujen alkukehitykseen Pohjois-Savossa. Summary: Soil properties of peat-based fields and their effect on the initial development of downy birch in Pohjois-Savo, southern Finland. Suo 50: 17-34.

— & Saksa, T. 1997. Metsitystulos Pohjois-Savon kivennäismaapelloilla. Metsätieteen aikakauskirja - Folia Forestalia 2/1997: 165-180.

Hytönen, J. & Ekola, E. 1993. Maan ja puuston ravinnetila Keski-Pohjanmaan metsitetyillä pelloilla. Summary: Soil nutrient regime and tree nutrition on afforested fields in central Ostrobothnia, western Finland. Folia Forestalia 822. 32 p.

— 2003. Effects of wood, peat and coal ash fertilization on Scots pine foliar nutrient concentrations and growth on afforested former agricultural peat soils. Silva Fennica 37: 219-234.

Ilvessalo, Y. 1933. Occurrence of forest site types on different soils. Communicationes Instituti Forestalis Fenniae 18(5). 36 p.

Johansson, T. 1996. Site index curves for Norway spruce (*Picea abies* (L.) karst.) planted on abandoned farm land. New Forests 11: 9-29.

Johnson, D.W. 1992. Effects of forest management on soil carbon storage. Water, Air and Soil Pollution 64: 83-120.

Kähäri, J., Mäntylahti, V. & Rannikko, M. 1987. Suomen peltojen viljavuus 1981-1985. Summary: Soil fertility of Finnish cultivated soils in 1981-1985. Viljavuuspalvelu Oy, Helsinki. 105 p.

Kaila, A. 1972. Basic exchangeable cations in Finnish mineral soils. Journal of the Scientific Agricultural Society of Finland 44: 164-170.

— & Ryti, R. 1968. Calcium, magnesium and potassium in clay, silt and fine sand fractions of some Finnish soils. Journal of the Scientific Agricultural Society of Finland 40: 1-13.

Kalisz, P.J. 1986. Soil properties of steep Appalachian old fields. Ecology 67: 1011-1023.

Karlsson, A., Albrektson, A. & Sonesson, J. 1997. Site index and productivity of artificially regenerated *Betula pendula* and *Betula pubescens* stands on former farmland in southern and central Sweden. Scandinavian Journal of Forest Research 12: 256-263.

Kaunisto, S. 1991. Maa-analyysin käyttö kasvupaikan ravinnetilan arvioimiseksi eräillä Alkkian metsitetyillä suopelloilla. Summary: Soil analysis as a means of determining the nutrient regime on some afforested peatland fields at Alkkia. Folia Forestalia 778. 32 p.

— & Paavilainen, E. 1988. Nutrient stores in old drainage areas and growth of stands. Communicationes Instituti Forestalis Fenniae 145: 1-39.

Kinnunen, K. & Aro, L. 1996. Vanhojen pellonmetsitysten tila Länsi-Suomessa. Folia Forestalia - Metsätieteen aikakauskirja 1996(2): 101-111.

Kivisaari, S. 1971. Influence of texture on some soil moisture constants. Acta Agralia Fennica 123: 217-222.

Koerner, W., Dambrine, E., Dupouey, J.L. & Benoît, M. 1997. Influence of past land use on the vegetation and soils of present day forest in Vosges mountains, France. Journal of Ecology 85: 351-358.

Lähde, E. & Savonen, E.-M. 1983. Effects of watering on the development of containerized Scots pine seedlings and water and air conditions in peat growing medium. Folia Forestalia 571: 1-40.

Lakanen, E. & Hyvärinen, S. 1971. The effect of some soil characteristics on the extractability of macronutrients. Annales Agriculturae Fenniae 10: 135-143.

—, Sillanpää, M., Kurki, M. & Hyvärinen, S. 1970. Maan viljavuustekijäin keskinäiset vuorosuhteet maalajeittain. Summary: On the interrelations of pH, calcium, potassium and phosphorus in Finnish soil tests. Journal of the Scientific Agricultural Society of Finland 42: 59-67.

Lindstrom, M.J. & Onstad, C.A. 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. Journal of Soil and Water Conservation 39: 149-152.

Lotocki, A. 1977. Effect of root aeration and form of nitrogen on photosynthetic productivity of Scots pine (*Pinus sylvestris* L.). Acta Societatis Botanicorum Poloniae 46: 303-316.

Magnusson, T. 1992. Temporal and spatial variation of the soil atmosphere in forest soils of northern Sweden. Doctoral dissertation, Swed. Univ. Agric. Sciences, Dept Forest Site Research, Umeå. Stencil No 22. ISSN 0280-9168. 135 p.

Makeschin, F. 1994. Effects of energy forestry on soils. Biomass and Bioenergy 6: 63-79.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Science 142: 279-288.

Manrique, L.A., Jones, C.A. & Dyke, P.T. 1991. Predicting soil water retention characteristics from soil physical and chemical properties. Communications in Soil Science and Plant Analysis 22: 1847-1860.

Mapa, R.B., Green, R.E. & Santo, L. 1986. Temporal variability of soil hydraulic properties with wetting and drying subsequent to tillage. Soil Science Society of America Journal 50: 1133-1138.

McKeague, J.A., Eilers, R.G., Thomasson, A.J., Reeve, M.J., Bouma, J., Grossman, R.B., Favrot, J.C., Renger, M. & Strebel, O. 1984. Tentative assessment of soil survey approaches to the characterization and interpretation of air-water properties of soils. Geoderma 34: 69-100.

McLay, C.D.A., Allbrook, R.F. & Thompson, K. 1992. Effect of development and cultivation on physical properties of peat soils in New Zealand. Geoderma 54: 23-37.

Messing, I., Alriksson, A. & Johansson, W. 1997. Soil physical properties of afforested and arable land. Soil Use and Management 13: 209-217.

Myllys, M. & Sinkkonen, M. 2004. Viljeltyjen turve- ja multamaiden pinta-ala ja alueellinen jakauma Suomessa. Abstract: The area and distribution of cultivated organic soils in Finland. Suo 55: 53-60.

Oades, J.M. 1988. The retention of organic matter in soils. Biogeochemistry 5: 35-70.

Oikarinen, M. 1983. Growth and yield models for Silver birch (*Betula pendula*) plantations in southern Finland. Communicationes Instituti Forestalis Fenniae 113: 1-75.

Onstad, C.A., Wolfe, J.L., Larson, C.L. & Slack, D.C. 1984. Tilled soil subsidence during repeated wetting. Transactions of the ASAE 27: 733-736.

Paavilainen, E. 1967. Männyn juuriston suhteesta turpeen ilmatilaan. Summary: Relationships between the root system of Scots pine and the air content of peat. Communicationes Instituti Forestalis Fenniae 63: 1-20.

Päivänen, J. 1973. Hydraulic conductivity and water retention in peat soils. Acta Forestalia Fennica 129. 70 p.
Pessi, Y. 1961a. The ash content of the plough layer of peat lands cultivated by different methods. Journal of the Agricultural Society of Finland 33: 215-222.
— 1961b. Results from a soil improvement and fertilizing test on fen land at Leteensuo. Journal of the Agricultural Society of Finland 33: 223-232.
Peterken, G.F. 1993. Long-term floristic development of woodland on former agricultural land in Lincolnshire, England. In: Watkins, C. (ed.). Ecological effects of afforestation. CAB International. p. 31-43.
Petersen, G.W., Cunningham, R.L. & Matelski, R.P. 1968. Moisture characteristics of Pennsylvania soils: I. Moisture retention as related to texture. Soil Science Society of America Proceedings 32: 271-275.
Puustjärvi, V. 1977. Peat and its use in horticulture. Turveteollisuusliitto ry. Publication 3. Liikekirjapaino, Helsinki. ISBN 951- 95397-0-0. 160 p.
Rawls, W.J., Gish, T.J. & Brakensiek, D.L. 1991. Estimating soil water retention from soil physical properties and characteristics. Advances in Soil Science 16: 213-234.
Reeve, M.J., Smith, P.D. & Thomasson, A.J. 1973. The effect of density on water retention properties of field soils. Journal of Soil Science 24: 355-367.
Richter, D.D., Markewitz, D., Heine, P.R., Jin, V., Raikes, J., Tian, K. & Wells, C.G. 2000. Legacies of agriculture and forest regrowth in the nitrogen of old-filed soils. Forest Ecology and Management 138: 233-248.
Ritchie, J.T. 1981. Soil water availability. Plant and Soil 58: 327-338.
Rivers, E.D. & Shipp, R.F. 1972. Available water capacity of sandy and gravelly North Dakota soils. Soil Science. 113: 74-80.
Rolfe, G.L. & Boggess, W.R. 1973. Soil conditions under old field and forest cover in southern Illinois. Soil Science Society of America Proceedings 37: 314-318.
Rousseva, S.S., Ahuja, L.R. & Heathman, G.C. 1988. Use of a surface gamma-neutron gauge for in situ measurement of changes in bulk density of the tilled zone. Soil &Tillage Research 12: 235-251.
Salter, P.J., Berry, G. & Williams, J.B. 1966. The influence of texture on the moisture characteristics of soils. III Quantitative relationships between particle size, composition, and available-water capacity. Journal of Soil Science 17: 93-98.
— & Williams, J.B. 1967. The influence of texture on the moisture characteristics of soils IV. A method of estimating the available-water capacities of profiles in the field. Journal of Soil Science 18: 174-181.
Sandor, J.A. & Eash, N.S. 1995. Ancient agricultural soils in the Andes of southern Peru. Soil Science Society of America Journal 59: 170-179.
Saramäki, J. & Hytönen, J. 2004. Nutritional status and development of mixed plantations of Silver Birch (*Betula pendula* Roth) and Downy birch (*Betula pubescens* Ehrh.) on former agricultural soils. Baltic Forestry 10: 2-11.
SAS 1989. SAS/STAT User's Guide, Version 6. SAS Institute Inc., Gary, NC. 943 p.
Schoenholtz, S.H., Miegroet, H.Van & Burger, J.A. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest Ecology and. Management 138: 335-356.
Selby, J.A. 1980. Field afforestation in Finland and its regional variations. Communicationes Instituti Forestalis Fenniae 99(1). 126 p.
Shaykewich, C.F. & Zwarich, M.A. 1968. Relationships between soil physical constants and soil physical components of some Manitoba soils. Canadian Journal of Soil Science 48: 199-204.

Siegel-Issem, C.M., Burger, J.A., Powers, R.F., Ponder, F. & Patterson, S.C. 2005. Seedling root growth as a function of soil density and water content. Soil Science Society America Journal 69: 215-226.

Sippola, J. 1974. Mineral composition and its relation to texture and to some chemical properties in Finnish subsoils. Annales Agriculturae Fenniae 13: 169-234.

— & Tares, T. 1978. The soluble content of mineral elements in cultivated Finnish soils. Acta Agriculturae Scandinavica Supplement 20: 11-25.

Soane, B.D., Blackwell, P.S., Dickson, J.W. & Painter, D.J. 1981. Compaction by agricultural vehicles: a review. II. Compaction under tyres and other running gear. Soil & Tillage Research 1: 373-400.

Starr, M. & Westman, C.J. 1978. Easily extractable nutrients in the surface peat layer of virgin sedge pine swamps. Silva Fennica 12: 65-78.

Tamm, C.O. 1964. Determination of nutrient requirements of forest stands. International Review of Forestry Research 1: 115-170.

Tamminen, P. 1991. Kangasmaan ravinnetunnusten ilmaiseminen ja viljavuuden alueellinen vaihtelu Etelä-Suomessa. Summary: Expression of soil nutrient status and regional variation in soil fertility of forested sites in southern Finland. Folia Forestalia 777. 40 p.

Urvas, L. 1985. Viljelyn vaikutus turpeen ravinepitoisuuteen. Summary: Effect of cultivation on the nutrient status of peat soils. Suo 36: 61-64.

— & Erviö, R. 1974. Metsätyypin määräytyminen maalajin ja maaperän kemiallisten ominaisuuksein perusteella. Abstract: Influence of the soil type and the chemical properties of soil on the determining of the forest type. Journal of the Scientific Agricultural Society of Finland 3: 307-319.

—, Erviö, R. & Hyvärinen, S. 1978. Soil nutrient status as related to soil textural classification. Annales Agriculturae Fenniae 17: 75-82.

Valmari, A. 1983. Suon viljely. In: Suomen suot ja niiden käyttö. Suoseura ry. IPS:n Suomen kansallinen komitea, Helsinki. p. 42-48.

— 1921. Beiträge zur chemischen Bodenanalyse. Acta Forestalia Fennica 20(4). 67 p.

van den Berg, M., Klamt, E., van Reeuwijk, L.P. & Sombroek, W.G. 1997. Pedotransfer functions for the estimation of moisture retention characteristics of Ferrasols and related soils. Geoderma 78: 161-180.

Vomocil, J.A. & Flocker, W.J. 1961. Effect of soil compaction on storage and movement of soil air and water. Transanctions of the ASAE 4: 242-246 .

Vuokila, Y. & Väliaho, H. 1980. Growth and yield models for conifer cultures in Finland. Communicationes Instituti Forestalis Fenniae 99(2). 271 p.

Wang, C.G. 1997. Soil nutrient regime classification for white spruce stands in the Sub-boreal Spruce Zone of British Columbia. Canadian Journal of Forest Research 27: 679-685.

Wesseling, J. & Wijk, W.R. 1957. Land drainage in relation to soils and crops I. Soil physical conditions in relation to drain depth. In Luthin, J.N. (ed.). Drainage of agricultural lands. Amer. Soc. Agron. Madis. Wisc. p. 461-504.

Westman, C.J. 1981. Fertility of surface peat in relation to the site type and potential stand growth. Acta Forestalia Fennica 172. 77 p.

— & Laiho, R. 2003. Nutrient dynamics of drained peatland forests. Biogeochemistry 63: 269-298.

Wilson, S.M., Pyatt, D.G., Malcolm, D.C. & Connolly, T. 2001. The use of ground vegetation and humus type as indicators of soil nutrient regime for an ecological site classification of British forests. Forest Ecology and Management 140: 101-116.

Xu, J.L., Nieber, J.L. & Gupta, S.C. 1992. Compaction effect on the gas diffusion coefficient in soils. Soil Science Society of America Journal 56: 1743-1750.

Yli-Halla, M., Mokma, D.L., Peltovuori, T. & Sippola, J. 2000. Suomalaisia maaprofiileja. Abstract: Agricultural soil profiles in Finland and their classification. Maatalouden tutkimuskeskuksen julkaisuja. Sarja A. 78. Maatalouden tutkimuskeskus. 108 p.

Zas, R. & Serrada, R. 2003. Foliar nutrient status and nutritional relationships of young *Pinus radiata* D. Don plantations in northwest Spain. Forest Ecology and Management 174: 167-176.

Zou, C., Penfold, C., Sands, R., Misra, R.K. & Hudson, I. 2001. Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings. Plant and Soil 236: 105-115.