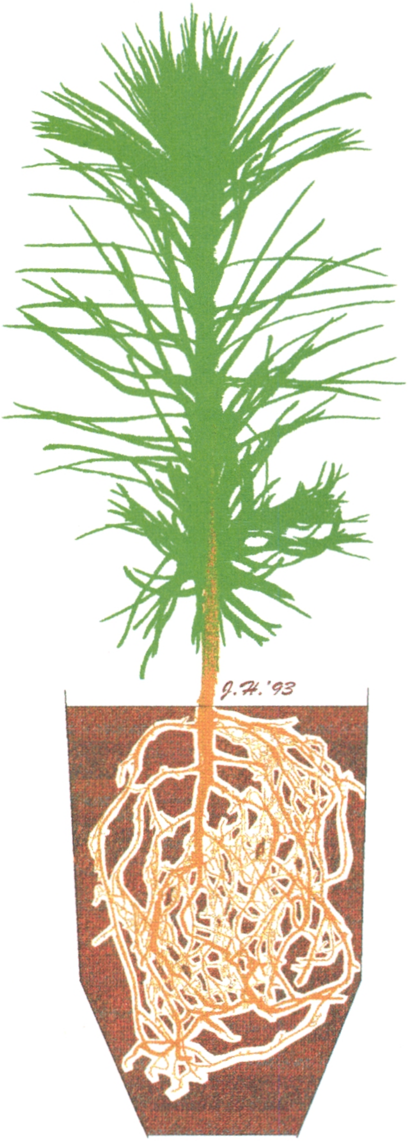

Hydrological Properties of Peat-based Growth Media

Juha Heiskanen

Metsäntutkimuslaitoksen tiedonantoja 524
The Finnish Forest Research Institute, Research Papers 524

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ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Agriculture and Forestry of
the University of Helsinki, for public criticism in Auditorium II of Metsätalo,
Unioninkatu 40 B, Helsinki, on December 14, 1994, at 12 o'clock noon.

Metsäntutkimuslaitoksen tiedonantoja 524
The Finnish Forest Research Institute, Research Papers 524

Suonenjoki 1994

Heiskanen, J. 1994. Hydrological properties of peat-based growth media. Metsäntutkimuslaitoksen tiedonantoja 524. The Finnish Forest Research Institute, Research Papers 524. 41 p. (ISBN 951-40-1391-3, ISSN 0358-4283)

The hydrological and related physical properties and their variations in light *Sphagnum* peat-based growth media used or potentially usable in the production of containerized tree seedlings were analyzed, and the potential implications of these properties on water and aeration conditions in the media were evaluated. Methodological considerations concerning the determination of the hydrological properties and conditions are also presented.

In general, the physical properties of the media were considered to provide favourable water and aeration conditions for containerized tree seedlings. Under infrequent irrigation without exposure to free rain, all the media studied probably can provide a large amount of easily available water and sufficiently large air-filled pores for aeration. However, retention of easily available water by coarse sheet peat and loose peat media to which half hydrogel had been added was low. In dry conditions (matric potentials <–50 kPa), the addition of hydrogel increased water retention considerably. However, the hydraulic conductivity of peat decreased sharply during drying, which evidently reduces the availability of water. Under frequent irrigation or exposure to precipitation on hardening fields, low aeration probably limits seedling growth in peat-based media. Only coarse sheet and chip peat may then provide sufficient aeration. Air-filled porosity of loose peat media can also be increased by addition of coarse perlite or water-repellent rockwool. Addition of coarse perlite also tended to increase the saturated hydraulic conductivity and wettability of dry peat.

Water retention characteristics did not differ markedly between the textural grades of peat media used in tree nurseries. Variations in water retention characteristics between different greenhouses within media were large, causing potential unevenness in the growth and irrigation requirements of seedling crops. The largest variations occurred between trays within greenhouses.

The methods used for determining water retention and unsaturated hydraulic conductivity were estimated to be feasible and relatively precise. For peat-based media, however, the constant-head method used for determining saturated hydraulic conductivity may give too low values. It was further judged that the availability of water from growth media to seedlings can readily be evaluated by measuring water potential, while the determination of available oxygen and actual aeration may be too complex for practical use. Aeration is readily evaluable indirectly by using air-filled porosity.

Keywords: aeration, hydraulic conductivity, physical properties, water potential, water retention, wettability

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Hakapaino Oy, Helsinki 1994

Preface

I wish to thank R. Rikala, M.Sc., M. Saarinen, M.Sc., E. Siivola, M.Sc., Docents H. Smolander, M. Starr, P. Puttonen, Drs. P. Aphalo, A. Jalkanen, T. Karvonen, T. Repo and Professors H. Mannerkoski, R. Heinonen and C.J. Westman for constructive comments on the manuscripts of the studies included in this thesis. I also thank J. Heinonen, M.Sc. and Dr. H. Henttonen and Docent J. Lappi for statistical advice. I thank Drs. J. von Weissenberg and R. Sen and Docent M. Starr for revising and improving the English language of the manuscripts. Special thanks to Mr. J. Laitinen and Mrs. A. Aaltonen for pleasant cooperation and for technical assistance, data collection and measurements. I also thank R. Rikala, M.Sc., Docents H. Smolander and M. Nygren and Professor E. Mälkönen for constructive comments and Docents E. Ahti and J. Laine for the official pre-examination and Dr. J. von Weissenberg for revising the language of this dissertation.

I am also grateful for a grant from the Academy of Finland for Study II, for a grant from the Niemi Foundation for compiling this dissertation and for the research premises and facilities that were available at the Suonenjoki Research Station of the Finnish Forest Research Institute during working on the studies included in this thesis.

Last but not least, I wish to thank my family and those various individuals and friends who have supported me indirectly during the process of working on this thesis.

Juha Heiskanen

Contents

ORIGINAL ARTICLES (I–V)

List of articles

The thesis is a summary based on the following articles, which are referred to in the text by Roman numerals (I–V):

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

II Heiskanen, J. and Laitinen, J. 1992. A measurement system for determining temperature, water potential and aeration of growth medium. Silva Fennica 26: 27–35.

III Heiskanen, J. 1993. Variation in water retention characteristics of peat growth media used in tree nurseries. Silva Fennica 27: 77–97.

IV Heiskanen, J. 1993. Water potential and hydraulic conductivity of peat growth media in containers during drying. Silva Fennica 27: 1–7.

V Heiskanen, J. 1994. Physical properties of two-component growth media based on *Sphagnum* peat and their implications for plant-available water and aeration. Plant and Soil. (In press).

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List of basic variables

Air-filled porosity, (Va)	Ratio of the volume of air-filled pores to total sample volume (= total porosity – water content), %
Bulk density, (Bd)	Ratio of the mass of solids to saturated sample volume, g cm^{-3}
Gravitational potential, (Ψg)	Water potential component due to gravitation, kPa
Matric potential, (Ψm)	Water potential component due to adsorption and capillarity, kPa
Oxygen diffusion rate, (ODR)	Rate at which oxygen diffuses through an area, μg m^{-2} s^{-1}
Osmotic potential, (Ψo)	Water potential component due to solutes in water, kPa
Particle density, (Ds)	Ratio of the mass of solids to their volume without pores, g cm^{-3}
Saturated hydraulic conductivity, (Ks)	Ratio of water flux to a matric potential gradient in saturated conditions, m s^{-1}
Total porosity, (Vt)	Ratio of the volume of pores to total sample volume (estimated as (Ds–Db) Ds^{-1}), %
Unsaturated hydraulic conductivity, (K(Ψm))	Ratio of water flux to a matric potential gradient as a function of matric potential in unsaturated conditions, m s^{-1}
Water content, (θ)	Ratio of the volume of water retained to total sample volume, %
Water potential, (Ψt)	Sum of water potential components, kPa
Water retention (characteristics), (θ(Ψm))	Water content as a function of matric potential, %

1 Introduction

1.1 Use of peat-based growth media

Since the 1940s, greenhouse culturing of crop plants has became increasingly common in Western countries (Bunt 1988, Puustjärvi 1989). Traditional mould soils and composts were superseded by commercial peat-based mixtures, which were introduced especially in the USA and Germany. Other commonly used components of such mixtures are mineral soils, perlite, vermiculite, bark and sawdust. Pure low-humified *Sphagnum* peat is the dominant growth medium in greenhouse culturing in Finland and has also become established elsewhere in Europe. However, in many countries that must import *Sphagnum* peat, other pure materials such as rockwool and various growth media mixtures, in which peat has been totally substituted with other materials, are much used (Bunt 1988, Landis et al. 1990).

In Finland, about $20 \cdot 10^6$ m^3 a^{-1} peat is harvested, about 8 % of which are used for the production of peat growth media (Turveteollisuustilastoja... 1993). In Finnish tree nurseries pure peat is almost exclusively used as growth medium in containerized seedling production, in which, according to estimates, $2–3 \cdot 10^4$ m^3 peat is used annually. The peat growth media used are produced mainly from low-humified peat consisting of residues of *Sphagnum* sp. mosses. Milled peat material is usually harvested from peat bogs and transported to a factory where it is stored in stacks before processing. Sieved and graded peat growth medium is compressed into bales and then delivered to nurseries. Into most peat growth media, fertilizers are also incorporated. In nurseries peat is finally unpacked and is usually emptied into a filling machine, which loosens, fills and compresses peat into the containers of seedling trays.

1.2 Physical functions of peat-based growth media

As is true for all growth media, the role of peat is to provide favourable conditions for the growth of plants. Peat should firstly supply adequate amounts of water for root uptake. Scant water retention by a peat growth medium may induce water stress as well as decreased transpiration and growth of the plant at high rates of evaporation. Plant physiology and morphology are also affected by poor availability of water (Kramer and Kozlowski 1960, Kozlowski et al. 1991). Aeration should provide adequate diffusion of O_2 into and diffusive removal of excess CO_2 from the growth medium so that the oxygen supply to roots is sufficient for aerobic respiration and for uptake of water and nutrients (Kramer and Kozlowski 1960, Kozlowski et al. 1991). Excess water retention may impede aeration, which in most plant species eventually leads to hypoxia. In addition to water and oxygen, root growth is also dependent on the texture, density and mechanical resistance of the growth medium.

To meet the requirements of an adequate water and oxygen supply for plant growth, peat-based growth media should possess suitable hydrological and related physical properties. Operational requirements must also be met by the growth medium used in seedling culturing. As the primary requirement, the growth medium should provide physical support for the roots so that the plant can grow upright. Furthermore, physical properties desired in a growth medium are pore size distribution that provides favourable division of water and air content in the pore space during culturing, adequate wettability, rapid drainage of excess water, high resistance to compaction, and spatial and temporal invariability during culturing (Warkentin 1984, Bunt 1988, Whitcomb 1988, Landis et al. 1990). In the production of containerized plants, other attributes of a good growth medium are ease of mixing and filling into containers, low mass (low bulk density) and adequate resiliency and firmness (Whitcomb 1988, Landis et al. 1990).

The physical properties of pure peat growth media are affected primarily by the degree of humification, which increases as the peat colour tarnishes from light and dark to black (Puustjärvi 1977, Bunt 1988). According to the von Post scale, the degrees of humification for the various colour classes are H1–3, H4–6 and H7–10 (Puustjärvi 1970, 1977, Bunt 1988). As defined by Nordic standards, peat growth media are also graded as fine, medium or coarse in texture (Puustjärvi 1982a). The physical properties of light peat are known to be determined primarily by the composition of plant species making up the peat and secondarily by particle size distribution (Puustjärvi 1973, 1977 English translation). Within dark and black peat, the degree of humification tends to be a more marked factor than the peat composition for defining the physical properties (Päivänen 1969, Puustjärvi 1977). In addition to pore size distribution, the surface properties of peat have an effect on water retention characteristics and wettability (Päivänen 1973, Puustjärvi 1977). For plant culturing, these properties of peat can, in principle, be modified by various additive materials and chemicals (Bunt 1988, Jenkins and Jarrell 1989, Landis et al. 1990).

Official statutes have also been set for the properties of peat growth media produced and sold in Finland. According to the regulations of the Finnish Ministry of Agriculture and Forestry, first class light, low-humified (H1–3) peat medium for cultivation should contain at least 90 % remains of *Sphagnum* mosses, of which over 80 % should belong to the Acutifolia group. Less than 3 % shrubs and wood remnants and less than 6 % cotton-grass remnants are allowed in the dry mass of peat (Maa- ja... 1986). Peat growth media classified into the second class consist of light (H1–3) or dark (H4–6) peat, at least 75 % of which should consist of *Sphagnum* moss residues.

1.3 Research framework

The physical properties of a growth medium are physical attributes, which can be considered to be relatively static, i.e. they tend not to alter over time. These properties are, for example, texture and ability to conduct water. Physical conditions, in turn, indicate transient states in the medium, such as water content and temperature (Hillel 1971, 1982, Currie 1984). The pore space of the matrix of the growth medium is occupied by water and air in proportions that vary over time. During drying of the medium, the decreasing water potential results in water movement from a zone of higher to a zone of lower water potential (Hillel 1971, 1982, Currie 1984). An increasing proportion of pores becomes empty and filled with air, thus decreasing the amount of water-conducting pores and water flux. While water content decreases during drying, air content and thus gaseous diffusion increase correspondingly. Diffusion is usually the dominant mechanism in the gaseous exchange between air space in the soil and the atmosphere (Hillel 1982, Glinski and Stepniewski 1985, Rolston 1986).

In the production of containerized seedlings, the confined space of the container characterizes the hydrological conditions in the growth medium. The confined medium forms a percolation barrier against drainage of free water through the bottom hole of the container. When excess water has drained out after each sufficiently abundant irrigation or precipitation, a persistent saturated layer occurs at the bottom of the container. The water content then retained by the growth medium is called the container capacity (White and Mastalerz 1966).

Water and aeration conditions in the growth medium determine, in part, the water and oxygen availability from the medium to the seedling roots (Fig. 1). In addition to atmospheric environment, irrigation, fertilization and other ambient conditions, the seedlings themselves affect the hydrological conditions in the growth medium by water uptake for transpiration, which is further regulated by seedling physiology and ambient conditions (Kramer and Kozlowski 1960, Kozlowski et al. 1991). Availability of water and oxygen from the growth medium is usually evaluated by determining the water and air contents, which are derived from the water retention characteristics of the medium (I). Water potential is used to indicate water movement within the context of the soil-plant-atmosphere continuum (SPAC) concept (van den Honert 1948, Slatyer 1967, Hillel 1982, Pallardy 1989). Air-filled porosity and oxygen diffusion rate are most commonly used to estimate aeration and oxygen availability (Hillel 1982, Glinski and Stepniewski 1985, Bunt 1988). In seedling culturing, in order to provide adequate availability of water and oxygen to seedlings, drought and waterlogged conditions should be avoided. Therefore, neither water nor air content in the growth medium should persistently be allowed to fall below the lowest limit (Fig. 2).

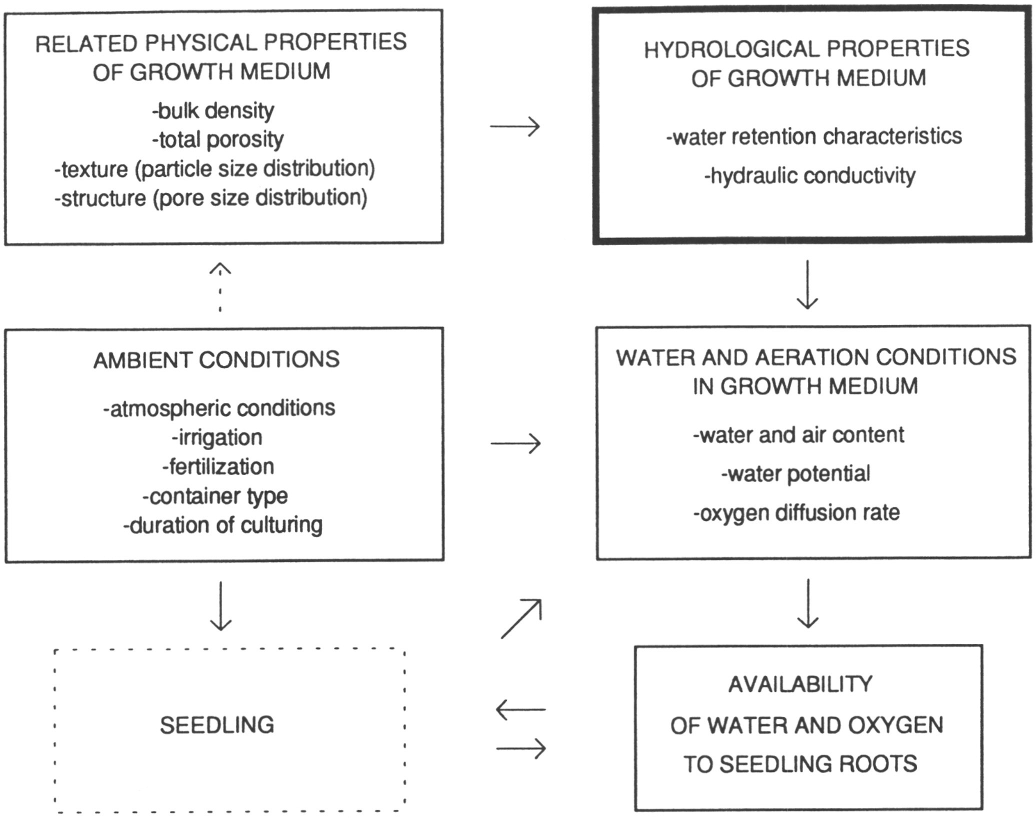

Figure 1. General framework showing the importance of the hydrological properties of growth medium used for production of containerized tree seedlings.

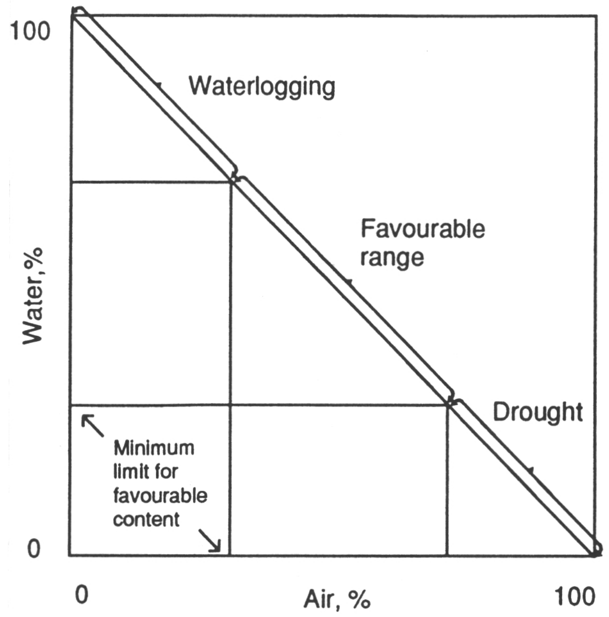

Figure 2. Schematic description of the division of total porosity (=100 %) in the growth medium into water and air and the favourable range of these variables for seedling growth.

1.4 Research aims

Although several studies and handbooks are available concerning pure peat and peat-based growth media mixtures (Päivänen 1973, Puustjärvi 1977, Bunt 1988, Landis et al. 1990), there is a lack of information about the implications of the hydrological and related properties and their variations for production of containerized tree seedlings (I). Furthermore, the information available is based mainly on examination of the means of the physical properties. Little is known about the variations in hydrological and related properties of the media. In addition, the methods of determination and the results achieved by these methods may vary considerably (I, De Kreij and De Bess 1989, Heiskanen 1990). The applicability of methods and the relevance of the results and their interpretations for peat-based growth media thus appear to be poorly known.

The aim of the present research was to determine the hydrological and related physical properties and their variations in the peat-based growth media used or potentially usable in the production of containerized tree seedlings, mainly in the Nordic countries, and from the standpoint of seedling culturing, to discuss and evaluate the implications of these properties for water and aeration conditions in the media. Moreover, the validity of the methods for measuring the hydrological properties and conditions was to be assessed. Thus, an effort was made to characterize and assess the measurement of hydrological properties and conditions of growth media (I–V), to analyze the water retention characteristics and their variation in peat growth media used in Finnish tree nurseries (III), to determine the matric potential and unsaturated hydraulic conductivity of peat in containers during drying (IV) and to analyze the physical properties of several potential peat-based two-component growth media (V).

In this research, the hydrological properties and conditions are defined as those factors that directly characterize water retention and movement in the growth medium. Therefore, in particular, water retention characteristics, hydraulic conductivity, water potential and air-filled porosity are examined. This research provides information and theoretical background about the hydrological properties of the growth media and about their potential implications for water and aeration conditions in these media. The determination of optimum conditions directly applicable to the implementations of hydrological management practices in tree nurseries is, however, not within the scope of the research.

2 Materials and methods

2.1 Methods for assessing hydrological conditions

The known physical properties of various potential growth media and the present characterizations, standards and recommendations for water and aeration conditions which are considered favourable for plant crops were reviewed on the basis of the literature (I).

In Study II, methods were developed and applied by constructing a feasible, applicable measurement system for determining the temperature, matric potential and aeration of growth media in containers and by amassing experience concerning the suitability of the system for continuous measurement under greenhouse conditions. A sample of peat (Vapo D1K2, Vapo Corp., Finland) in an experimental container was used to test the functioning of the measurement system.

2.2 Growth media

The material of Study III consisted of commercial, prefertilized peat media used routinely in Finnish tree nurseries. The peat media represented the products of 2 textural grades (coarse and medium) of 2 Finnish producers, which account for the major part of the production of peat growth medium in Finland (Vapo and Kekkilä Corp.). The peat media of the Vapo Corp. were D1K2 and E1K2 and those of the Kekkilä Corp. were ST-400 M6 and PP6 for coarse and medium grades, respectively. The material was sampled from newly filled containers in 4 tree nurseries preceding the culturing season in 1990. In order to include the actual variations in nurseries, the material was collected from the filled trays rather than directly from the delivery bales of the producers.

Peat growth media of each producer and grade combination were sampled using a hierarchically (multi-stage) randomized design (III). Each peat sample was collected from a different, randomly selected seedling tray. For each of the 4 producer and grade combinations, 5 groups of 5 randomly selected samples were collected, each from a different, randomly selected greenhouse. The samples within greenhouses were considered to represent temporal variation in batches in the whole year's production lot within producers. In addition, 10 samples of compressed sheet peat (Vapo Corp.) produced for the

Vapo container-growing method and 10 samples of Swedish chip peat (Hasselfors Corp.) were collected from a production batch. A total of 120 samples were collected and analyzed.

In Study IV, preculture samples of 2 commonly used peat media (Vapo E1K2 and D1K2) and a peat-perlite mixture were analyzed. The mixture consisted of coarse perlite (33 % by volume) (Nordisk Perlite Corp., Denmark) and peat (67 % by volume) (Vapo E1K2). The media were placed in containers TK708 (straight cube shape) and TA710 (circular cross section becoming narrower towards the bottom) (Lännen Corp., Finland). Each medium and container combination was replicated 3 times. The total number of samples in the containers analyzed was 18.

The material of Study V consisted of two-component mixtures based on preculture peat (Vapo E1K2). The additive materials in peat were coarse and fine perlite (type 05-60 and 00-10, Nordisk Perlite Corp., Denmark), loose, nongranulated water-repellent and granulated water-absorbent rockwool (type BU-20 and 012-519, Grodania Corp., Denmark) and hydrogel (Waterworks America Corp., USA). The volumetric proportions of the additives in the mixtures were 10, 25 and 50 %. Water retention characteristics were measured from 10 replicates for peat and each mixture and from 5 replicates for pure additive materials (repellent rockwool and hydrogel excluded). Thus a total of 175 samples were analyzed.

2.3 Laboratory measurements

The laboratory measurements used in the studies (III–V) are briefly outlined in this section. A detailed description of the methods used has been presented in Study III and by Klute (1986), Klute and Dirksen (1986) and Heiskanen and Tamminen (1992).

In Studies III–V, volumetric water retention $\theta(\Psi m)$ for samples in 250 cm^3 open-ended cube-shaped metal containers was measured using a pressure plate apparatus (Soilmoisture Equipment Corp., USA). Decreasing matric potentials (–0.1, –1, –5, –10, –50, –100 and –1500 kPa) were applied successively over the samples until water flow from the pressure chambers had ceased. After rewatering, the same samples were used in all the next successive applications of decreasing matric potential (Heiskanen 1990). After each matric potential application, samples were weighed and their volume was determined by measuring the vertical and horizontal dimensions with a ruler (±0.5 mm).

In Studies III–V, the particle size distribution of the media was determined by sieving air-dried samples through standard sieves of 20, 10, 5 and 1 mm hole size (Puustjärvi 1977, Wilson 1983, Kurki 1985) (in V, also 0.06 mm). Loss on ignition, which provides an approximate estimate of organic matter content, was determined by igniting a sample weighing about 2 g at 550 °C for 3 hours. Particle density was measured using liquid pycnometers with water as the filling liquid and a water bath (Heiskanen 1992). Bulk density was determined as the ratio of dry mass (dried at 105 °C) to saturated volume. Saturated hydraulic conductivity was measured by applying the constant-head method (Klute and Dirksen 1986, Kretzschmar 1989).

In Study IV, unsaturated hydraulic conductivity K(Ψm) was measured by applying the method described in detail by Hartge and Horn (1989). Matric potential was measured over time with tensiometers from three vertical levels within samples in containers exposed to evaporation. Water retention θ(Ψm) was measured from separate, parallel samples. To each tensiometrically measured matric potential value Ψm, a respective water content θ was related using the average water retention curve θ(Ψm) for each type of medium. By using the estimated temporal water flux and spatial matric potential gradient in containers during drying, the average unsaturated hydraulic conductivity was calculated by applying the principle of Darcy's law (Weeks and Richards 1967, Hillel 1971, 1982).

2.4 Statistical analysis

In Study III, variation in the water retention characteristics of peat media used in nurseries was analyzed using mixed linear models (Searle 1971, Sokal and Rohlf 1981). The effects of producer and grade were considered to be fixed and those of greenhouse and tray random. The effects of greenhouse and tray were nested hierarchically within the higher effects. The tray effect was included in the residual effect, which was also expected to include measurement errors. In order to express the effects on the same scale and units as the means of the variables used, the fixed effects were presented as deviations from the general mean and the random effects as standard deviations.

To estimate the tray (sample) effect within greenhouses, the random measurement error in the water retention characteristics was estimated using separate data (III). These data were collected by subsampling main samples randomly from each producer and grade combination (sheet and chip peat excluded). The water retention for the subsamples were measured twice after the two successive applications of each given matric potential (–1, –10, –100 kPa). The difference between the two measurement values was then determined. By using a procedure with mixed linear models, an estimate was determined for the random measurement error and another for the variation due to trays within greenhouses.

In all studies (II–V), standard statistical procedures were used. Means and standard deviations of variables were calculated for the groups of media compared. Levene's test was used to test the homogeneity of variances. To test the differences between the means of the groups, one-way analysis of variance (ANOVA) and Tukey's test were used. These tests were also used when variances were unequal, because the significance levels obtained were close to those achieved with the Brown-Forsythe test, which does not require equal variances. Multivariate analysis of variance (MANOVA) was used for the designs of repeated measurements. Correlation coefficients and regression equations were used to assess relationships between variables.

3 Results

3.1 Assessment of hydrological conditions

Based on the literature review (I), it was found that favourable water availability for tree seedlings usually occurs at lower matric potentials (–5 to –50 kPa) than for horticultural plants (–1 to –10 kPa). Information concerning oxygen demand is rather scarce and in favourable conditions no clear differences were seen. Matric potential and oxygen diffusion rate appear to indicate the physical growth conditions of the growth medium most directly, and they should thus be used in describing and monitoring these conditions. During the growth period, the respective favourable levels for these variables are, in general, >–50 kPa and >70 μg m^{-2} s^{-1}.

A portable system based on a computer, a datalogger, temperature sensors and tensiometers was found to provide relatively feasible, real-time and parallel measurement of temperature and matric potential of growth medium in greenhouse conditions (II). The measurements of matric potential with small tensiometers fitted to pressure sensors (standard deviations <0.1 kPa at different matric potentials at given temperature) and temperature with semiconductor sensors (typical deviations <0.5 °C) were accurate and relatively easy to obtain. However, the measurement technique used for oxygen diffusion rate with an ODR-meter and Pt-sensors was based on separate and short, non-continuous measurements and was more complicated (II). This measurement required special care with the insertion and handling of electrodes, selection of the applied voltage and interpretation of the results. In light peat medium, it was found that the ODR-measurement is applicable at >–5 kPa matric potentials.

3.2 Hydrological and related properties of pure peat growth media and their variation in tree nurseries

The textural grades of the various loose, light peat media used in nurseries were rather similar (III–V). However, sheet and chip peat were coarser, since they contained significantly less <1 mm particles than the loose peat media. Loss on ignition (93.1–95.6 % on average) and particle density (1.60–1.67 g cm^{-3}) did not differ markedly between peat media, while the bulk density (0.057–0.087 g cm^{-3})

was clearly lowest for chip peat (III). The saturated hydraulic conductivity of the peat media varied considerably (0.9–5.2 mm min^{-1}) but was markedly higher for chip peat than for the loose peat or sheet peat media (III). The unsaturated hydraulic conductivity of peat decreased linearly on a log-log scale (c. 10^{-5} to 10^{-10} m s^{-1}) with a decrease in matric potential (c. –3 to –60 kPa) (IV).

At each of the three vertical levels measured, the matric potential of light peat in plantless containers exposed to drying was rather similar down to –10 kPa (IV). With matric potentials <–20 in the middle of a container, matric potentials <–80 kPa occurred at the peat surface when water repellency was encountered. When the matric potential at the upper level reached about –80 kPa, the decrease in height of the peat medium was 7–23 %, being markedly less in TA710 than in TK708 containers. In water retention measurements, peat media shrank an average of 0–16 % during desorption from 0 to –100 kPa matric potential (III, V). The decrease in the sample volumes was greatest between 0 and –1 kPa matric potential at desorption.

On average, all the peat media studied retained water similarly (c. 95 to 15 %) at desorption (–0.1 to –1500 kPa) (III). Sheet peat, however, tended to release water most at matric potentials down to –10 kPa at desorption, while at lower matric potentials it retained more water than the other peat media. Furthermore, between –100 and –1500 kPa matric potential, chip peat released more water than the other peat media. Peat particles <1 mm tended to increase and particles 1–5 mm to decrease the water retention of the peat media. However, when the matric potential was low (<–50 kPa), water retention clearly increased with bulk density. At –1500 kPa matric potential, water retention decreased with an increase in loss on ignition.

The greatest source of variation in the water retention of peat media at desorption was, in general, the variation within greenhouses (III). The greatest variation was at –1 kPa matric potential, to which the variation within greenhouses (standard deviation c. 11 %-units) contributed most. At –50 and –100 kPa matric potentials, the deviation from the general mean due to producer (c. 2 %-units) was, however, greater than the standard deviation of the residual effect (which included tray effect and measurement error). The grade effect was not statistically significant nor was the interaction between producer and grade (deviations from the mean <1 %-units). The greenhouse effect was obvious at matric potentials between –5 and –1500 kPa (standard deviations <2 %-units). The greenhouse effect was, however, lower than the residual effect within greenhouses. The greater variation within greenhouses was due to the tray (sample) effect, because variation within greenhouses due to random measurement error (standard deviations 2.4, 1.6 and 0.6 %-units at –1, –10 and –100 kPa matric potential, respectively) was estimated to have a smaller effect.

Mean air-filled porosity at –1 kPa matric potential (i.e. water content retained between 0 and –1 kPa matric potential) was markedly lower in loose peat media (<32 % on average) than in sheet and chip peat (>43 %) (III). On the other hand, between –1 and –10 kPa matric potential, sheet and chip peat retained less water (<26 %) than the loose peat media (>33 %). Water retention between –10 and –50 kPa (2–20 %) and between –50 and –1500 kPa matric potential (6–14 %) was lower and differed less between peat media. Within all the selected matric potential ranges studied (0 to –1, –1 to –10, –10 to –50, –50 to –1500 kPa), the water retention differed markedly between producers (III). It also differed between grades but only between matric potentials –50 and –1500 kPa, at which range there was also a marked interaction between producer and grade. The variation between greenhouses was small compared with the variation within greenhouses (between trays).

3.3 Hydrological and related properties of peat-based growth media mixtures

The additive materials used with peat (coarse and fine perlite, loose, nongranulated water-repellent and granulated water-absorbent rockwool and hydrogel) differed markedly in particle size distribution and particle structure (V). The bulk densities of the media mixtures were rather similar (on average, 0.075 g cm^{-3} for peat) (V). However, increased additions of water-absorbent rockwool to peat tended to increase bulk density markedly (up to 0.16 g cm^{-3}). Addition of repellent rockwool or perlite also tended to increase bulk density, while addition of hydrogel decreased it slightly (down to 0.05 g cm^{-3}).

The saturated hydraulic conductivity varied considerably within and between peat-based mixtures (on average, 0.05–0.25 cm min^{-1}) and did not significantly differ from each other, although increased additions of perlite to peat clearly tended to increase it (V). The unsaturated hydraulic conductivity of a peat-perlite mixture was slightly lower than that of pure peat (<1 order of magnitude) (IV). Drying down to about –80 kPa matric potential at the upper level in containers caused markedly lower vertical shrinkage for the peat-perlite medium (5–15 %) than for pure peat (IV). At desorption from 0 to –100 kPa matric potential, volumetric shrinkage (5–25 %) was considerably lower in peat containing perlite and somewhat lower in peat containing rockwool than in the other media studied (V). Addition of hydrogel tended to increase the shrinkage at matric potentials <–1 kPa (by up to 10 %-units).

During water retention measurements, the wettability of the medium was observed to be higher in media containing perlite than in other media, especially the drier the surface of the medium was (V). At matric potentials down to about –50 kPa, peat-perlite mixtures retained slightly less water than pure peat. Addition of water-repellent rockwool to peat tended to decrease water retention at desorption. At matric potentials <–1 kPa, addition of water-absorbent rockwool also decreased water retention slightly. Media containing hydrogel possessed markedly higher water retention between –1 and –100 kPa matric potential than the other media. Air-filled porosity at a matric potential of –1 kPa (i.e. water content retained between 0 and –1 kPa matric potential) was lower in peat to which hydrogel had been added than in other media. Coarse perlite and water-repellent rockwool addition to peat tended to increase this air-filled porosity. Between matric potentials of –1 and –10 kPa, water retention was markedly decreased in peat that contained half hydrogel or half water-repellent rockwool. On the other hand, between matric potentials of –50 and –1500 kPa, addition of hydrogel increased water retention considerably (up to 50 %).

4 Discussion

4.1 Hydrological and related properties of peat-based growth media

The textural grades of light peat media used in nurseries (III–V) were finer than the Nordic quality standards for unprocessed peat media obtained with a similar sieving technique (Puustjärvi 1982a). This was probably due to the fact that the particles comminuted or deaggregated during transportation and handling in nurseries or during manufacture by the producers. It is obvious that the container-filling procedure in nurseries had strongly contributed to crushing and to the uniformity of texture (Heiskanen 1994c). Prefertilization of peat media increases ash content, which apparently increased the amount of small particles and the particle density slightly and decreased loss on ignition (III). The saturated hydraulic conductivity for the pure peat media studied (III, V) was comparable to values reported previously for similar types of peat media (Korpijaakko and Radforth 1972, Päivänen 1973, Puustjärvi 1982c).

The unsaturated hydraulic conductivity of peat decreased linearly with matric potential on a log-log scale (IV). Due to the lower hydraulic conductivity of perlite (Jackson 1974), the hydraulic conductivity of a peat-perlite mixture was slightly lower than that of pure peat medium. The values obtained are relatively similar to those reported previously for natural peat (Bartels and Kuntze 1973, Illner and Raasch 1977, Loxham and Burghardt 1986). Furthermore, Puustjärvi (1991) reported similar hydraulic conductivities for a light, uncompressed peat growth medium at matric potentials of about –1 to –10 kPa. Due to intra-particle pores, peat possesses rather low hydraulic conductivity under unsaturated conditions compared with mineral soils (Bartels and Kuntze 1973, see Örlander 1984, 1985). At matric potentials below –10 kPa, the hydraulic conductivity of light peat was comparable to coarse sand (IV).

The water retention of the peat media (III–V) used in Finnish tree nurseries was, in general, comparable to that reported in the literature for similar peat media (Puustjärvi 1969, 1977, Päivänen 1973, Verdonck et al. 1983, Heiskanen 1990). Small peat particles (<1 mm) tend to increase and coarser particles (1–5 mm) to decrease water retention (III). Similar interactions have previously been found for uncompressed peat growth medium, in which an increase of particles <1 mm increases water retention at a matric potential of –1 kPa, while particles >6 mm decrease this water retention (Puustjärvi 1977, 1982b).

The greatest source of variation in the water retention characteristics of peat media was, in general, the variation within greenhouses between seedling trays (III). The grade effect was not statistically significant, which was apparently influenced by the decreased and rather uniform particle size of the media (Heiskanen 1994c). The variation between greenhouses was less than the variation within greenhouses, which probably indicates that the manufacture of peat by a given producer and peat handling in nurseries were fairly similar over a longer period of time. Therefore, because the variation within greenhouses due to random measurement error was relatively low (III), the marked tray effect was apparently caused by the different properties of peat before the actual manufacturing process. This is probably due to natural variations within peat harvesting areas and to changes during storage (e.g. self heating, aggregation, humification). Sorting of peat fractions in peat delivery bales probably also contributed to the variation between trays. Within selected matric potential ranges, the variation in water retention was also most marked between trays within greenhouses. Variation within trays may have existed, but this was not studied.

Sphagnum peat-perlite mixtures (IV, V) retained less water than pure peat, at least at matric potentials down to about –50 kPa, as has also been reported elsewhere (Verdonck 1983, Heiskanen 1994d). The pure perlites studied (V) showed intermediate water retention characteristics compared with those reported previously for perlite of various textural grades (Jackson 1974, Haynes and Goh 1978, Chen et al. 1980, Handreck 1983, Verdonck 1983, Verdonck et al. 1983). Pure absorbent rockwools retain almost as much water as peat but at desorption release it almost totally at matric potentials <–5 kPa, and small (<50 %) additions do not usually alter water retention characteristics of peat media markedly (V, Scagel and Davis 1988, Fonteno and Nelson 1990, Nelson and Fonteno 1991). However, addition of water-repellent rockwool to peat tends to decrease water retention at desorption (V, Langerud 1986, Scagel and Davis 1988). Mineral soils and mineral-based nursery soils commonly have lower total porosity and retain less water than peat (Päivänen 1973, Westman 1983).

Air-filled porosity at a matric potential of –1 kPa (i.e. water content retained between 0 and –1 kPa matric potential) was clearly lower in pure peat and even lower in peat to which hydrogel had been added (III, V) than that considered favourable for plants (c. >40 %) (I, Heiskanen 1994b). Due to high water retention in wet conditions, reduced aeration in pure peat (Puustjärvi 1977) and especially in growth media containing various hydrogels has also been indicated previously (Flannery and Busscher 1982, Lennox and Lumis 1987, Tripepi et al. 1991, Heiskanen 1994a). Furthermore, coarse perlite (Verdonck 1983) and water-repellent rockwool

(Langerud 1986, Scagel and Davis 1988) added to peat have been shown to increase air-filled porosity at a matric potential of –1 kPa, as was found in this study (V).

With matric potentials <–20 kPa in the middle of containers, matric potentials <–80 kPa may occur at the peat surface when wettability is decreased (IV). The surface properties of dry organic materials may even cause water repellency and unwettability (Hillel 1971, Puustjärvi 1977). Wettability appears to be higher in peat media containing perlite than in pure peat or other peat-based mixtures (IV, V, Heiskanen 1994d). Addition of perlite as well as vermiculite and mineral soils has also previously been indicated to increase the wettability of growth media mixtures (Bunt 1988).

Peat-based media usually tend to shrink at desorption. The shrinkage (on average <16 % of the initial volume) of pure peat media was generally somewhat less than that reported previously (III). This is at least partly due to the compression that preceded measurement of water retention (Heiskanen 1990). The volume of relatively dry, loose, low-humified *Sphagnum* peat may be up to 25 % lower than when it is wetted (Puustjärvi 1969, 1977, Bunt 1988). The shrinkage was, however, shown to be considerably lower in peat containing perlite and somewhat lower in peat containing rockwool (IV, V, Heiskanen 1994d). Shrinkage can also be decreased by using containers that become narrower towards the bottom (IV).

The shrinkage of the growth medium tends to increase bulk density and thus water retention expressed per apparent, shrunk volume of the medium at a specific matric potential compared with that expressed per initial saturated volume. Thus, shrinkage decreases both total and air-filled porosities correspondingly. The most marked increase in water retention caused by the shrinkage was found between matric potentials of 0 and –1 kPa (III, V). Water retention within the ranges of the lower matric potentials were not markedly affected by shrinkage. Consequently, shrinkage decreases the amount of coarse pores and increases that of fine pores (III, V, Heiskanen 1994d).

4.2 Hydrological conditions of growth media and seedling culturing

Availability of water and oxygen to tree seedlings based on the literature

There are a few studies available concerning water and aeration conditions of growth medium in relation to growth and water relations of tree seedlings (I). According to Jarvis and Jarvis (1963), two-year-old Scots pine (*Pinus sylvestris* L.) and one-year-old silver birch (*Betula pendula* Roth.) seedlings had markedly lowered transpiration rates at matric potentials below –30 to –70 kPa in sandy soil (total water potential –150 to –200 kPa). In mineral soils, over two-year-old conifer seedlings of several species have been shown to grow well at matric potentials down to about –100 kPa (Sands and Rutter 1959, Jarvis and Jarvis 1963). The growth of Sitka spruce seedlings (*Picea sitchensis* Carr.) was found to be greater at a matric potential of –6 kPa than at –60 kPa in loam, and at –5 kPa than at –30 kPa in peat (Coutts 1982). Water availability, measured as needle and plant water conductance, of one-year-old Scots pine seedlings grown in fine *Sphagnum* peat, was clearly reduced when the matric potential dropped to –50 kPa (Örlander and Due 1986a, b). At matric potentials >–5 kPa, the water availability declined, possibly indicating insufficient aeration.

With intensive fertilization, osmotic water potential may markedly decrease the availability of water. The osmotic water potential in fertilized peat growth media in greenhouse culturing of ornamentals forms the largest proportion of the total water potential (Puustjärvi 1978, 1980, Charpentier 1988). At ordinary levels of fertilization, the osmotic potential is between –50 and –90 kPa. Probably due to the osmotic adjustment of plant cells, matric potential may, however, have a somewhat greater effect on the availability of water and its uptake by plants than osmotic potential (Slatyer 1967, Puustjärvi 1980, Schleiff 1986, Shalhevet and Hsiao 1986). The root growth of oak (*Quercus rubra* L.) seedlings was shown to decrease strongly until at osmotic potentials <–400 to –600 kPa (Larson 1980).

Waterlogging reduces aeration and oxygen content, which, in turn, decreases the capacity of roots to absorb and conduct water and minerals (Kramer and Kozlowski 1960, Kozlowski et al. 1991). Soil aeration by gaseous diffusion increases with increasing temperature and air-filled porosity (Stolzy 1974, Hillel 1982, Campbell 1985). An air-filled porosity of about 10 % is the lowest limit for gaseous diffusion in several soil types (Wesseling and Wijk 1957), while an air-filled porosity of 10–15 % is considered to be the minimum for root respiration and growth (Vomocil and Flocker 1961). When the oxygen content of the air space in the growth medium diminishes <10 %, the growth of several conifers has been shown to decline (Leyton and Rousseau 1985). The critical oxygen diffusion rate for most plants is about 30, while favourable values are usually >70 µg m^{-2} s^{-1} (Stolzy 1974, Glinski and Stepniewski 1985, Bunt 1988).

Present standards and recommendations for hydrological conditions

Water availability and aeration in growth medium used for horticultural plants is generally assessed using physical criteria derived from the physical properties, especially the water retention characteristics, of the growth medium (I). De Boodt and Verdonck (1972) suggested that, for horticultural plants, in favourable growth medium easily available water should be 20–30 % (between –1 and –5 kPa matric potential). An air-filled porosity of about 20 % is regarded as favourable for ornamental plants (Bik 1973). According to Puustjärvi (1977), plant growth is favoured when peat in the greenhouse has a matric potential >–5 kPa and an air space >50 %. It has been suggested that, during the dormancy period, the water content should be lower and the air space higher than that during the growth period (Bik 1973, Puustjärvi 1977, Bunt 1983). Compared with the recommendations given by De Boodt and Verdonck (1972), for most ornamentals Verdonck et al. (1981) recommended less water (and more air) at container capacity. Verdonck and Gabriels (1988) suggested that, at container capacity, somewhat more air should be retained in black and light peat mixtures than in peat and bark compost mixtures.

A matric potential range of –10 to –75 kPa (Day 1980, McDonald 1984) and an air-filled porosity of 20 % (Warkentin 1984) are commonly recommended for cultivation of tree seedlings in open nursery soils. In a greenhouse, however, seedling growth in peat is usually greater with higher matric potentials and volumes of air space (I, Puustjärvi 1977, Örlander and Due 1986a, b, Heiskanen 1994a, b). In production of containerized seedlings, a matric potential of –10 kPa is often used as the target limit for reirrigations (Landis et al. 1989).

Implications of the hydrological properties of the peat-based growth media studied

The amount of easily available water to plants from the peat-based growth media studied (III, V) was probably high (water content retained between –1 and –10 kPa matric potential was c. >30 %) (see e.g. De Boodt and Verdonck 1972). The available water between matric potentials of –10 and –50 kPa, which can be considered to be a water reserve for plants growing under slightly suboptimal moisture conditions, was rather low in all the media analyzed (<10 %). Thus, in plants persistently exposed to these conditions growth may be reduced. Within the driest matric potential range studied (–50 to –1500 kPa), the slowly available water reserve was markedly elevated in peat containing half hydrogel. An increase in water retention due to hydrogels has also been reported previously (Eikhof et al. 1973, Gehring and Lewis 1980, Johnson 1984, Taylor and Halfacre 1986, Woodhouse and Johnson 1991).

Irrigation tolerance can be considered to be the amount of water retained within the matric potential range used (i.e. θmax – θmin) (III). In practical irrigation, the wider this tolerance and the less its variation, then obviously the easier it is to regulate the amounts of water and timing of irrigation. Great variations in the water and aeration characteristics of peat have been found to cause variations in plant growth within a crop (Puustjärvi 1975a, 1977). Large variation in water retention between trays may thus cause problems in water or oxygen availability to seedlings within greenhouses, even though the irrigation regime for a greenhouse would, on average, be favourable.

The average amount of irrigation water needed to increase the matric potential from –10 to –1 kPa was shown to be 37 % of the volume in pure, loose peat media, which corresponds to 37 mm water in a 10 cm thick peat layer (III). The time before –10 kPa is again reached in the peat media and irrigation is needed would be about 10 days, because the average rate of evapotranspiration in greenhouses is 2–4 mm a day (Rikala 1985). This period is relatively long and the required amount of irrigation water (37 mm) is large. This means that irrigation is, in principle, fairly easy to adjust. However, larger-than-average water retention at container capacity may result in restricted aeration and waterlogging in different trays, if air-filled porosity is less than about 40 % (von Richard et al. 1958, Lotocki 1977, Puustjärvi 1975a, 1977, Heiskanen 1994b). The standard deviation for the amount of retained water (between –1 to –10 kPa) within greenhouses was relatively large, about 10 %-units. This may decrease irrigation tolerance and increase the need for more accurate monitoring of irrigation in order to maintain conditions in the greenhouse within favourable limits. In addition, possible variations within trays further reduce irrigation tolerance, when even more dense frequencies with smaller amounts of water are required. Moreover, great shrinkage at desorption reduces aeration (III, V, Heiskanen 1994d). This risk may increase when roots and compaction reduce the amount of coarse pores over time (Puustjärvi 1975b, Mannerkoski 1982, Langerud 1986). The oxygen diffusion rate, however, determines the actual aeration, which is also affected by other factors, such as container type, ventilation and temperature.

Different methods of irrigation (varying in water flux, flux evenness, drop size) may have a great effect on the distribution of water into different trays and also within trays and containers. If peat is irrigated frequently with relatively small quantities of water at a time, all the water may be retained by the upper part of the medium and by the foliage of the seedlings while the lower parts of the container remain dry (Landis et al. 1989). The transpiration of seedlings further decreases the water content in the container. On the other hand, a moist peat surface may promote growth of algae and mosses (Cronberg 1991, Tinus and McDonald 1979), which may block the pores of the peat structure, thus restricting aeration of the growth medium. Consequently, although the average aeration limit would be exceeded temporarily, light peat apparently requires relatively infrequent reirrigations, during each of which a sufficiently large quantity of water is applied within a short time (Puustjärvi 1977, Heiskanen 1994b, d, cf. Langerud and Sandvik 1991). Due to their lower water retention capacity, however, smaller containers require more frequent irrigation than larger ones (Langerud and Sandvik 1988, 1991, Heiskanen 1994b).

Nevertheless, excess drying (matric potential < c. –80 kPa) should also be avoided due to the risk of surface crusting and unwettability of peat, which may cause difficulties in irrigation (IV). During excess drying, the strong decrease in the hydraulic conductivity of peat and the possible weakening of soil-root contact due to shrinkage may also considerably decrease the availability of water to seedlings.

4.3 Methodological considerations

Assessment of availability of water and oxygen

The previously recommended levels for proportions of water and air have usually been obtained using different methods which are not necessarily comparable with each other (I). Moreover, neither air- nor water-filled porosity alone actually and commensurably describes the availability of air or water to the roots in all media and management regimes. For example, the demand for air-filled porosity in peat (45–50 %) (Puustjärvi 1977, 1980) is higher than the values recommended for mineral soils. It has also been suggested that clay-rich humic soils should contain air 20 %, horticultural soil mixtures 30 % and peat media 40 % (Penningsfeld 1974). These differences in the air-filled porosities probably originate from differences in the internal structure of the media. Peat has a partly open intra-particle structure (moss cells) which tends to retain air (and water) inside the particles but without significantly contributing to the effective aeration (Puustjärvi 1975a, Solbraa 1979, Handreck 1983). If the level of retention of the available air and water inside the particles can be determined, the air-filled porosity would then describe the effective aeration. In mineral soils, the measurable air space is apparently close to this effective air-filled porosity. Gaseous diffusion is, however, a dynamic process and therefore the effective rate of gas exchange is more important to oxygen availability than the volume of the air space (Hillel 1982). Thus, available oxygen is determined by the oxygen diffusion rate, which is dependent on the diffusion coefficient of the medium, the prevailing oxygen concentration gradient and temperature (McIntyre 1970, Stolzy 1974, Hillel 1982, Glinski and Stepniewski 1985).

Similarly to air retention, water retention is also affected by the internal structure of the medium and may not provide an accurate and commensurable measure of water availability (I). Since the water potential is defined as the amount of work required to remove water from its reference state to the state desired, to overcome a water potential difference $\Delta\Psi$ (kPa), a specific quantity of work

W (kJ) is needed to be exerted upon a water volume V (m^3) (Hillel 1971, Korvaar et al. 1983, Campbell 1985). Thus, $W = \Delta\Psi \cdot V$. Therefore, the water potential can, in principle, be considered to indicate the potential energy which must be available for water uptake from the growth medium. Thus, availability of water from various growth media to seedlings (in given ambient conditions, see Fig. 1) can apparently be more directly and commensurably described by the water potential than by the water and air contents of the media (I).

Average favourable matric potential or water and air contents usually suffice to determine the adequacy of the availability of water and oxygen to seedlings from a particular growth medium. When accurate evaluation of water availability is required, the hydraulic conductivity of the growth medium as a function of matric potential should also be determined (I, IV, Glinski and Lipiec 1990, da Silva et al. 1993). Furthermore, at low osmotic potentials (with intense fertilization) it is necessary to estimate the total water potential as the sum of the matric and the osmotic potential (I, Puustjärvi 1980).

In addition, large variations in temperature have to be considered for water availability. With decreasing temperature water viscosity increases, resulting in decreased rates of water movement in the growth medium-plant-atmosphere continuum. Water uptake by roots is largely determined by temperature conditions (Hillel 1971, 1982, Campbell 1985). Furthermore, assessment of water availability merely on the basis of the properties of the growth medium is not applicable if, for example, adequate contact between the medium and the roots does not occur during culturing (Cowan 1965, Newman 1974, Currie 1984, Glinski and Lipiec 1990). Mycorrhizas may also have a significant impact on the water uptake of seedlings (Dixon et al. 1980, Duddridge et al. 1980, Parke et al. 1983, Stenström 1990; cf. Sands and Theodorou 1978, Sands et al. 1982).

Measurement of hydrological conditions

The measurement system used for determination of matric potential and oxygen diffusion rate probably require further development for practical application in order to readily and continuously quantify these variables from the small containers in seedling culturing (II). Correct pressure transducers and the shape and material of tensiometer tips should be selected to ensure their suitability for different measurement conditions. Accurate results require calibration for each type of pressure transducers. During measurements some monitoring is also required, e.g. to ensure proper contact of the sensors with the growth medium. In addition, tensiometers measure matric potential only down to c. –90 kPa. If the water retention characteristic of the medium is known, time domain reflectometry (TDR) (Topp et al. 1984, Baker and Allmaras 1990, Van Loon et al. 1990, Zegelin et al. 1992) may in the future also be applied for estimating the matric potential. These two methods (tensiometer, TDR) evidently allow a great number of measurements to be taken over the common range of moisture levels occurring during seedling growth in various growth media and management regimes.

At low osmotic potentials, the osmotic potential can be roughly estimated by measuring the electrical conductivity of the growth medium (Puustjärvi 1980). The most feasible method for determining the total water potential appears to be the thermocouple psychrometer technique (Landis et al. 1989). The hydraulic conductivities of different media at the same water potentials may differ somewhat, but measurements of hydraulic conductivity (IV) may be too complex and time consuming for routine use in practical seedling production.

The present ODR-measurement techniques are based on separate and non-continuous measurements and require the utmost care and many repeated measurements, because of the great variation due to heterogeneity of the growth media (II, McIntyre 1970, Mannerkoski 1985). The measurement of ODR is applicable for the most critical, wettest conditions, e.g. near container capacity, and at matric potentials down to about –50 to –100 kPa in mineral soils (Glinski and Stepniewski 1985). However, because the drying of the water film causes inactivation of the electrodes, it was shown that in light peat medium the measurement is applicable only at matric potentials >–5 kPa (II). At present, ODR-determination seems rather complex to use and to interpret the results, and further application is needed for practical use. Alternatively, air-filled porosity of the medium apparently provides a feasible indirect estimate of aeration (at given conditions of temperature and oxygen concentration) (Hillel 1982, Campbell 1985). Oxygen diffusivity (diffusion coefficient) of the medium could also be used to estimate aeration indirectly, but this is rather complex to measure (Rolston 1986).

Measurement of hydrological properties

Before sample collection and analysis, an appropriate sampling method should be selected in order to determine the actual means and variations of peat properties in nurseries. Merely examining mean water retention characteristics does not provide information about variations and their effects in various work units (III). For example, if management practices are determined on the basis of a mean value from greenhouses and is thus applied similarly in all greenhouses, great variations between greenhouses may cause marked variation in the growth of seedling crops. Consideration of the variation in peat properties within greenhouses between trays may be reasonable for adjusting management practices within seedling crops. Then, adequately samples should be collected from within greenhouses. This should also be done when only the greenhouse means are to be analyzed (i.e. samples are combined within greenhouses). For practical culturing, it may also be reasonable to consider smaller scale variation within trays.

The methods used here can, in general, be considered to be well suited for measuring and interpreting the properties of peat-based media for culturing of containerized seedlings (III–V). Comparison of water retention characteristics may, however, require values achieved by analogous methods (Heiskanen 1990). Water retention characteristics were determined from samples considered to represent properties that are in accordance with those occurring in actual nursery conditions. In this respect, the sample handling and sample containers used in the measurements evidently were appropriate (see Puustjärvi 1969, De Kreij and De Bess 1989, Heiskanen 1990). When marked shrinkage occurs at desorption, and wet conditions and waterlogging are expected in the growth media during culturing, volume determinations are needed in the water retention measurements.

Variations in the results of water retention measurements (III–V) may have been caused by possible differences in initial degree of saturation, in handling of samples and in the contact area between samples and ceramic disks. Desorption times may also have varied, resulting in incomplete equilibria of the water content at different matric potentials. It is also possible that released peat colloids and precipitates may, to some extent, have blocked the ceramic disks at desorption, thus altering desorption times and affecting the results. The room temperature during laboratory measurements may have affected the results, but this effect was probably relatively small (Päivänen 1973). The precision of the water retention measurement was nevertheless fairly good, because the random measurement error had less effect than other sources of variation (III). This was due to the large variation in the porosity of the peat media when the smaller measurement error did not appear. On the other hand, at a matric potential of –10 kPa the measurement error (standard deviation 1.6 %-units) was significant, which was evidently contributed by the relatively low variation in the actual water retention.

The water retention characteristics used were also moderately accurately predicted on the basis of particle size, bulk density and loss on ignition (III). They probably could have been predicted more accurately if the heterogeneity of peat material had been measured more accurately. In particular, use of more and finer particle fraction classes might have provided a more accurate description of peat texture. On the other hand, variation in the air-dry water content of samples used in sieving was observed to affect the estimation of texture slightly. If this water content was 10 % of the moist mass or less, more fine particles (< 1mm) tended to occur. If the water content was 20 to 40 %, the particle size estimates did not appear to vary greatly. Although it is a common standard, the sieving technique with dry peat may in general overvalue small particles, thus possibly not describing the structure and water retention of moist peat in the most accurate way.

The constant-head method used (III, V) for the determination of saturated hydraulic conductivity includes slight flow of water along the edges of the sample cores (Päivänen 1973). In nurseries, however, growth media in containers allow similar water flow in wet conditions; and in this respect the method used provides applicable results. On the other hand, the values achieved were, in general, rather low, being close to those of unsaturated (at c. –4 kPa) hydraulic conductivity (IV). The saturated conductivity in various peat media and peat-based mixtures was also relatively similar (III, V). The constant-head method required a long time period (1–2 days) to saturate samples. Therefore, at persistent full saturation the low and invariable hydraulic conductivity may be due to low permeability of the pores, because the peat colloids have probably swollen more, thus blocking more of the pores than at desorption just after transient saturation. Saturation of a shorter duration has been shown to give higher hydraulic conductivity values even for mineral soils (Sillanpää 1956). Due to the fact that the initial water contents are usually lower and the saturation times shorter after irrigation or precipitation in nurseries, the saturated hydraulic conductivity of peat-based growth media is probably higher than that achieved in this study (III, V). Thus, the estimates of saturated hydraulic conductivity are probably too low if applied in nurseries. During autumn rains on the hardening fields, however, persistent saturated conditions and low hydraulic conductivities may occur in the containers.

The temperature dependence of saturated hydraulic conductivity is mainly due to the kinematic viscosity of water (Campbell 1985). This effect was considered (III, V) by using correction coefficients in saturated conditions (Sillanpää 1956). In unsaturated conditions, the effect of temperature on viscosity and density of water is more complex and evidently is much smaller than the effect of the matric potential (Hillel 1971, Korvaar et al. 1983, Iwata et al. 1988). In addition, during $K(\Psi m)$ measurements (IV), the variations in temperature were rather small (within 2–3 °C) and thus their effect was probably negligible. Possible solutes in water may also affect hydraulic conductivity (Klute and Dirksen 1986). Furthermore, although hydraulic conductivity at sorption differs from that at desorption (i.e. hysteresis), determinations were done at desorption (Hillel 1971, Klute and Dirksen 1986), since drying is apparently more crucial to the availability of water to seedlings.

The average deviation in the unsaturated hydraulic conductivity about the logarithmic regression lines was about half an order of magnitude for peat and for a peat-perlite mixture (IV). These deviations from linearity were mainly due to the natural heterogeneity of the media. However, part may have been due to the methods used. Because the water retention characteristics were determined from the parallel samples, the measured characteristics may have differed from the actual characteristics of the media in the containers during the measurement of hydraulic conductivity. There may also have been differences in shrinkage and other properties of the medium materials. In addition, deviations from the stationary water flow during the measurement, due to the possibility of varying evaporation rate and nonisothermal water flow, may have caused slight inaccuracies in the values for hydraulic conductivity. Nevertheless, despite these potential limitations and the different measurement techniques, the estimated hydraulic conductivity values appeared to be valid and to be similar to those reported in the literature for similar types of media (IV).

5 Conclusions

The hydrological and related physical properties and their variations in the light *Sphagnum* peat-based growth media used or potentially usable in tree seedling culturing were analyzed. The potential implications of these properties on seedling culturing and the methods of determination of hydrological properties and conditions were also evaluated.

In general, the physical properties of the peat-based media appeared well suited for providing favourable water and aeration conditions (I–V). Under short-term culturing and infrequent irrigation without exposure to free rain, all the media studied are likely to provide a large amount of the easily available water (mainly water retained between matric potentials of –1 and –10 kPa) and sufficiently large, air-filled pores, which are a prerequisite for aeration (I, III, V). However, retention of easily available water by coarse sheet peat and loose peat media to which half hydrogel has been added was low. In dry conditions (matric potentials <–50 kPa), addition of hydrogel increased water retention considerably (V). During drying, however, the hydraulic conductivity of peat decreased steeply, which apparently reduces water availability (IV). Under long-term culturing, with frequent irrigation and during exposure to precipitation on hardening fields, aeration may be a limiting factor for seedling growth in peat-based media (I, III). In this respect, only coarse sheet and chip peat probably can provide sufficient aeration (III). By addition of coarse perlite and water-repellent rockwool to loose peat media, the air-filled porosity can, however, be increased (V). Addition of coarse perlite also tended to improve the saturated hydraulic conductivity and wettability of dry peat (V).

Water retention characteristics did not differ markedly between textural grades of the peat media used in tree nurseries (III). Variations in water retention characteristics of media between different greenhouses were found to cause potential unevenness in the growth and irrigation requirements of seedling crops. The variations were, however, largest between trays within greenhouses. This variation apparently originated from the initial heterogeneity and sorting of peat material within peat delivery bales.

The methods used for determining water retention and unsaturated hydraulic conductivity were judged to be feasible and relatively precise (III–V). However, the constant-head method used for determining saturated hydraulic conductivity may give underestimates for peat-based media. It was further assessed that water availability to seedlings from various growth media is readily measurable and can be evaluated in terms of water potential, while the determination of available oxygen and actual aeration may be too complex for practical use (I, II). Aeration can, however, be readily evaluated indirectly by determining air-filled porosity.

In conclusion, within the limits found for the hydrological properties and their variations in peat-based growth media, irrigation practices can be aimed at meeting the favourable range for water and air contents of the medium by avoiding both drought and waterlogging (Fig. 2). When these limits are considered, the optimum conditions can, in principle, be achieved by manipulating amounts and frequencies of irrigation and the composition of the growth medium. The optimal physical properties and conditions may, however, vary at different phases of seedling production. During the phases of seedling hardening and outplanting, hydrological conditions are partly uncontrollable, which may lead to extreme conditions critical for seedling survival and growth. Furthermore, the actual methods used in management practices and the prevailing growth conditions in individual containers during each phase of seedling production are the criteria which, in the final analysis, determine the accurate means and allowable limits of variation for the relevant water and aeration conditions and the water retention characteristics for seedling growth. The relevant hydrological criteria for growth media in different management regimes and the application of these criteria for implementation in seedling production can be found through development work.

References

Baker, J.M. & Allmaras, R.R. 1990. System for automating and multiplexing soil moisture measurement by time-domain reflectometry. Soil Science Society of America Journal 54: 1–6.

Bartels, R. & Kuntze, H. 1973. Torfeigenschaften und ungesättigte hydraulische Leitfähigkeit von Moorböden. Zeitung für Pflanzenernährung und Bodenkunde 134: 125–135.

Bik, A.R. 1973. Some thoughts on the physical properties of substrates with special reference to aeration. Acta Horticulturae 31: 149–160.

Bunt, A.C. 1983. Physical properties of mixtures of peats and minerals of different particle size and bulk density for potting substrates. Acta Horticulturae 150: 143–153.

Bunt, A.C. 1988. Media and mixes for container-grown plants. 2nd ed. Unwin Hyman, London. 309 p.

Campbell, G.S. 1985. Soil physics with Basic. Transport models for soil-plant systems. Developments in soil science 14. Elsevier, Amsterdam. 150 p.

Charpentier, S. 1988. Water potential in the substrate-solution system in horticulture. Acta Horticulturae 221: 25–33.

Chen Y., Banin, A. & Ataman, Y. 1980. Characterization of particles and pores, hydraulic properties and water-air ratios of artificial growth media and soils. Proc. 5th Int. Congr. Soilless Culture. May 18–24. ISOSC, Wageningen. pp. 63–82.

Cowan, I.R. 1965. Transport of water in the soil-plant-atmosphere system. Journal of Applied Ecology 2: 221–239.

Currie, J.A. 1984. The physical properties in the seedbed. Aspects of Applied Biology 7: 33–54.

Coutts, M.P. 1982. Growth of sitka spruce seedlings with roots divided between soils of unequal matric potential. New Phytologist 92: 49–61.

Cronberg, N. 1991. Åtgärder för kontroll av lungmossa i planteskolemiljö. Swedish Univ. Agr. Sci., Dept. For. Regen., Garbenberg. Plantnytt 6: 1–4.

Day, R.J. 1980. Effective nursery irrigation depends on regulation of soil moisture and aeration. Proc. North Am. For. Tree Nursery Soils Workshop, July 28-August 1 1980, Syracuse, New York. pp. 52–71.

De Boodt, M. & Verdonck, O. 1972. The physical properties of the substrates in horticulture. Acta Horticulturae 26: 37–44.

De Kreij, C. & De Bess, S.S. 1989. Comparison of physical analysis of peat substrates. Acta Horticulturae 238: 23–36.

Dixon, R.K., Wright, G.M., Behrns, G.T., Teskey, R.O. & Hinckley, T.M. 1980. Water deficits and root growth of ectomycorrhizal white oak seedlings. Canadian Journal of Forest Research 10: 545–548.

Duddridge, J.A., Malibari, A. & Read, D.J. 1980. Structure and function of mycorrhizal rhizomorphs with special reference to their role in water transport. Nature 287: 834–836.

Eikhof, R.H., King, P.A. & Moline, S.W. 1973. The influence of a hydrophilic polymer on the water requirements and shelf life of container grown plants. Nat. Agric. Plastics Assoc. Conf. Proc. 11: 117–126.

Flannery, R.L. & Busscher, W.J. 1982. Use of a synthetic polymer in potting soils to improve water holding capacity. Communications in Soil Science and Plant Analysis 13: 103–111.

Fonteno, W.C. & Nelson, P.V. 1990. Physical properties of and plant responses to rockwool-amended media. Journal of the American Society for Horticultural Science 115: 375–381.

Gehring, J.M. & Lewis, A.J. 1980. Effect of hydrogel on wilting and moisture stress of bedding plants. Journal of the American Society for Horticultural Science 105: 511–513.

Glinski, J. & Lipiec, J. 1990. Soil physical conditions and plant roots. CRC Press, Boca Raton, Fla. 250 p.

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

Handreck, K.A. 1983. Particle size and the physical properties of growing media for containers. Communications in Soil Science and Plant Analysis 14: 209–222.

Hartge, K.H. & Horn, R. 1989. Die physikalische Untersuchung von Böden. 2. Aufl. Enke, Stuttgart. 175 p.

Haynes, R.J. & Goh, K.M. 1978. Evaluation of potting media for commercial nursery production of container-grown plants. New Zealand Journal of Agricultural Research 21: 449–456.

Heiskanen, J. 1990. Näytelieriön täyttötavan vaikutus kasvuturpeen vedenpidätyskykyyn. Summary: The effect of sample handling on the water retention of growth peat substrate. Suo 41: 91–96.

Heiskanen, J. 1992. Comparison of three methods for determining the particle density of soil with liquid pycnometers. Communications in Soil Science and Plant Analysis 23: 841–846.

Heiskanen, J. 1994a. Effect of peat-based two-component growth media on the growth of containerized Scots pine seedlings. Suo 45: 17–29.

Heiskanen, J. 1994b. Irrigation regime affects water and aeration conditions in peat growth medium and the growth of containerized Scots pine seedlings. New Forests. (In press).

Heiskanen, J. 1994c. Mechanical container filling alters texture and water retention of peat growth media. HortTechnology. (In press).

Heiskanen, J. 1994d. Water status of Sphagnum peat and a peat-perlite mixture in containers subjected to different irrigation regimes. HortScience. (In press).

Heiskanen, J. & Tamminen, P. 1992. Maan fysikaalisten ominaisuuksien määrittäminen. Metsäntutkimuslaitoksen tiedonantoja 424. 32 p.

Hillel, D. 1971. Soil and water. Physical principles and processes. Academic Press, Orlando. 288 p.

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

van den Honert, T.H. 1948. Water transport in plants as a catenary process. Discussions of the Faraday Society 3: 146–153.

Illner, K. & Raasch, H. 1977. Der Einfluss von Torfeigenschaften auf die kapillare Leitfähigkeit in Niedermoorböden. Archiv für Acker- und Pflanzenbau und Bodenkunde 21: 753–758.

Iwata, S., Tabuchi, T. & Warkentin, B.P. 1988. Soil-water interactions. Mechanisms and applications. Marcel Dekker, New York. 380 p.

Jackson, D.K. 1974. Some characteristics of perlite as an experimental growth medium. Plant and Soil 40: 161–167.

Jarvis, P.G. & Jarvis, M.S. 1963. The water relations of tree seedlings II. Transpiration in relation to soil water potential. Physiologia Plantarum 16: 236–253.

Jenkins, J.R. & Jarrell, W.M. 1989. Predicting physical and chemical properties of container mixtures. HortScience 24: 292–295.

Johnson, M.S. 1984. Effect of soluble salts on water absorption by gel-forming soil conditioners. Journal of the Science of Food and Agriculture 35: 1063–1066.

Klute, A. 1986. Water retention: Laboratory methods. In: Klute, A. (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agronomy 9. Am. Soc. Agr. Soil Sci. Soc. Am. Publisher, Madison, Wisconsin. pp. 635–662.

Klute, A. & Dirksen, C. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute, A. (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agronomy 9. Am. Soc. Agr. Soil Sci. Soc. Am. Publisher, Madison, Wisconsin. pp. 687–734.

Korpijaakko, M. & Radforth, N.W. 1972. Studies on the hydraulic conductivity of peat. Proc. 4th Int. Peat Congr. Vol III. pp. 323–333.

Korvaar, P., Menelik, G. and Dirksen C. 1983. Elements of soil physics. Developments in soil science 13. 3rd. ed. Elesevier, Amsterdam. 230 p.

Kozlowski, T.T., Kramer, P.J. & Pallardy, S.G. 1991. The physiological ecology of woody plants. Academic Press, San Diego. 657 p.

Kramer, P.J. & Kozlowski, T.T. 1960. Physiology of trees. McGraw-Hill Book, New York. 642 p.

Kretzschmar, R. 1989. Kulturtechnisch-bodenkundliches Praktikum. Ausgewählte Laboratoriumsmethoden. Eine Einleitung zum selbständigen Arbeiten an Böden. 6. Aufl. Christian-Albrechts Univ., Kiel. 514 p.

Kurki, L. 1985. Kasvuturpeen laadun merkitys. Turveteollisuus 4: 86–87.

Landis, T.D., Tinus, R.W., McDonald, S.E. & Barnett, J.P. 1989. Seedling nutrition and irrigation. The container tree nursery manual. Vol 4. USDA, Forest Service, Washington DC. Agric Handbook 674. 119 p.

Landis, T.D., Tinus, R.W., McDonald, S.E. & Barnett, J.P. 1990. Containers and growing media. The container tree nursery manual. Vol 2. USDA, Forest Service, Washington DC. Agric Handbook 674. 87 p.

Langerud, B.R. 1986. A simple in situ method for the characterization of porosity in growth media. Plant and Soil 93: 413–425.

Langerud, B.R. & Sandvik, M. 1988. Physical conditions in peat/perlite mixtures subjected to different irrigation regimes. Acta Horticulturae 221: 363–370.

Langerud, B.R. & Sandvik, M. 1991. Transpiration of containerized Picea abies seedlings grown with different irrigation regimes. Scandinavian Journal of Forest Research 6: 79–90.

Larson, M.M. 1980. Effects of atmospheric humidity and zonal soil water stress on initial growth of planted northern red oak seedlings. Canadian Journal of Forest Research 10: 549–554.

Lennox, T.L. & Lumis, G.P. 1987. Evaluation of physical properties of several growing media for use in aerial seedling containers. Canadian Journal of Forest Research 17: 165–173.

Leyton, L. & Rousseau, Z. 1985. Root growth of tree seedlings in relation to aeration. In: Thimann, K.V. (ed.) The physiology of forest trees. Ronald Press, New York. pp. 467–475.

van Loon, W.K.P., Perfect, E., Groenevelt, P.H. & Kay, B.D. 1990. A new method to measure bulk electrical conductivity in soils with time domain reflectometry. Canadian Journal of Soil Science. 70: 403–410.

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.

Loxham, M. & Burghardt, W. 1986. Saturated and unsaturated permeabilities of North German peats. In: Fuchsman, C.H. (ed.) Peat and water. Aspects of water retention and dewatering in peat. Elsevier, London, New York. pp. 37–59.

Maa- ja metsätalousministeriön päätös eräiden lannoitevalmisteiden laatuvaatimuksista. 1986. Suomen Asetuskokoelma N:o 384. Helsinki. pp. 885–886.

Mannerkoski, H. 1982. Effect of tree roots on the bulk density of peat. Proc. Int. Peat Soc. Comm. II., Minsk. pp. 182–188.

Mannerkoski, H. 1985. Effect of water table fluctuation on the ecology of peat soil. Univ. Helsinki. Publ. Dept. Peatland For. 7: 1–190.

McDonald, S.E. 1984. Irrigation in forest-tree nurseries: Monitoring and effects on seedling growth. In: Duryea, M.L. & Landis, T.D. (eds.) Forest Nursery Manual: Production of bareroot seedlings Martinus/Dr. W. Junk Publishers, The Hague-Boston-Lancaster. pp. 107–121.

McIntyre, D.S. 1970. The platinum microelectrode method for soil aeration measurement. Advances in Agronomy 22: 235–283.

Nelson, P.V. & Fonteno, W.C. 1991. Physical analysis of rockwool slabs and effects of fiber orientation, irrigation frequency and production technique on Chrysanthemum production. Journal of Plant Nutrition 14: 835–866.

Newman, E.I. 1974. Root and soil water relations. In: Carson, E.W. (ed.) The plant root and its environment. Univ. of Virginia, Charlottesville. pp. 363–440.

Örlander, G. 1984. Some aspects of water relations in planted seedlings of Pinus sylvestris L. Dr. Thesis. Swedish Univ. Agr. Sci, Dept. Silviculture, Umeå. 30 p.

Örlander, G. 1985. Skogsskötsel i södra Sverige. Swedish Univ. Agr. Sci., Uppsala. Skogsfakta Konferens 7: 41–44.

Örlander, G. & Due, K. 1986a. Location of hydraulic resistance in the soil-plant pathway in seedlings of Pinus sylvestris L. grown in peat. Canadian Journal of Forest Research 16: 115–123.

Örlander, G. & Due, K. 1986b. Water relation of seedlings of Scots pine grown in peat as a function of soil water potential and soil temperature. Studia Forestalia Suecica 175: 1–13.

Päivänen, J. 1969. The bulk density of peat and its determination. Silva Fennica 3: 1–19.

Päivänen, J. 1973. Hydraulic conductivity and water retention in peat soils. Acta Forestalia Fennica 129: 1–70.

Pallardy, S.G. 1989. Hydraulic architecture and conductivity: An overview. In: Kreeb, K.H., Richter, H. & Hinckley, T.M. (eds.) Structural and functional responses to environmental stresses: Water shortage. SPB Academic Publ., The Hague. pp. 3–19.

Parke, P.G., Linderman, R.G. & Black, C.H. 1983. The role of ectomycorrhizas in drought tolerance of Douglas-fir seedlings. New Phytologist 95: 83–95.

Penningsfeld, F. 1974. Bases of production, examination and use of growth media. Acta Horticulturae 37: 1918–1921.

Puustjärvi, V. 1969. Fixing peat standards. Peat & Plant News 2: 3–8.

Puustjärvi, V. 1970. Degree of decomposition. Peat & Plant News 4: 48–52.

Puustjärvi, V. 1973. Kasvuturve ja sen käyttö. Turveteollisuusliitto r.y., Helsinki. 173 p.

Puustjärvi, V. 1975a. Growth disturbances induced by low air space. Peat & Plant Yearbook 1973–1975. pp. 17–19.

Puustjärvi, V. 1975b. On the factors contributing to changes in peat structure in greenhouse culture. Peat & Plant Yearbook 1973–1975. pp. 11–14.

Puustjärvi, V. 1977. Peat and its use in horticulture. Turveteollisuuslitto r.y. Publication 3. Liikekirjapaino, Helsinki. 160 p.

Puustjärvi, V. 1978. The water uptake as a function of matric potential and osmotic pressure in peat culture. Peat & Plant Yearbook 1978: 13–20.

Puustjärvi, V. 1980. Nutrient standards of fertilized peat. Peat & Plant Yearbook 1980: 28–43.

Puustjärvi, V. 1982a. Textural classes of horticultural peat. Peat & Plant Yearbook 1981–1982. pp. 28–32.

Puustjärvi, V. 1982b. The size distribution of peat particles. Peat & Plant Yearbook 1981–1982. pp. 33–47.

Puustjärvi, V. 1982c. Turpeen tasoituskastelu I. Puutarha 5: 256–257.

Puustjärvi, V. 1989. Kasvuturve alkuvaiheistaan nykyhetkeen. Summary: The role of peat in horticulture up to the present. Suo 40: 99–102.

Puustjärvi, V. 1991. Kasvu ja kasvun hallinta kasvihuoneviljelyssä. Kauppapuutarhalitto ry. Tuotanto-osaston julkaisu 10. Mestari-Offset Oy, Vantaa. 287 p.

von Richard, F., Chausson, J.-S. & Surber, E. 1958. The influence of soil moisture tension and soil structure on the growth of young spruce seedlings. Schweizeriche Anstalt für das forstlische Versuchswesen, Mitteilungen 34: 1–34.

Rikala, R. 1985. Paakkutaimien kastelutarpeen määrittäminen haihdunnan perusteella. Summary: Estimating the water requirements of containerized seedlings on the basis of evaporation. Folia Forestalia 627: 1–18.

Rolston, D.E. 1986. Gas diffusivity. In: Klute, A. (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agronomy 9. Am. Soc. Agr. Soil Sci. Soc. Am. Publisher, Madison, Wisconsin. pp. 1089–1102.

Sands, K. & Rutter, A.J. 1959. Studies in the growth of young plants of Pinus sylvestris L. II. The relation of growth to soil moisture tension. Annals of Botany 23: 269–284.

Sands, R., Fiscus, E.L. & Reid, C.P.P. 1982. Hydraulic properties of pine and bean roots with varying degrees of suberization, vascular differentation and mycorrhizal infection. Australian Journal of Plant Physiology 9: 559–569.

Sands, R. & Theodorou, C. 1978. Water uptake by mycorrhizal roots of radiata pine seedlings. Australian Journal of Plant Physiology 5: 301–309.

Scagel, R.K. & Davis, G.A. 1988. Recommendations and alternative growing media for use in containerized nursery production of conifers: Some physical and chemical properties of media and amendments. USDA, For. Serv. Rocky Mountain Experiment Station. General Technical Report RM-167: 60–65.

Schleiff, U. 1986. Water uptake by barley roots as affected by the osmotic and matric potential in the rhizosphere. Plant and Soil 94: 143–146.

Shalhevet, J. & Hsiao, Th.C. 1986. Salinity and drought. A comparison of their effects on osmotic adjustment, assimilation, transpiration and growth. Irrigation Science 7: 249–264.

Searle, S.R. 1971. Linear models. John Wiley & Sons, New York. 532 p.

Sillanpää, M. 1956. Studies on the hydraulic conductivity of soils and its measurement. Acta Agralia Fennica 87: 1–109.

da Silva, F.F., Wallach, R. & Chen, Y. 1993. Hydraulic properties of Sphagnum peat moss and tuff (scoria) and their potential effects on water availability. Plant and Soil 154: 119–126.

Slatyer, R.O. 1967. Plant-water relationships. Academic Press, London. 366 p.

Sokal, R.R. & Rohlf, F.J. 1981. Biometry. The principles and practice of statistics in biological research. 2nd. ed. Wilt Freeman and Co, New York. 859 p.

Solbraa, K. 1979. Composting of bark. I. Different bark qualities and their uses in plant production. Norwegian For. Res. Inst. Medd. Norsk Inst. Skogforsk. 34: 281–333.

Stenström, E. 1990. Ecology of mycorrhizal Pinus sylvestris seedlings – Aspects of colonization and growth. Dr. Thesis. Swedish Univ. Agr. Sci., Dept. For. Myc. Path., Uppsala. 44 p.

Stolzy, L.H. 1974. Soil atmosphere. In: Carson, E.W. (ed.) The plant root and its environment. Univ. of Virginia, Charlottesville. pp. 335–361.

Taylor, K.C. & Halfacre, R.G. 1986. The effect of hydrophilic polymer on media water retention and nutrient availability to Ligustum lucidum. HortScience 21: 1159–1161.

Tinus, R.W. & McDonald, S.E. 1979. How to grow tree seedlings in containers in greenhouses. Rocky Mountain For. Ran. Exp. Sta. Forest Service, USDA. General Technical Report RM-60. 256 p.

Topp, G.C., Davis, J.L., Bailey, W.G. & Zebchuk, W.D. 1984. The measurement of soil content using a portable TDR hand probe. Canadian Journal of Soil Science 64: 313–321.

Tripepi, R.R., George, M.W., Dumroese, R.K. & Wenny, D.L. 1991. Birch seedling response to irrigation frequency and a hydrophilic polymer amendment in a container medium. Journal of Environmental Horticulture 9: 119–123.

Turveteollisuustilastoja 1992. 1993 Turveteollisuusliitto r.y. Painoporras, Jyväskylä. 8 p.

Verdonck, O. 1983. New developments in the use of graded perlite in horticultural substrates. Acta Horticulturae 150: 575–581.

Verdonck, O., De Vleeschauwer, D. & De Boodt, M. 1981. The influence of the substrate to plant growth. Acta Horticulturae 126: 251–258.

Verdonck, O. & Gabriels, R. 1988. Substrate requirements for plants. Acta Horticulturae 221: 19–23.

Verdonck, O., Pennick, R. & De Boodt, M. 1983. The physical properties of different horticultural substrates. Acta Horticulturae 150: 155–160.

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

Warkentin, B.P. 1984. Physical properties of forest-nursery soils: Relation to seedling growth. In: Duryea, M.L. & Landis, T.D. (eds.) Forest nursery manual: Production of bareroot seedlings. Martinus Nijhoff, Dr. W. Junk Publishers, The Hague, Boston, Lancaster. pp. 53–61.

Whitcomb, C.E. 1988. Plant production in containers. Revised edition. Lacebark Publications, Stillwater, Oklahoma. 633 p.

White, J.W. & Mastalerz J.W. 1966. Soil moisture as related to "container capacity". Journal of the American Society for Horticultural Science 89: 758–765.

Weeks, L.V. & Richards, S.J. 1967. Soil-water properties computed from transient flow data. Soil Science Society of America Proceedings 31: 721–725.

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. pp. 461–504.

Westman, C.J. 1983. Taimitarhamaiden fysikaalisia ja kemiallisia ominaisuuksia ja niiden suhde orgaanisen aineksen määrään. Summary: Physical and physiscochemical properties of forest tree nursery soils and their relation to the amount of organic matter. Acta Forestalia Fennica 184: 1–34.

Wilson, G.C.S. 1983. The physico-chemical and physical properties of horticultural substrates. Acta Horticulturae 150: 19–32.

Woodhouse, J. & Johnson, M.S. 1991. Water storing soil polymers and the growth of trees. Arboricultural Journal 15: 27–35.

Zegelin, S.J., White, I. & Russel, G.F. 1992. A critique of the time domain reflectometry technique for determining field soil-water content. In: Topp, C.G., Reynolds, D.W. & Green, R.E. (eds.) Advances in measurement of soil physical properties: Bringing theory into practice. SSSA Special publication 30. Soil Science Society of America. Madison,WI, USA. pp. 187–208.

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Favourable Water and Aeration Conditions for Growth Media Used in Containerized Tree Seedling Production: A Review

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Scand. J. For. Res. 8: 337–358, 1993

Favourable Water and Aeration Conditions for Growth Media used in Containerized Tree Seedling Production: A Review

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Scandinavian Journal of Forest Research

Heiskanen, J. (Finnish Forest Research Institute, Suonenjoki Res. Sta., SF-77600 Suonenjoki, Finland). Favourable water and aeration conditions for growth media used in containerized tree seedling production: A review. Accepted March 19, 1993. Scand. J. For. Res. 8: 337–358, 1993.

The importance of soil water and aeration conditions on the growth of containerized tree seedlings in conjunction with the physical properties of various growth media used are reviewed and discussed. Favourable water and aeration conditions in these different growth media are described and some implications for the Nordic production of containerized tree seedlings are considered. It is concluded that matric potentials of > -50 kPa and oxygen diffusion rates $> 70\ \mu g\ m^{-2}\ s^{-1}$ in the growth medium should be achieved during the growth period. Light, low humified *Sphagnum* peat, which is the most commonly used growth medium in the Nordic countries, provides favourable growth conditions in the greenhouse. However, when these growth conditions are not properly managed, light peat may not favour good seedling growth. Seedling hardening and outplanting phases are critical for outplanted seedling success, but little control can be exerted over them. Thus the physical properties of growth media should be evaluated and manipulated to enhance growth and quality particularly during these phases. The physical properties of peat can be improved by the addition of suitable amendments. *Key words: growing medium, nursery management, physical properties, seedling production, substrate.*

INTRODUCTION

Although a variety natural and artificial materials are used as growth media in plant production, peat and peat based mixtures are most commonly used for the cultivation of greenhouse plants in the Nordic countries. Peat is also the medium of choice for the production of containerized forest tree seedlings. The growth conditions in light and low humified *Sphagnum* peat can be easily manipulated under greenhouse management practices (Puustjärvi, 1973, 1975*a*). In central Europe and North America, various growth medium mixtures, in addition to peat, are used for containerized seedling production (Tinus & McDonald, 1979; Cull, 1981; Davey, 1984) due to the fact that local peats are often dark and highly humified (Verdure, 1981; Verdonck & Pennick, 1986). The properties of dark peat are not as good as those of light *Sphagnum* peat for plant growth (Puustjärvi, 1973).

Good seedling production in light peat does, however, require the controlled growth conditions commonly found in greenhouses. Light peat has a low hydraulic conductivity at low water potentials and is very prone to evaporation which results in low water availability under dry conditions (Beardsell et al., 1979*a*, *b*; Örlander & Due, 1986*a*, *b*). Alternatively, under wet conditions, peat may retain excessively water which gives rise to inadequate aeration. In the selection and manipulation of a growth medium the main aim should be the optimization of physical properties and subsequent growth conditions (Bunt, 1988). The formulation of a suitable growth medium and the adjustment of growth conditions require information on the physical properties of potential media and the growth requirements of seedlings at each phase of production.

The physical properties of growth media used in horticulture have been extensively examined. Studies assessing the growth requirements of plants in relation to the physical properties and growth conditions of growth media have been made, although recommendations do not usually cover different plant species during all phases of growth. In addition, the physical characteristics used (porosity, water and air retention) may not be ideal for accurately describing the actual levels of water availability and aeration under different management regimes, growth media and plant growth phases. It is therefore important to identify those properties and conditions that directly affect the growth and quality of the plants finally produced.

In the Nordic countries, there have been few studies dealing with the physical properties and conditions of growth media used for forest tree seedling production and fewer still on the actual growth requirements of seedlings. Usually, a growth medium is evaluated by measuring the growth response of seedlings or by comparing the conditions in the medium to those recommended for horticultural plants. The general growth requirements of tree seedlings are basically similar to those of most horticultural plants, although certain differences should be recognized.

In this review, the growth requirements of horticultural plants and forest tree seedlings are examined in order to identify the relevant physical properties and variables required of a growth medium. The physical properties of peat and various other growth media are reviewed and discussed in relation to water and aeration conditions needed for the production of containerized forest tree seedlings. Finally, suitable water and aeration conditions in the growth medium are defined and recommendations and some implications for Nordic containerized tree seedling production are discussed.

Throughout the following test, the percentage values of medium properties mentioned are on a volume basis ($v\ v^{-1}$) and the term, water potential, refers to the matric potential, unless otherwise indicated.

PHYSICAL CONDITIONS IN GROWTH MEDIA

Interactions between growth medium and plant

A growth medium should ideally incorporate both the physical, chemical and biological requirements for good plant growth together with those requirements of practical plant production (White, 1974; Tinus & McDonald, 1979; Bunt, 1988). The most important physical factors affecting growth are the water and aeration conditions of the growth medium. These not only determine the availability of water and air, but also affect the thermal properties, biological activity and mineral nutrient availability of the medium. The pore size distribution, which is determined by particle size distribution and structure (Hillel, 1982; Currie, 1984), is the most important physical property affecting the water and aeration conditions of the medium. Structure is mainly related to the bulk density of the media which is a measure of the degree of compaction (Hillel, 1982). Compaction decreases total porosity and hence diminishes aeration, but increases the mechanical strength of the medium.

Water moves in the direction of a decreasing water potential gradient (Hillel, 1971). Water viscosity decreases with increased temperature resulting in increased rates of water movement. Water uptake by roots is mainly determined by temperature and water potential gradients in the growth medium-plant-atmosphere continuum. In addition to the need for adequate contact between the medium and the roots (Glinski & Lipiec, 1990), water movement from the medium to the roots requires sufficiently high water content and hydraulic conductivity (Cowan, 1965; Newman, 1974; Hasegawa & Sato, 1985; from Glinski & Lipiec, 1990). Water retention and hydraulic conductivity are influenced by surface properties and pore size distribution of the medium (Hillel, 1971, 1982; Päivänen, 1973). As the growth medium dries, causing air gaps to develop between the soil particles and the roots, hydraulic conductivity decreases thus increasing resistance of water movement to the roots (Newman, 1974). Roots can, to some extent, ensure adequate water uptake by growing across areas of reduced water potential (Glinski & Lipiec, 1990). Water uptake by roots themselves also influence water potential in the medium.

Roots can also cope to a certain degree with variation in water availability by adjusting the osmotic potential of cells (Bradford & Hsiao, 1982). Plant available water is generally regarded as the amount of water retained in a soil at potentials between field capacity (c. -10 kPa) and the wilting point (c. -1550 kPa) (Hillel, 1971, 1982). However, these limits may not be appropriate for different containerized growth media receiving regular irrigation (see below). In addition, the intensive application of fertilizers in greenhouse cultivation practice may result in a significant decrease in osmotic potential (Puustjärvi, 1973), which limits water availability. However, the soil matric potential is likely to have a greater effect on plant water availability and uptake than the soil osmotic potential (Puustjärvi, 1980; Schleiff, 1986; Shalhevet & Hsiao, 1986).

The movement of water and nutrients from the bulk medium to the roots also depends on the adsorptive root contact area (Glinski & Lipiec, 1990), which is, in turn, affected by root morphology known to be influenced by particles making up the medium (Lemaire, 1989). A high root contact area is favoured in media with a small particle size. Various compounds released from roots increase the degree of contact between the medium particles and the roots (Rovira et al., 1979; from Glinski & Lipiec, 1990). The adsorptive root contact area is also increased by the presence of mycorrhiza (Dixon et al., 1980; Duddridge et al., 1980; Parke et al., 1983; Stenström, 1990). However, mycorrhiza do not always have a significant impact on the water uptake of seedlings (Sands & Theodorou, 1978; Sands et al., 1982) because the intensive watering and fertilization regimes used often negatively influence the colonization of container seedlings by mycorrhizal fungi in tree nurseries (Sarjala & Kupila-Ahvenniemi, 1982; Lehto, 1989). In addition, the roots are not necessary in continuous and full contact with the particles making up the medium. A large number of plant roots are located in soil pores that have larger diameters than those of the roots (Seikh & Rutter, 1969; Russell, 1977; cf. Barber, 1974).

Gas exchange in the soil should maintain a sufficient oxygen supply to the roots and the simultaneous removal of respiratory CO_2. Soil aeration takes place mainly by gaseous diffusion (Stolzy, 1974), which increases with temperature (Campbell, 1985). An air space of about 10% is generally considered the lowest limit for gaseous diffusion in soils (Wesseling & Wijk, 1957) while an air filled pore space of 10–15% is considered the minimum for root respiration and growth (Vomocil & Flocker, 1961). Root growth is often limited in compacted media with a low amount of coarse pores and low air space due to excessive watering (Hook & Scholtens, 1978; Warkentin, 1984). Plants are usually able to physiologically and anatomically adapt to waterlogginbg in the short term, but prolonged anaerobic conditions will eventually kill most species (Kawase, 1981; Topa & McLeod, 1986).

By nature, soil aeration is a dynamic process and therefore the effective rate of gas exchange is of more significance to the plant than the volume of the air space (Hillel, 1982). The oxygen diffusion rate (ODR) is usually regarded as the best measure of aeration at water potentials down to about -50 to -100 kPa (Stolzy, 1974; Glinski & Stepniewski, 1985). Most plant roots do not grow at ODR values $<0.20\ \mu g\ cm^{-2}\ min^{-1}$ (Stolzy, 1974).

Dry conditions have been shown to increase mortality and weaken root development of Scots pine seedlings in the nursery and subsequently after outplanting into forest sites (Lähde & Savonen, 1983). Excessive watering also decreases plant growth and the resulting high water content and low air space in the growth medium usually promotes fungal root infections (Cooley et al., 1985; Ownley et al., 1990; Beyer-Ericson et al., 1991). The growth of tree seedlings in the nursery may periodically suffer from root dieback and other fungal infections (Venn, 1985; Lilja et al., 1992). Poor aeration in peat media has been suggested to be one of the primary reasons for the fungal infections in the nursery (Langerud & Sandvik, 1987; Beyer-Ericson et al., 1991). On the other hand, Hoitink (1989) reported less *Rhizoctonia* and *Pythium* damping-off and *Fusarium* damages when using a fresh *Sphagnum* peat medium compared with other growth media.

Before outplanting, forest tree seedlings are usually left to harden in open fields during which time autumn rains may significantly increase the water content of the growth medium. The water retention of peat increases with increasing compaction and repeated wetting and drying cycles (Heiskanen, 1990), which will further have a negative effect on aeration (Langerud, 1986). Oxygen deficiency that follows may cause death of the root tips and plant growth disturbances (Hook & Scholtens, 1978; Langerud, 1986; Langerud & Sandvik, 1987). Containerized Scots pine seedlings grown in peat may also suffer from water deficiency after outplanting into the forest site. This can arise from inadequate water absorption due to poor soil-root contact and low hydraulic conductivity in the peat which may retard root growth into the surrounding soil (Coutts, 1982; Örlander, 1985; Örlander & Due, 1986*a*, *b*). In addition, plant available water is easily lost by evaporation in uncovered peat during dry conditions (Beardsell et al., 1979*a*, *b*).

Effect of containers on water and aeration conditions

The primary function of a container is to provide a discrete space for the growth medium. This restricted space also affects the physical conditions of the medium. The maximum water content retained by the containerized growth medium when freely drained is referred to as the container capacity (White & Mastalerz, 1966). In principle, the concept is comparable to the field capacity in unconfined soils but as drainage and hence the water potential is limited by the height of the container, container capacity occurs at a higher water potential than field capacity and hence corresponds to a greater water content. A perched water table is created in the container because the excess irrigation water cannot freely drain away. This gives rise to a persistent saturated layer in the bottom of the container.

Container capacity varies in relation to the container filling height, because the water potential is a function of distance from the water table. As a result, a water potential gradient is set up between the top and bottom of the container. Water retention at container capacity also depends on the type and volume of the medium (Bilderback & Fonteno, 1987; Milks et al., 1989*a*, *b*). Physical characteristics of the container (e.g. wall permeability and shape as well as presence of drainage holes) are also likely to significantly affect water potential and hence container capacity.

In horticulture, a water potential value of -1 kPa (-10 cm H_2O) is used to estimate the container capacity (Wilson, 1983*a*). Hence, if the filling height of the container is about 20 cm, the average water potential under the wettest conditions is -1 kPa. In horticulture, the critical air space of a growth medium is also determined at a water potential of -1 kPa. Under these wet conditions, roots tend to spread to the periphery of the container, where aeration is improved. Manipulation for increased aeration in the centre of the container may considerably increase both root and shoot growth (Biran & Eliassaf, 1980).

Recommendations for water and aeration conditions

Most recommendations on the physical properties and conditions of a growth medium usually refer to horticultural plant production. For ornamental plants, an air space volume of about 20% is regarded as favourable (Bik, 1973). For ornamentals cultivated in small containers, Bugbee & Frink (1986) found that best growth was achieved in media with air space of between 10 and 25%. Allmen & Gysi (1983) stated that during the active growth period the air space in media mixtures can be 20–50% and the water content 50–80% of the field capacity for various ornamentals grown in the open.

De Boodt & Verdonck (1972) suggested that in favourable growth medium most of the water is retained at potentials >-5 kPa (Table 1). The water potential should not be allowed to fall below -10 kPa. According to Puustjärvi (1973), growth is favoured when peat in the greenhouse has a water potential >-5 kPa and an air space $>50\%$ (Table 2). If the matric potential is about -5 kPa, the air space of peat would also be rather close to 50% according to the recommendations of De Boodt & Verdonck (1972). It has been suggested that, during the dormancy period, the water content should be lower and air space higher than that during the growth period (Bik, 1973; Puustjärvi, 1973; Bunt, 1983). Compared with the recommendations given by De Boodt & Verdonck (1972), Verdonck et al. (1981) recommended less water (and more air) at container capacity for most ornamentals (Table 1). Verdonck & Gabriels (1988) suggested that, at -1 kPa, a little more air should be retained in black and light peat mixtures than in peat and bark compost mixtures (Table 1).

A soil water potential range of -10–-75 kPa for forest tree seedlings grown in the open was recommended by Day (1980) and McDonald (1984). Sands & Rutter (1959) found that the growth of one-year-old and three-year-old Scots pine seedlings was significantly lower at a minimum water potential of -30 kPa and -50–-150 kPa, respectively, than at a minimum potential of -10 kPa. When the potential was lowered from -10 kPa to <-500 kPa, the diurnal transpiration of two- to three-year-old Scots pine seedlings was

Table 1. *Recommended water retention characteristics for horticultural growth media*

Total porosity % (v v^{-1})	Water retention (%, v v^{-1}) at -1 kPa	-5 kPa	-10 kPa	Source
85	55–65	20–45	15–41	DeBoodt & Verdonck 1972
70–90	40–50	–	–	Verdonck et al., 1981
80–90	65–80	40–55	–	Verdonck & Gabriels 1988[a]
90–92	70–77	40–57	–	Verdonck & Gabriels 1988[b]

[a] For black and light peat mixtures, [b] peat and bark compost mixtures

Table 2. *Favourable water retention characteristics for peat after Puustjärvi (1973)*

Peat	Bulk density g cm^{-3}	Total porosity %	Favourable water content % (v v^{-1}) Upper limit (50% air)	Lower limit (-5 kPa)	Difference
Coarse light *Sphagnum*	0.04	97	47	23	24
Medium light *Sphagnum*	0.07	96	46	39	7
Fine dark *Sphagnum*	0.11	93	43	52	−9
Black	0.17	89	39	60	−21

nearly totally inhibited (Rutter & Sands, 1958). Water availability, measured as needle and plant water conductance, of one-year-old Scots pine seedlings grown in fine graded *Sphagnum* peat, was clearly reduced when the water potential dropped to −50 kPa (Örlander & Due, 1986*a*, *b*). At potentials > −5 kPa, the water availability declined, possibly indicating insufficient aeration.

Glerum & Pierpoint (1968) found reduced growth of three-year-old conifer seedlings (*Pinus resinosa*, *Picea glauca*, *Larix laricina*) following droughts of −100, −600 and −1500 kPa when compared with the sufficiently watered (> −100 kPa) control condition. The growth of spruce seedlings (*Picea sitchensis*) was found to be greater at a water potential of −6 kPa than at −60 kPa in loam, and at −5 kPa than at −30 kPa in peat (Coutts, 1982). In the same study, enhanced root growth occurred in the wetter areas of the growth medium when the water content was unevenly distributed. Jarvis & Jarvis (1963) reported almost constant transpiration in two-year-old Norway spruce (*Picea abies*) seedlings when the total soil water potential diminished to −700 kPa. With two-year-old Scots pine and one-year-old silver birch (*Betula pendula*) seedlings, lowered transpiration rates were clearly detected from −150– −200 kPa (matric potential −30– −70 kPa). The root growth of oak (*Quercus rubra*) seedlings strongly decreased at osmotic water potentals < −400– −600 kPa (Larson, 1980).

In general, an air space of about 20% has been regarded as favourable for the growth of forest tree seedlings (Warkentin, 1984). When the oxygen content of the air space in the growth medium diminishes < 10%, the growth of several conifers has been shown to decline (Leyton & Rousseau, 1985). According to Huikari (1954, 1959), a clear reduction in the growth of Scots pine and Norway spruce seedlings occurs under anaerobic conditions while white birch seedlings (*Betula pubescens*) show greater tolerance to low soil oxygen levels. Trees tolerate wet, anaerobic conditions outside the active growth period but during this period the primary roots are sensitive to excessive water content (Orlov, 1962; from Lippu & Puttonen, 1990). If the water is mobile and high in oxygen, tree roots can continue to grow under saturated conditions (Paavilainen, 1966).

It can thus be concluded that favourable water availability for tree seedlings generally occurs at lower water potentials (−5– −50 kPa) than for horticultural plants (−1– −10 kPa). Information concerning oxygen demand is rather scarce and clear differences are not detectable in the favourable ranges. In addition, the different plant specific growth requirements in the various growth media and management regimes used are not comparable because the water and aeration conditions discussed have usually been expressed only as average volumetrical water and air proportions. These values have often been obtained using different methods which are also not necessarily comparable with each other.

PHYSICAL PROPERTIES OF DIFFERENT GROWTH MEDIA

As growth media can be composed of either single or mixtures of materials, their evaluation requires information on the physical properties of the materials. Selection and formulation of a mixture usually involve growth experiments or appropriate models in order to assess the physical properties (Spomer, 1974; Jenkins & Jarrell, 1989), which are often additive to those of its components. In the following, a concise review of the physical properties and growth conditions of various medium materials is presented. The main differences between the materials and their applicability as growth media are outlined. The data presented are strictly speaking specific to the conditions and methods used (Table 4).

Natural materials

Peat. Light peat—According to the von Post's scale (H1–10), the degree of humification of raw, light peat is between H1–3. The properties of light peat are primarily determined by

Table 3. *Grades of peat conforming to Scandinavian standards (Puustjärvi 1975a, 1981)*

Grade	Maximum proportion of <1 mm particles % $(\mathrm{m\ m^{-1}})$	Maximum permitted particle size mm
Coarse	30	40
Medium	40	15
Fine	70	6

the composition of plant species making up the peat and secondarily by particle size distribution of the peat (Puustjärvi, 1973). In the Nordic countries, the grading of milled peat is based on greatest allowed particle size and the proportion of the particles <1 mm in diameter (Puustjärvi, 1981, Table 3). The wettability and water retention of peat media are also strongly dependent on their surface properties as organic materials often become hydrophobic and unwettable when allowed to dry out (Hillel, 1971). In order to enable wetting and irrigation, the peat should not be allowed to dry out below a certain level. Wetting can also be promoted by the addition of surfactants to the irrigation water.

Coarse, light *Sphagnum* peat retains less water at potentials <-1 kPa than medium graded peat (Tables 2, 3 and 4). The proportion of air to water in coarse graded peat is greater than that in finer graded peat at water potentials <-0.5 kPa (Puustjärvi, 1973). At -0.5 kPa, the air space of the peat increases with grade coarseness up to 8 mm, after which it becomes almost constant. When particle sizes fall to 1 mm, the water content at -0.5 kPa becomes so great that the air space is not more than 20% (Puustjärvi, 1973; Verdonck & Pennick, 1986). Compared to fine peat, coarse peat retains more easily available water to plants (Puustjärvi, 1973, Table 2). With coarse peat, the need to control irrigation is therefore less critical because of the increased tolerance to irrigation levels and timing.

At water potentials <-10 kPa, the water retention of peat increases with increasing bulk density (Päivänen, 1973). According to Päivänen's results, the water retention of natural *Sphagnum* bog peat varied with the bulk density between 60–90, 25–70, 17–40 and 8–20% at potentials -1, -10, -100 and -1500 kPa, respectively. The saturated water content (total porosity) of the peat decreased with increasing bulk density. Saturated hydraulic conductivity (Piezometer method) clearly diminished over the humification range H1–10 (von Post's scale).

The osmotic water potential in fertilized peat growth media used in greenhouse cultivation forms the largest proportion of the total water potential (Puustjärvi, 1978, 1980). At the recommended fertilization levels, the osmotic potential is -50–-90 kPa. The corresponding electrical conductivity level of the peat solution extract is 1.5–2.5 mS $\mathrm{cm^{-1}}$ (Puustjärvi, 1978, 1980). Charpentier (1988) estimated that, during the drying of peat, lower osmotic potential compared to matric potential prevail at total potentials down to about -100 kPa.

At saturation, the hydraulic conductivity of light *Sphagnum* peat growth medium (H1–3) is about $11\,000\times10^{-6}$–560×10^{-6} cm $\mathrm{s^{-1}}$, while at matric potentials -3–-10 kPa it drops to 30×10^{-6}–200×10^{-6} cm $\mathrm{s^{-1}}$ (Puustjärvi, 1982). The hydraulic conductivity of coarse peat is usually lower than that of fine peat under unsaturated conditions. According to Bartels & Kuntze (1973), the hydraulic conductivity of low humified bog peat (H2–3) diminished from 1.39×10^{-6} to 0.0023×10^{-6} cm $\mathrm{s^{-1}}$ as the water potential decreased from -10 to -100 kPa. These hydraulic conductivity values are comparable to those for coarse sand. Thus, the hydraulic conductivity of peat is generally relatively low. The hydraulic

Table 4. *Physical properties of different growth media*

Medium	Bulk density g cm^{-3}	Total porosity % (v v^{-1})	Water retention (%, v v^{-1}) at −1 kPa	−5 kPa	−10 kPa	Source
Peat, light, coarse	0.04	97	48	23	18	Puustjärvi, 1973
Peat, light, medium	0.07	96	70	39	29	Puustjärvi, 1973
Peat, light	0.08	95	68	35	27	Verdonck et al., 1983
Peat, light	–	–	73	49	39	Olsson & Wästerlund, 1982
Peat, dark, fine	0.11	93	83	52	43	Puustjärvi, 1973
Peat, dark	0.12	91	52	37	33	Regulski, 1983
Peat, black	0.11	92	75	50	44	Verdonck et al., 1983
Peat, black	0.17	89	89	60	50	Puustjärvi, 1973
Peat, black	0.21	85	78	42	36	Verdonck & Pennick, 1986
Bark, mix	0.16	83	45	35	21	Pivot, 1985
Bark, mix, composted	–	82	33	31	30	Pivot, 1985
Bark, mix, cultivated	0.21	75	51	34	33	Pivot, 1985
Bark, mix, composted	–	75	56	36	33	Olsson & Wästerlund, 1982
Pine bark, < 10 mm	0.17	89	34	–	24	Lemaire et al., 1980
Pine bark, > 10 mm	0.17	89	27	–	24	Lemaire et al., 1980
Pine bark	0.19	78	39	27	24	Bilderback, 1985
Hardwood bark	0.27	83	53	42	38	Bilderback, 1985
Pine bark, composted	0.28	84	36	29	26	Lorenzo et al., 1981
Cork, 0–1 mm	0.08	95	15	12	12	Verdonck, 1983*b*
Cork, 1–3 mm	0.08	94	8	8	7	Verdonck, 1983*b*
Pine leaf mould	0.16	89	51	32	29	DeBoodt & Verdonck, 1972
Pine leaf mould	0.20	87	75	45	41	DeBoodt & Verdonck, 1972
Oak leaf mould	0.19	87	50	34	30	DeBoodt & Verdonck, 1972
Pine sawdust	0.15	86	39	28	23	Haynes & Goh, 1978
Pine sawdust	0.14	83	44	33	31	Prasad, 1979*a*
Wood residues, composted	0.14–0.37	81–89	54–62	–	38–48	Riviere & Milhau, 1983
Pine litter	0.14	91	48	38	34	Verdonck, 1983*b*
Pine litter	0.13	93	45	28	25	Verdonck et al., 1983
Hortifibre	0.5–0.7	95–97	15–33	–	10–11	Lemaire et al., 1989
Gasifier residue	0.21	79	47	31	29	Regulski, 1983
Cocofibre dust	0.07	95	56	40	35	Verdonck, 1983*b*
Sludge	0.34	76	65	59	58	Verdonck et al., 1983
Perlite, extra fine	1.13	53	48	46	45	Verdonck, 1983*a*
Perlite, fine	0.39	82	81	74	50	Verdonck, 1983*a*
Perlite, medium	0.06	97	77	34	28	Verdonck, 1983*a*
Perlite, coarse	0.19	91	23	19	18	Verdonck, 1983*a*
Perlite, medium	0.14	–	83	–	29	Jackson, 1974
Perlite, coarse	0.16	81	51	30	14	Haynes & Goh, 1978
Vermiculite, fine	–	94	86	49	–	Bunt, 1983
Vermiculite, coarse	–	96	60	53	–	Bunt, 1983
Expanded clay, 0–4 mm	0.69	74	15	11	10	Verdonck et al., 1983
Expanded clay, 4–10 mm	0.42	84	7	6	6	Verdonck et al., 1983
Expanded clay, 10–16 mm	0.34	87	9	8	8	Verdonck et al., 1983
Pumice	0.62	74	28	17	13	Haynes & Goh, 1978
Pumice, packed	0.57	59	39	24	22	Prasad, 1979*b*
Rockwool	0.07	97	62	3	3	Benoit & Ceustermans, 1988
Polyurethane	0.07	93	5	4	4	Benoit & Ceustermans, 1988
Phenolic foam	0.01	98	94[a]	3	–	Milks et al., 1989*b*

[a] At −0.4 kPa

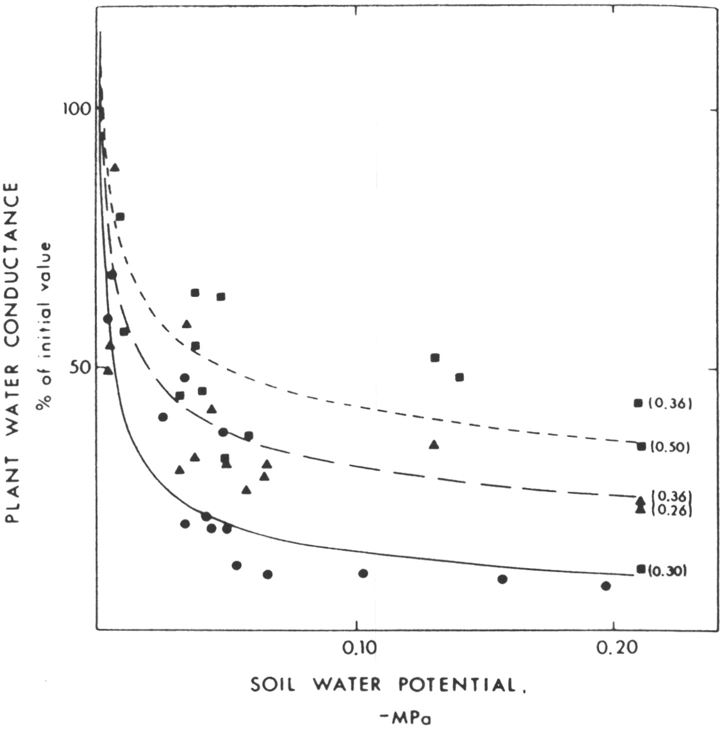

Fig. 1. Relationships between soil water potential and plant water conductance of Scots pine seedlings in different growth media: ● peat, ▲ 40:60 silt-peat, ■ 60:40 silt-peat. Water potentials < -0.25 MPa are given in parenthesis (from Örlander & Due, 1986*a*).

conductivity and therefore also the water availability of peat may be enhanced by incorporating silt into peat (Fig. 1) (Örlander & Due, 1986*a*).

The bulk density of peat increases with the degree of humification. The bulk density of *Sphagnum* peat growth medium (H1–3) is about 0.04–0.08 g cm^{-3} at a corresponding total porosity of 97–94% (Puustjärvi, 1973). During use as a growth medium, peat settles and decomposes, and so tends to become more compact. For example, Puustjärvi (1973) found that the total volume of a *Sphagnum* peat decreased by 20–25% after two years in cultivation but without any great change in the porosity. Root colonization of the growth medium also tends to increase the bulk density and decrease the pore space (Barber, 1974; Mannerkoski, 1982). *Sphagnum* peat containing, gravimetrically, more than 3% shrub remnants decomposes and compacts more rapidly than peat without a shrub component (Puustjärvi, 1975*b*). Peat containing fibres of cotton-grass (*Eriophorum* sp.) provides a coarse and aerated medium because the 60–100 mm long fibres retain 45–50% water at a water potential of -1 kPa (Byrne & Carty, 1989). The presence of coarse particles, such as fibres and wood residues 9–18 mm in diameter, increase the air filled porosity of the medium (Byrne & Carty, 1989). Wood residues in such a mixture may, however, decompose relatively quickly and increase media compactness (Puustjärvi, 1975*b*).

Scots pine seedlings have been shown to grow relatively well in pure peat media, but even better growth responses have been achieved in mixtures of mineral soils and humus matter (Mäkitalo & Sutinen, 1986). The biomass of Scots pine seedlings grown in compressed chips of *Sphagnum* peat (Hasselfors chip) was found to be 30% higher than seedlings grown in fine graded control peat (Hulten, 1973). This difference may be due to the coarser structure of the peat chips, which provides better aeration.

Dark and black peat are peats with a degree of humification of H4–6 and H7–10 (von Post), respectively, the properties of which are described by Puustjärvi (1973). Dark peat properties depend both on the floristic composition and the degree of humification, while those of black peat are almost entirely dependent on the degree of humification. The bulk density of dark peat varies between 0.08–0.13 g cm^{-3}, while that of black peat is >0.13 g cm^{-3}. The corresponding total porosities are 95–91 and $<91\%$. Water retention increases with increased peat decomposition (Tables 2 and 4).

The physical properties of black peat have been regarded as relatively poor for plant growth (Puustjärvi, 1973; Verdure, 1981) (Table 2). Low total porosity and high water retention lead to low peat aeration and hydraulic conductivity, which may improve after the development of peat structure following long term freezing and thawing cycles (Puustjärvi, 1973). Black peat can also be dried in order to enhance structure and aeration (Verdure, 1981; Verdonck & Pennick, 1986). The physical properties of black peat may also be improved through addition of various amendments (see below).

Wood residues. Bark—The bulk density of bark is dependent on particle size and the tree species. According to Wilson (1983*a*), the average bulk density of bark is 0.1–0.3 and the particle density 2 g cm^{-3}, while for Scots pine and Norway spruce respective estimates are 0.3–0.4 and 1.3–2.2 g cm^{-3} (Isomäki, 1974). The particle density for organic plant matter is usually 1.4 to 1.6 g cm^{-3} (Cassens, 1974; Heiskanen, 1992). The higher values quoted for bark may be either due to methodological errors or the inclusion of mineral impurities. During composting, the bulk density of bark increases (Solbraa, 1979, 1986).

As bark material is usually rather coarse, good aeration is offset by low water retention properties. Before use, bark is usually composted and mixed with *Sphagnum* peat in order to enhance water retention and mechanical strength (Solbraa, 1979). Composting and mixing are also necessary to diminish the harmful effects of toxic components, e.g. tannins, manganese and chlorine, which originate from the bark (Solbraa, 1979, 1986). During decomposition, there is a slight decrease in total porosity but water and air relations (pore size distribution) show considerable change. Pivot (1985) found the air filled porosity of Norway and white spruce (*Picea alba*) bark to be higher before than after 35 days composting, and increased water retention after 252 days cultivation (Table 4).

According to Handreck (1983), when the particle size of radiata pine bark increases from 0.2 to 10 mm, significant increases in the air space from 2 to 64% occur at -1 kPa. The air space is somewhat higher than that of sand fractions of the same particle sizes. With bark fractions 0.25–0.5 mm and <0.25 mm, the greatest water retention is between -1 and -10 kPa and -1 and -300 kPa, respectively. Bark fractions <0.5 mm, when mixed with other ingredients (peat, perlite, vermiculite, sand), can strongly affect the proportion of water and air in the mixture (Handreck, 1983). Richards et al. (1986) found that the cumulative proportion of pine (*Pinus radiata*) bark fractions >1 mm correlated with several physical properties of the mixtures. Coarse bark additions usually decrease the water retention and increase the aeration of compact peat (Haynes & Goh, 1978; Lemaire et al., 1980; Verdonck & Pennick, 1986). Pine (*Pinus pinaster*) bark <10 mm retains more water at potentials >-10 kPa than coarser bark with the same total porosity (Table 4). A finer pine (*Pinus pinea*) bark compost even retained a little more water at potentials <-1 kPa (Lorenzo et al., 1981) (Table 4).

Pine bark usually retains less water than finer hardwood bark (Bilderback, 1985) (Table 4). Hardwood barks usually decompose and compact in a shorter time period than conifer barks. The low water retention of pine bark and aeration of hardwood bark may both be increased through mixing of the barks. Tilt & Bilderback (1987) reported that, in such bark mixtures, the air space (at container capacity) decreases and water retention increases when the proportion of <0.5 mm particles increases (Handreck, 1983). Addition of cork with a low bulk density can strongly enhance aeration (Verdonck, 1983*a*) (Table 4).

According to Laatikainen (1973), slightly better growth of one-year-old Scots pine seedlings under regulated greenhouse conditions can be obtained using a bark medium compared to a low humified *Sphagnum* peat, and better still when a mixture of the two materials is used. Algae and fungi, which may hinder aeration of the medium, do not grow well on the surface of Norway spruce and Scots pine bark (Isomäki, 1974). Additionally, under dry conditions, pine bark may be particularly suited as a growth medium because it allows only scant evaporation and contains water available to plants (Beardsell et al., 1979*b*).

Leaves and needles—According to De Boodt & Verdonck (1972), fresh pine leaf mould and oak leaf mould retain about the same amount of water but aged pine leaf mould clearly retains more water. From their relatively low water retention values (Table 4), it can be judged that the moulds are relatively coarse and airy materials. Shredded pine cones have been suggested as a usable ingredient for mixtures (Sanderson & Martin, 1980).

Litter—Judged from the water retention characteristics presented by Verdonck (1983*a*) and Verdonck et al. (1983), pine litter is also a coarse and airy material with properties comparable to bark (Table 4). A fibrous ligno-cellulose material, Hortifibre, produced from pine (*Pinus pinaster*, *P. sylvestris*) litter, has high total porosity and good aeration (Lemaire et al., 1989) (Table 4), which when added to compact peat improve aeration of the mixture.

Wood—If composted and suitably fertilized, sawdust can be used in mixtures (Cheng, 1987). Pure sawdust has a rather high total porosity and it retains rather little water (Haynes & Goh, 1978; Prasad, 1979*a*) (Table 4). Composed pine tree chips alone or mixed with pine bark compost are also considered as suitable growth media (Laiche, 1986). Crushed and composted wood residues (Rivere & Milhau, 1983) clearly retain more water than sawdust (Table 4), although water retention of these fairly coarse materials can be enhanced by e.g. addition of peat. Regulski (1983) suggested that gasifier residue, which is produced from burned wood chips and bark, used either alone or mixed with peat is suitable as a growth medium in greenhouse production (Table 4). *Crop plant substances*. Various local plant residues can provide useful material for growth media. For example, cereal straw residues and spent mushroom compost could be of use in containers (Cull, 1981). According to Verdonck (1983*a*), coco fibre dust, and cotton and jute fibres are also good adjuncts (Table 4). For some ornamental species, the use of composted bagasse resulted in growth that was comparable to that achieved using peat moss and pine bark (Trochoulias *et al.*, 1990). *Manures and waste sludges*. Composted animal (cow, pig) solid waste can produce a fibrous material with physical properties similar to low decomposed *Sphagnum* peat. Such animal waste fibre has been shown to be a successful growth media for tomato (Cull, 1981). Digested methano-organic cow manure slurry (Cabutz) can also be used alone or as a component in a mixture (Chen et al., 1983). Human sewage sludge, suitably treated, can also be used (Cull, 1981) and may have a relatively high water retention (Verdonck et al., 1983) (Table 4). Sludge and piggery and poultry slurry mixed with bark has an increased water retention capacity compared with pure bark (Verdonck, 1983*a*). Dried, dewatered sewage sludge composted with saturated *Sphagnum* peat can be used as a growth medium (Charlie et al., 1983), although some of the phytotoxic characteristics and continuing decomposition and subsequent shrinkage of sludges may cause problems (Cull, 1981). Compost from municipal household refuse mixed with soil-based media has shown promising results with container-grown nursery plants (Cull, 1981). *Mineral soils*. Suitable mineral soils provide good growth conditions for seedling production in the open but because of weight considerations are not ideally suited to container seedling production (Tinus & McDonald, 1979). However, mineral soils can be added to light and porous materials (e.g. peat and bark) to increase bulk density, stability and wettability (Bunt, 1983; Pokorny & Henny, 1984). The diameter, shape and surface texture of the mineral particles affect the water retention capacity of the mixture. Additions of fine sand (0.4 mm) or coarse grit (2.5 mm) to peat (H3–5) respectively decreased or increased the air-filled pore space (at −1 kPa) (Bunt, 1983). Similarly, the incorporation of fine sand (<0.5 mm) to coarse bark resulted in a decreased air space (Handreck, 1985). Örlander (1985) reported that the water uptake of Scots pine seedlings decreased relative to increasing mineral particle size (silt to sand) additions to media of fine textured, low humified *Sphagnum* peat.

A locally important ingredient in growth media is volcanic ash (Beardsell et al., 1979*a*; Bech et al., 1983; Pallares & Gonzalez, 1984). Coal cinders have been used to enhance water retention and increase bulk density of bark (Neal & Wagner, 1983), although nutrient imbalances may result. Brown coal (lignite) of various size fractions has been shown to retain water well, but a small fraction is available to plants (Richards et al., 1986).

Synthetic materials

Perlite. Perlite is a form of volcanic rock that has been expanded by heating to 1 000–1 100°C (Verdonck et al., 1980), producing an inner, partly open micelle structure (Bunt, 1983). The various grades of perlite have different physical properties (Table 4) and are used in differing horticultural situations (Martyr, 1981; Verdonck, 1983*b*). Very fine perlite, having the highest bulk density and lowest total porosity (Table 4), retains little water for plant use (Verdonck, 1983*b*). Fine perlite has clearly a lower bulk density, a higher total porosity and contains a fair amount of water at potentials < -5 kPa and it is thus suitable as an amendment for coarse medium materials. Medium-fine perlite contains a considerable amount of water at potentials > -5 kPa while coarse perlite retains very little water but can be used for increasing the air filled pore space of a mixture. Lower porosities for each grade of perlite can be produced through compaction (Prasad, 1979*b*).

According to Jackson (1974), medium fine perlite (55–85% <0.6 mm) releases almost all adsorbed water when a water potential of −100 kPa is reached, which suggests that little water permeates the micelle structure of the grains. The hydraulic conductivity fell from 10^{-9} to almost 10^{-12} cm s^{-1} when matric potential was reduced from −10 to −1 000 kPa. The low hydraulic conductivity of perlite may restrict the water uptake by plants under dry conditions and at high transpiration rates (Jackson, 1974). Further, Langerud (1986) and Langerud & Sandvik (1987) have found that perlite (grade not specified) mixed with low humified *Sphaghnum* peat may restrict gas exchange. Joyal et al. (1989), on the other hand, found that dust-free perlite added to dark *Sphagnum* peat improves the physical properties of the medium. This difference is probably due to the different grades of peat and perlite added.

Vermiculite. Vermiculite is a micaceous material that has been heated to 1 000–1 100°C (Verdonck et al., 1980; Wilson, 1983*b*). It has a plate-like structure which enables high water adsorption (Table 4) and, like perlite, is available in different grades. Fine vermiculite (0.75 mm) retains more water at −1 kPa but at −5 kPa a little less water than coarse vermiculite (2.5 mm) (Bunt, 1983), which allows better rooting and growth at a lower water content than coarse vermiculite (Scalabrelli et al., 1983). Park & Chung (1987) reported delayed wilting in mixtures of vermiculite and *Sphagnum* peat compared with mineral soil based media.

Expanded clay. When a clay mixture extruded into cylindric grains is heated to 1 100°C a porous granular product is formed of which the 3–10 mm grade is the most suitable for horticulture (Verdonck et al., 1980). Expanded clay, e.g. Argex, has a low water retention capacity and a high air filled pore space, especially as coarse grained, and is mostly used in hydrophonics (Verdonck *et al.*, 1980; De Boodt et al., 1981). Verdonck et al. (1983) found that adding 75% Argex to black peat increased air filled pore space at −1 kPa from 25% to 53%. Similar kinds of porous mineral materials such as Solite (Conover & Poole, 1986) and brick pellets (Leca) (Unestam & Stenström, 1989) have been used as growth medium materials. The physical properties of pumice are fairly close to those of expanded clay or perlite (Haynes & Goh, 1978, Prasad, 1979*b*) (Table 4).

Rockwool. Rockwool is most commonly made from a form of basalt by a melting treatment at temperatures >1 500°C (Smith, 1987). Different additives are incorporated into the molten mass to make it either water repellent or adsorbent. Granular formulations or compressed slab and cubes are available. The former can be used as a growth medium on its own or as an adjunct with other materials. The different types and uses of rockwool have been described by Smith (1987). Rockwool has a large total porosity and high water retention at high potentials. Benoit & Ceustermans (1988) reported that rockwool (Grodan PL) releases almost all its water at a water potential of < −1 kPa. Rockwool has been used as an amendment to increase the air filled pore space and gas exchange of growth media (Langerud, 1986).

Containerized conifer seedlings (*Pinus sylvestris*, *Pinus contorta*, *Picea abies*) have been successfully grown in rockwool (Nilson, 1977; Örlander & Gemmel, 1979; Hänninen, 1982). A study by Högberg (1984) showed that root and shoot growth of Scots pine seedlings grown in rockwool was comparable to that in peat. Few studies on the development of seedlings grown in rockwool after outplanting at the forest site have been published in the Nordic countries, but in practice it has also been regarded as comparable to that in peat (Hänninen, 1982; Hulten 1983; Grene, 1984).

Polystyrene and polyurethane. Polystyrene and polyurethane are light, porous materials made of hardened plastic foam (Table 4). Polystyrene is used in the form of closed granules and polyurethane as blocks or mats. Due to a high proportion of coarse pores these materials provide good aeration for growth mixtures (Lorenzo et al., 1981; Verdonck & Pennick, 1986). Prasad (1979*b*) and D'Angelo & Titone (1988) added polystyrene chips to compact peat to increase its air filled pore space (at −1 kPa). Pure polystyrene retains little water because of its water repellency (Prasad, 1979*b*). Compressed polyurethane-ether mats, Aggrofoam (Benoit & Ceustermans, 1988), and phenolic foam, Oasis Rootcube matrix (Milks et al., 1989*a*), have high total porosities, very low bulk densities and also retain little water (Table 4).

Hydrogels. Most synthetic hydrophilic polymers (hydrogels) on the market are starch-hydrolyzed polyacrylonitrile copolymers or acrylamide and acrylic acid salt co-polymers which retain water at many times their dry weight. These growth medium additives have been regarded as 'rechargeable water reservoirs' to increase wilting time (shelf life) of container grown plants. With some ornamentals, the wilting time has been shown to significantly increase when using hydrogel as an amendment in greenhouse mixtures (Eikhof et al., 1973; Gehring & Lewis, 1980). A polyacrylic polymer, Permabsorb, was found to increase the water retention of a mixture, but decreased aeration or toxicity reduced the growth of some horticultural plants (Flannery & Busscher, 1982). Media amended with a polyacrylamide hydrogel, Agrosoke, improved the water uptake efficiency of some ornamentals and also increased nutrient absorption (Wang & Boogher, 1987). Lennox & Lumis (1987) examined different hydrophilic gels and reported that, applied at the recommended rates, the gels do not significantly increase easily available water retention of growth media unless a surfactant is added. Addition of gels may in some cases increase water retention of some media at higher potentials than −1 kPa and also at lower potentials than −100 kPa.

FAVOURABLE GROWTH CONDITIONS AND SOME IMPLICATIONS FOR NURSERY SEEDLING PRODUCTION

The quality of seedlings destined for reforestation is affected at all the stages of production from germination to outplanting. In order to define favourable physical properties and conditions for a growth medium, the seedling growth and quality requirements throughout the nursery production phase should be known. To achieve favourable water and aeration conditions, a first priority is media selection based on known and appropriate physical properties. Favourable conditions should then be achieved and maintained through appropriate management and monitoring practices at each phase of seedling production. In the greenhouses, any selected growth conditions can in principle be maintained by manipulating irrigation, radiation etc., but during the hardening periods in open fields, transportation and early post-outplanting development, optimum conditions cannot be sustained. Under these uncontrollable phases, the properties of the growth medium affecting seedling growth become particularly important.

In order to describe the water and aeration conditions of a growth medium favourable to tree seedling production, relevant and easily measurable variables and their favourable levels should be determined. Present recommendations for the favourable water and aeration conditions are based on the production of fast growing horticultural plants usually under controllable greenhouse conditions. The general physical and chemical growth requirements for tree seedling production are basically similar to those for most horticultural plants, but some differences exist (Lennox & Lumis, 1987; Riviere et al., 1990). In general, tree seedlings are likely to require, due to e.g. lower growth rates with some conifers, reduced water availability as concluded earlier. Because of the need for high aeration, the recommendation for peat media in the production of horticultural plants proposed by Puustjärvi (1973, 1980) (Table 2) may, however, be appropriate for the production of containerized forest tree seedlings. On the other hand, the container size for tree seedling production are often smaller than for the horticultural plants. Under such conditions the roots have a more restricted reservoir of water, air and nutrients when their supply may become more critical especially at high transpiration rates.

The availability of water and air for plant growth are usually determined from water and air filled porosities of the growth media. The air or water filled porosity alone, however, do not actually and commensurably describe the availability of air or water to the roots in all media. For example, the demand of air filled porosity in peat (45–50%) (Puustjärvi, 1973, 1980) is higher compared with the values recommended for mineral soils. Penningsfeld (1973) claimed that clay-rich humic soils should contain 20%, horticultural soil mixtures 30% and peat media 40% air. This difference in the air-filled porosities is likely to be due to the differences in internal structure of materials e.g., peat has a partly open intra-particle structure and thus high air retention inside the particles. This intra-structure of the medium particles does not significantly contribute to the effective aeration (Puustjärvi, 1975*a*; Solbraa, 1979; Handreck, 1983) and may also similarly affect the water retention of the medium. Therefore, water retention characteristics expressed on the basis of water and air proportions may not accurately describe the effective physical properties of the growth media. There are indications that the components of soils and growth media (water content, particle size fractions) are, however, better related to growth when expressed volumetrically than gravimetrically (Joyner & Conover, 1965; Heiskanen, 1988).

Water movement in the growth medium and water uptake by roots are dependent on the water potential gradient. Therefore, defining water availability in terms of water (matric) potential, rather than average water content, is a better variable describing the effective growth conditions. A water potential level > -50 kPa can be considered as providing the greatest water availability for forest tree seedlings when aeration is not a restricting factor (Örlander, 1984; Örlander & Due, 1986*a*, *b*). At potentials < -50 kPa, water availability in peat is clearly decreased. Conifer seedlings older than one or two years grow well in suitable mineral soils at water potentials down to about -100 kPa (Sands & Rutter, 1959; Jarvis & Jarvis, 1963).

The matric potential is relatively easily measurable with small tensiometers (Heiskanen & Laitinen, 1992). If the water retention characteristic of the medium is known, time domain reflectometry (TDR) (Topp et al., 1984) may also be applied in the future for estimating the water potential. These two methods allow a great number of measurements to be taken *in situ* over the range of moisture levels during seedling growth (> -100 kPa) in various growth media and management regimes. The hydraulic conductivities of different media at the same water potentials may, however, be different, but the measurements of the hydraulic conductivity are complex and time consuming. At low osmotic potentials is it necessary to determine the total water potential as a sum of the matric and the osmotic potential (Puustjärvi, 1980). The total water potential can be measured using the thermocouple psychrometer technique (Landis et al., 1989).

As previously mentioned, air filled porosity (%) does not clearly describe the effective aeration in different media. If the measurements of air filled porosity include both inter- and intra-particle porosities but some of the air in the intra-pores is too strongly retained to be available for roots, the porosity values are not valid. If the retention level of available air and water inside the particles can be determined, the air filled porosity can be used as a variable describing the effective aeration. In mineral soils that do not have intra-particle pores, the effective air space is close to the measurable air filled porosity. Based on growth trials made, the air filled porosity of mineral soils should be at least about 20%.

The oxygen diffusion rate (ODR) is a better variable, than the air-filled porosity, for describing the effective aeration of various media, especially under the most critical, wettest conditions, i.e. near container capacity (Glinski & Stepniewski, 1985). The ODR is directly dependent on the rate at which oxygen diffuses to the surface of a root and it can be measured *in situ* from seedling containers. At present, however, ODR determination requires the utmost care and many repeated measurements, because of the great variation due to the heterogeneity in growth media. The critical ODR value for most plants is about $30\ \mu g\ m^{-2}\ s^{-1}$ (Stolzy, 1974; Glinski & Stepniewski, 1985). When the ODR is <50–$70\ \mu g\ m^{-2}\ s^{-1}$ root growth may be retarded. Favourable values for growth are usually $>70\ \mu g\ m^{-2}\ s^{-1}$ (Glinski & Stepniewski, 1985).

Based on the preceding review, the following conclusions can be drawn: 1) matric potential and ODR should be used to describe and monitor the physical growth conditions of the growth media, 2) during the growth period the respective levels for these variables should be > -50 kPa and $>70\ \mu g\ m^{-2}\ s^{-1}$. However, in order to readily quantify these variables, the methods require further development for practical application. The recommended conditions may result in different air/water proportions in different media. Peat, containing intra-particle pores, has a lower hydraulic conductivity under unsaturated conditions than media with no such pores (Bartels & Kuntze, 1973, Örlander, 1984, 1985). Peat thus supplies water more slowly to seedlings than mineral soil media (Fig. 2). Media having a partly open intra-particle structure should therefore contain more water (or air) than media without such a structure at the same water potentials and water (or air) availabilities. In addition to media, variation in many other factors, such as atmospheric conditions, mycorrhiza and fertilization, may also contribute to the differing growth condition requirements in containerized seedling production.

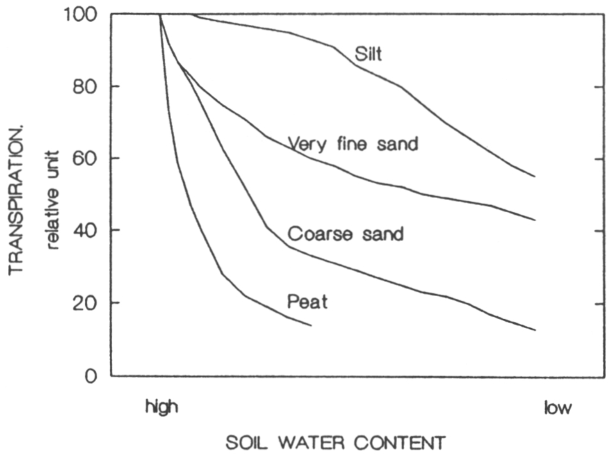

Fig. 2. Schematic presentation of the relationship between soil water status and the water uptake of Scots pine seedlings for different growth media (adapted from Örlander, 1985).

In peat media, the ODR would usually be sufficient to maintain effective aeration, if the water potential is kept < -5 kPa. Persistent water potentials > -5 kPa should be regarded as being harmful. The amount of water at potentials -5–-50 kPa is readily available to seedlings and can be used as limits for adjusting irrigation. After the nursery phase, growth conditions cannot be controlled. The water reservoir in a small container is also limited and it may be transpired by the seedling within few days. The amount of easily available water (between -5 and -100 kPa) should therefore be as great as possible. Some water will be needed in the medium at water potentials < -100 kPa. At the planting site, the seedlings are usually exposed to drought and the commonest source of stress after outplanting is water stress (Burdett, 1990). It is therefore crucial that roots grow quickly into surrounding soil. The significance of the root contact area, water potential gradient between the growth medium and the surrounding soil as well as the generally relevant criteria of physical properties for good growth media are as yet still poorly understood (Örlander & Due, 1986*a*).

The physical properties of raw, light *Sphagnum* peat are fairly well suited for providing the favourable growth conditions concluded. It is able to supply a large amount of water and air at water potentials ranging from -5 kPa to -50 kPa. Favourable growth conditions can therefore be readily maintained during the growing phase. The water and aeration conditions in low humified and fine graded *Sphagnum* peat under very wet conditions (at container capacity) are not as good, however, and may restrict seedling growth. In particular, excessive water and inadequate aeration may arise in peat that has been compacted and been in cultivation for more than one year, during which time the volume of the peat has decreased. On the other hand, under dry conditions, light, low humified and especially coarse graded peat provides little available water to the seedlings.

By addition of appropriate amendments to the peat, aeration at high water potentials and water retention and hydraulic conductivity at low water potentials can be improved. Amendments such as coarse perlite having a high saturated hydraulic conductivity would improve drainage and thus aeration under wet conditions. Under dry conditions, suitable amendments, such as rockwool and hydrogels, would increase water availability. These amendments shold not jeopardise the effective aeration of the mixture under wet conditions. However, the optimal physical properties and conditions cannot be achieved at all phases of seedling production, especially during the poorly controllable seedling hardening and outplanting phases which are critical for seedling growth. Therefore, the physical properties and conditions of growth media should be evaluated and manipulated to favour seedling growth and quality particularly under these phases. The actual need for the manipulation of the growth media and their conditions during these phases as well as the subsequent practical consequences on seedling production remain, however, to be firmly determined and established through further studies.

ACKNOWLEDGEMENTS

The author wishes to thank Drs. M. Starr and P. Puttonen, R. Rikala, M.Sc. and Profs. R. Heinonen and C. J. Westman, for comments on the manuscript. Thanks are also given to Drs. M. Starr and R. Sen for revising and improving the English language of the manuscript. The figures in the article were used with the kind permission of the copyright holders.

REFERENCES

Allmen, F. & Gysi, C. 1983. Physikalishe und chemische Substratuntersuchungen im Zierpflanzenbau. *Gartenbauwissenschaft 48*, 171–176. (In German).

Barber, S. A. 1974. Influence of the plant root on ion movement in soil. In *The plant root and its environment* (ed. Carson, E. W.), pp. 525–564. Univ. of Virginia, Charlottesville.

Bartels, R. & Kuntze, H. 1973. Torfeigenschaften und ungesättigte hydraulische Leitfähigkeit von Moorböden. *Z. f. Pflanzenern. u. Bodenk. 134*, 125–135. (In German).

Beardsell, D. V., Nichols, D. G. & Jones, D. L. 1979*a*. Physical properties of nursery potting-mixtures. *Sci. Hort. 11*, 9–17.

Bech, J., Abello, N., Longan, L. & Andres, J. 1983. Some physical and chemical properties of volcanic tuff from Olot, Spain. *Acta Hort. 150*, 169–173.

Benoit, F. & Ceustermand, N. 1988. Poly-urethane-ether foam (PU) as an ecologically sound growing substrate. *Soilless Culture 4*, 3–17.

Beyer-Ericson, L., Damm, E. & Unestam, T. 1991. An overview of root dieback and its causes on Swedish forest nurseries. *Eur. J. For. Path. 21*, 439–443.

Bik, A. R. 1973. Some thoughts on the physical properties of substrates with special reference to aeration. *Acta Hort. 31*, 149–160.

Bilderback, T. E. 1985. Physical properties of pine bark and hardwood bark media and their effects with 4 fertilizers on growth of *Ilex* x 'Nellie R. Stevens' Holly. *J. Environ. Hort. 3*, 181–185.

Bilderback, T. E. & Fonteno, W. C. 1987. Effects of container geometry and media physical properties on air and water volumes in container. *J. Environ. Hort. 5*, 180–182.

Biran, I. & Eliassaf, A. 1980. The effect of container size and aeration conditions on growth of roots and canopy of woody plants. *Sci. Hort. 12*, 385–394.

Bradford, K. J. & Hsiao, T. C. 1982. Physiological responses to moderate water stress. In *Encyclopedia of plant physiology 12B: Physiological plant ecology II* (eds. Lange, O. L., Nobel, P. S., Osmond, C. B. & Ziegler, H.), pp. 264–324. Springer-Verlag, Berlin-Heidelberg-New York.

Bugbee, G. J. & Frink, C. R. 1986. Aeration of potting media and plant growth. *Soil Sci. 141*, 438–441.

Bunt, A. C. 1983. Physical properties of mixtures of peats and minerals of different particle size and bulk density for potting substrates. *Acta Hort. 150*, 143–153.

Bunt, A. C. 1988. *Media and mixes for container-grown plants. A manual on the preparation and use of growing media for pot plants*. 2nd ed., 309 pp. Unwin Hyman, London.

Burdett, A. N. 1990. Physiological processes in plantation establishment and the development of specifications for forest planting stock. *Can. J. For. Res. 20* 415–427.

Byrne, P. J. & Carty, B. 1989. Developments in the measurement of air filled porosity of peat substrates. *Acta Hort. 238* 37–44.

Campbell, G. S. 1985. *Soil physics with basic. Transport models for soil-plant systems*. Developments in Soil Sci. 14. 150 pp. Elsevier, Amsterdam.

Cassens, D. L. 1974. Bark properties of eight western softwoods. *For. Prod. J. 24*, 40–45.

Charlie, W. R., Macfarlane, M. A. & Sweetland, E. 1983. Preparation and composting of peat and dewatered sewage-sludge. *Acta Hort. 150*, 503–507.

Charpentier, S. 1988. Water potential in the substrate-solution system in horticulture. *Acta Hort. 221*, 25–33.

Chen, Y., Inbar, Y., Raviv, M. & Dovrat, A. 1983. The use of slurry produced by methanogenic fermentation of cow manure as a peat substitute in horticulture—Physical and chemical characteristics. *Acta Hort. 150*, 553–561.

Cheng, B. T. 1987. Sawdust as a greenhouse growing medium. *J. Plant. Nutr. 19*, 1437–1446.

Conover, C. A. & Poole, R. T. 1986. Physical and chemical characteristics of potting media containing Solite. *Foliage Digest* August, 4–6.

Cooley, S. J., Hamm, P. B. & Hansen, E. M. 1985. Management guide to Phytophthora root rot in bareroot conifer nurseries of the Pacific Northwest. 10 pp. USDA-Forest Service, Pacific Northwest Region.

Coutts, M. P. 1982. Growth of sitka spruce seedlings with roots divided between soils of unequal matric potential. *New Phytol. 92*, 94–61.

Cowan, I. R. 1965. Transport of water in the soil-plant-atmosphere system. *J. Appl. Ecol. 2* 221–239.

Cull, D. C. 1981. Alternatives to peat as container media: Organic resources in the U.K. *Acta Hort. 126*, 69–77.

Currie, J. A. 1984. The physical environment in the seedbed. *Asp. Appl. Biol. 7*, 33–54.

D'Angelo, G. & Titone, P. 1988. Determination of the water and air capacity of 25 substrates employed for the cultivation of *Dieffenbachia amoena* and *Euphorbia pulcherrima*. *Acta Hort. 221*, 175–182.

Davey, C. B. 1984. Nursery soil organic matter: Management and importance. In *Forest Nursery Manual: Production of bareroot seedlings* (eds. Duryea, M. L. & Landis, T. D.), pp. 81–86. Martinus/Dr. W. Junk Publishers, The Hague-Boston-Lancaster.

Day, R. J. 1980. Effective nursery irrigation depends on regulation of soil moisture and aeration. Proc. North Am. For. Tree Nursery Soils Workshop, July 28–August 1 1980, Syracuse, New York, pp. 52–71.

De Boodt, M. & Verdonck, O. 1972. The physical properties of the substrates in horticulture. *Acta Hort. 26*, 37–44.

De Boodt, M., Verdonck, O. & De Vleeschauwer, D. 1981. Argex, a valuable growing medium for plants. *Acta Hort. 126*, 65–68.

Dixon, R. K., Wright, G. M., Behrns, G. T., Teskey, R. O. & Hinckley, T. M. 1980. Water deficits and root growth of ectomycorrhizal white oak seedlings. *Can. J. For. Res. 10*, 545–548.

Duddridge, J. A., Malibari, A. & Read, D. J., 1980. Structure and function of mycorrhizal rhizomorphs with special reference to their role in water transport. *Nature 287*, 834–836.

Eikhof, R. H., King, P. a. & Moline, S. W. 1973. The influence of a hydrophilic polymer on the water requirements and shelf life of container grown plants. *Nat. Agr. Plastics Assoc. Conf. Proc. 11*, 117–126.

Flannery, R. L. & Busscher, W. J. 1982. Use of a synthetic polymer in potting soils to improve water holding capacity. *Commun. Soil Sci. Plant Anal. 13*, 103–111.

Gehring, J. M. & Lewis, A. J. 1980. Effect of hydrogel on wilting and moisture stress of bedding plants. *J. Am. Hort. Sci. 105*, 511–513.

Glerum, C. & Pierpoint G. 1968. The influence of soil moisture deficits on seedling growth of three coniferous species. *The For. Chron. 44*, 26–29.

Glinski, J. & Lipiec, J. 1990. *Soil physical conditions and plant roots*. 250 pp. CRC Press, Boca Raton, Fla.

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

Grene, S. 1984. Rodform plantesystem. *Skoven 6/7*, 172–174. (In Danish).

Handreck, K. A. 1983. Particle size and the physical properties of growing media for containers. *Commun. Soil. Sci. Plant. Anal. 14*, 209–222.

Hänninen, P. 1982. Preliminary results concerning the use of rockwool as a growth medium for Scots pine seedlings in a greenhouse. Finnish For. Res. Inst. Metsäntutkimuslaitoksen tiedonant. 71, 21 pp. (In Finnish with English summary).

Hasegawa, S. & Sato, T. 1985. Soil water movement in the vicinity of soybean roots determined by root plane experiment. Trans. Jpn. Soc. Irrig. Drain. Reclam. Eng. (Nogyo Doboku Gakkai Ronbushu) 117, 17–24.

Haynes, R. J. & Goh, K. M. 1978. Evaluation of potting media for commercial nursery production of container grown plants. *N.Z. J. Agr. Res. 21*, 449–456.

Heiskanen, J. 1988. [Water retention characteristics of forest soils and their relation to forest site properties.] Lic. For. Thesis. Univ. of Helsinki, Dept. of Silviculture, Helsinki. 92 pp. (In Finnish).

Heiskanen, J. 1990. The effect of sample handling on the water retention of growth peat substrate. *Suo 41*, 91–96. (In Finnish with English summary).

Heiskanen, J. 1992. Comparison of three methods for determining the particle density of soil with liquid pycnometers. *Commun. Soil Sci. Plant Anal. 23*, 841–846.

Heiskanen, J. & Laitinen, J. 1992. A measurement system for determining temperature, water potential and aeration of growth medium. *Silva Fenn. 26*, 27–35.

Hillel, D. 1971. *Soil and water. Physical principles and processes.* 288 pp. Academic Press, Orlando.

Hillel, D. 1982. *Introduction to soil physics.* 365 pp. Academic Press, San Diego.

Högberg, K.-A. 1984. Substrat-Vattenhalt-Rotmorfologi. Swedish Agr. Univ., Dept. Reforestation, Garpenberg. Stencil 26, 12 pp. (In Swedish).

Hoitink, H. A. J. 1989. Disease suppressive properties of container media. *Spec. Circ. Ohio Agr. Res. Dev. Cent. 123*, 20–22.

Hook, D. D. & Scholtens, J. R. 1978. Adaptation and flood tolerence of tree species. In *Plant life in anaerobic environment* (eds. Hook, D. D. & Crawford, R. M. M.), pp. 299–331. Ann Arbor Science Publishers, Ann Arbor, Michican.

Huikari, O. 1954. Experiments on the effect of anaerobic media upon birch, pine and spruce seedlings. *Commun. Inst. For. Fenn. 42*, 13 pp.

Huikari, O. 1959. On the effect of anaerobic media upon the roots of birch, pine and spruce seedlings. *Commun. Inst. For. Fenn. 50*, 16 pp.

Hulten, H. 1973. Undersökning av chipstorv vid uppdragning av paperpot-plantor. Royal Coll. For., Dept. Reforestation, Stockholm, Rapp. Upps. 48, 16 pp. (In Swedish).

Hulten, H. 1983. Odligssystem Rockwool. Swedish Agr. Univ., Dept. Reforestation, Garpenberg, Plantnytt 5, 4 pp. (In Swedish).

Isomäki, 1974. Using possibilities of barking waste in sawmill industry. *Acta. For. Fenn. 140*, 81 pp. (In Finnish with English summary).

Jackson, D. K. 1974. Some characteristics of perlite as an experimental growth medium. *Plant and Soil 40*, 161–167.

Jarvis, P. G. & Jarvis, M. S. 1963. The water relations of tree seedlings II. Transpiration in relation to soil water potential. *Physiol. Plant. 16*, 236–253.

Jenkins, J. R. & Jarrell, W. M. 1989. Predicting physical and chemical properties of container mixtures. *HortSci. 24*, 292–295.

Joyal, P., Blain, J. & Parent, L. E. 1989. Utilization of tempe cells in determination of physical properties of peat based substrates. *Acta Hort. 238*, 63–65.

Joyner, J. N. & Conover, C. A. 1965. Characteristics affecting desirability of various media components for production of container-grown plants. *Soil and Crop Sci. Soc. Fla. Proc. 25*, 320–327.

Kawase, M. 1981. Anatomical and morphological adaptation of plants to waterlogging. *HortSci. 16*, 30–34.

Laatikainen, P. 1973. Milled peat and bark as substrates for Scots pine seedlings in greenhouses. *Silva Fenn. 7*, 45–59. (In Finnish with English summary).

Laiche, A. J. Jr. 1986. Container-plant growth media and fertility studies. Proc. Ann. Meet. Ark. State Hort. Soc. pp. 120–128.

Landis, T. D., Tinus, R. W., McDonald, S. E. & Barnett, J. P. 1989. *Seedling nutrition and irrigation.* The container tree nursery manual. Vol. 4, 119 pp. Agric handbook 674. USDA, Forest Service, Washington DC.

Langerud, B. R. 1986. A simple *in situ* method for the characterization of porosity in growth media. *Plant and Soil 93*, 413–425.

Langerud, B. R. & Sandvik, M. 1987. Development of containerized *Picea abies* (L.) Karst. seedlings grown with heavy watering on various peat, perlite and mineral wool mixtures. *New For. 1*, 89–99.

Larson, M. M. 1980. Effects of atmospheric humidity and zonal soil water stress on initial growth of planted northern red oak seedlings. *Can. J. For. Res. 10*, 549–554.

Lehto, T. 1989. Mycorrhizal status of Scots pine nursery stock in Finland. *Folia For. 726*, 15 pp. (In Finnish with English summary).

Lemaire, F. 1989. Influence of the physical characteristics of substrate on the root systems of ornamental plants grown in pots and containers. *Agronomie 9*, 795–801. (In French with English summary).

Lemaire, F., Dartigues, A. & Riviere, L. M. 1980. Properties of substrates with ground pine bark. *Acta Hort. 99*, 67–75.

Lemaire, F., Dartigues, A. & Riviere, L. M. 1989. Physical and chemical characteristics of a ligno-cellulosic material. *Acta Hort. 238*, 9–22.

Lennox, T. L. & Lumis, G. P. 1987. Evaluation of physical properties of several growing media for use in aerial seedling containers. *Can. J. For. Res. 17,* 165–173.

Leyton, L. & Rousseau, Z. 1985. Root growth of tree seedlings in relation to aeration. In *The physiology of forest trees* (ed. Thimann, K. V.), pp. 467–475. Ronald Press, New York.

Lilja, A., Lilja S., Poteri, M. & Ziren, L. 1992 Conifer seedling root fungi and root dieback in Finnish nurseries. *Scand. J. For. Res. 7,* 547–556.

Lippu, J. & Puttonen, P. 1990. The early development of seedling roots at the planting site: A literature review. *Silva Fenn. 24,* 57–75. (In Finnish with English abstract).

Lorenzo, P., Trillas, M. I., Sant, M. D. & Aguila, J. F. 1981. Effects of physical media properties on Codiaeum variegatum rooting response. *Acta Hort. 126,* 293–302.

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 media. *Folia For. 571,* 40 pp. (In Finnish with English summary).

Mäkitalo, K. & Sutinen, M.-L. 1986. Kasvualustan vaikutus männyn paakkutaimien kehitykseen. Finnish For. Res. Inst. Metsäntutkimuslaitoksen tidonant. 241, pp. 30–31. (In Finnish).

Mannerkoski, H. 1982. Effect of tree roots on the bulk density of peat. Proc. Int. Peat Soc. Comm. H., Minsk. pp. 182–188.

Martyr, R. F. 1981. New developments in the uses of graded horticultural perlite. *Acta Hort. 126,* 143–145.

McDonald, S. E. 1984. Irragation in forest-tree nurseries: Monitoring and effects on seedlings growth. In *Forest Nursery Manual: Production of bareroot seedlings* (eds. Duryea, M. L. & Landis, T. D.), pp. 107–121. Martinus/Dr. W. Junk Publishers, The Hague-Boston-Lancaster.

Milks, R. R., Fonteno, W. C. & Larson, R. A., 1989*a*. Hydrology of horticultural substrates: II. Predicting physical properties of media in containers. *J. Am. Soc. Hort. Sci. 114,* 53–56.

Milks, R. R. Fonteno, W. C. & Larson, R. A. 1989*b*. Hydrology of horticultural substrates: III. Predicting air and water content of limited-volume plug cells. *J. Am. Soc. Hort. Sci. 114,* 57–61.

Neal, J. C. & Wagner, D. F. 1983. Physical and chemical properties of coal cinders as a container media component. *HortSci. 18,* 693–695.

Newman, E. I. 1974. Root and soil water relations. In *The plant root and its environment* (ed. Carson, E. W.), pp. 363–440. Univ. of Virginia, Charlottesville.

Nilsen, S. 1977. Seedlings of Norway spruce, Scots pine and Lodgepole pine grown in rockwool. Norwegian For. Res. Inst. Medd. Norsk Inst. Skogforsk. 33, 234–252.

Olsson, M. T. & Wästerlund, I. 1982. Odlingssubstrat av nedbruten bark blandad med kycklinggödsel. Swedish Univ. Agr. Sci., Uppsala. Rapp. skogsekol. skoglig markl. 39, 17 pp. (In Swedish).

Örlander, G. 1984. Some aspects of water relations in planted seedlings of *Pinus sylvestris* L. Dr. Thesis. Swedish Univ. Agr. Sci. Dept. Silviculture, Umeå. 30 pp.

Örlander, G. 1985. Skogsskötsel i södra Sverige. Swedish Univ. Agr. Sci., Uppsala. Skogsfakta Konferens 7, 41–44. (In Swedish).

Örlander, G. & Due, K. 1986*a*. Location of hydraulic resistance in the soil-plant pathway in seedlings of *Pinus sylvestris* L. grown in peat. *Can. J. For. Res. 16,* 115–123.

Örlander, G. & Due, K. 1986*b*. Water relations of seedlings of Scots pine grown in peat as a function of soil water potential and soil temperature. *Stud. For. Suec. 175,* 13 pp.

Örlander, G. & Gemmel, P. 1979. Luftbeskärning av plantrötter. Ett plantodlingssystem för plantor odlade i mineralull. Swedish Univ. Agr. Sci., Umeå. Intern. Rapp. 1/1979, 11 pp. (In Swedish).

Orlov, A. J. 1962. Growth and death of pine, birch and spruce roots when periodically submerged in standing water. Soobsc. Lab. Lesoved 6 (Moscow), 62–82.

Ownley, B. H., Benson, D. M. & Bilderback, T. E. 1990. Physical properties of container media and relation to severity of Phytophthora root rot of Rhododendron. *J. Am. Soc. Hort. Sci. 115,* 564–570.

Paavilainen, J. 1966. On the relationships between the root system of white birch and Norway spruce and the ground water table. *Commun. Inst. For. Fenn.* 62, 15 pp.

Päivänen, J. 1973. Hydraulic conductivity and water retention in peat soils. *Acta For. Fenn. 129,* 70 pp.

Pallares, M. P. & Gonzalez, A. M. 1984. Caracterizacion de las propiedades fisicas, en los substratos empleados en horticultura ornamental. Comm. INIA Serio: Produc. Vegetal 61 (Madrid), 37 pp. (In Spanish).

Park, C. H. & Chung, H. D. 1987. The physicochemical properties of the media soils by mixing Sphagnum peat moss and vermiculite and its effect on the growth of cucumber plants. *J. Kor. Soc. Hort. Sci. 28,* 9–17. (In Korean with English summary).

Parke, P. G., Linderman, R. G. & Black, C. H. 1983. The role of ectomycorrhizas in drought tolerance of Douglas-fir seedlings. *New Phytol. 95,* 83–95.

Penningsfeld, F. 1973. Basis of production, examination and use of growth media. *Acta Hort. 37*, 1918–1921.

Pivot, D. 1985. Cultivation of gerbera on softwood bark of Picea abies and Abies alba: Physical characteritics of these substrates. *Acta Hort. 172*, 211–222.

Pokorny, F. A. & Henny, B. K. 1984. Construction of a milled pine bark and sand potting medium from component particles I. Bulk density: A tool for predicting component volumes. *J. Am. Soc. Hort. Sci. 109*, 770–773.

Prasad, M. 1979*a*. Physical properties of media for container grown crops. I. New Zealand peats and wood wastes. *Sci. Hort. 10*, 317–323.

Prasad, M. 1979*b*. Physical properties of media for container grown crops. II. Peat mixes. *Sci. Hort. 10*, 325–330.

Puustjärvi, V. 1973. *Kasvuturve ja sen käyttö*. 173 pp. Turveteollisuusliitto r.y. Julkaisu 1, Helsinki. (In Finnish).

Puustjärvi, V. 1975*a*. Micro and macrostructures of *Sphagnum* moss peat from the standpoint of its water economy. *Peat & Plant Yearbook* 1973–1975, 5–10.

Puustjärvi, V. 1975*b*. On factors contributing to changes in peat structure in greenhouse culture. *Peat & Plant Yearbook* 1973–1975, 11–14.

Puustjärvi, V. 1978. The water uptake as a function of matric potential and osmotic pressure in peat culture. *Peat & Plant Yearbook* 1978, 13–20.

Puustjärvi, V. 1980. Nutrient standards of fertilized peat. *Peat & Plant Yearbook* 1980, 28–43.

Puustjärvi, V. 1981. Textural classes of horticultural peat. *Peat & Plant Yearbook* 1981–1982, 28–32.

Puustjärvi, V. 1982. Turpeen tasoituskastelu I. *Puutarha 5*, 256–257. (In Finnish).

Regulski, F. J. Jr. 1983 Physical properties of container media composed of a gasifier residue in combination with Sphagnum peat, bark or sand. *J. Am. Soc. Hort. Sci. 108*, 186–189.

Richards, D., Lane, M. & Beardsell, D. V. 1986. The influence of particle-size distribution in pine bark:sand:brown coal potting mixes on water supply, aeration and plant growth. *Sci. Hort. 29*, 1–14.

Riviere, L. M. & Milhau, C. 1983. The use of wood waste composts in the making of substrates for container crops. *Acta Hort. 150*, 475–486.

Riviere, L. M., Foucard, S. C. & Lemaire, F. 1990. Irrigation of container crops in relation with the substrate. *Sci. Hort.* **43,** 39–349.

Rovira, A. D., Foster, R. G. & Martin, J. K. 1979. Note on terminology: Origin, nature and nomenclature of the organic materials in rhizosphere. In *The soil-root interface* (eds. Harley, J. L. & Russell, R. S.), pp. 1–4. Academic Press, London.

Russell, R. S. 1977, *Plant root systems: Their function and interaction with the soil*. 298 pp. McGraw-Hill, London.

Rutter, A. J. & Sands, K. 1958. The relation of leaf water deficit to soil moisture tension in *Pinus sylvestris* I. The effect of soil moisture on diurnal changes in water balance. *New Phytol. 57*, 50–65.

Sanderson, K. C. & Martin, W. C. Jr. 1980. Shredded pine cones as growing media. *Florists' Rev.* May 1, 61–63.

Sands, K. & Rutter, A. J. 1959. Studies in the growth of young plants of *Pinus sylvestris* L. II. The relation of growth to soil moisture tension. *Ann. Bot., N.S. 23*, 269–284.

Sands, R. & Theodorou, C. 1978. Water uptake by mycorrhizal roots of *radiata* pine seedlings. *Aust. J. Plant Physiol. 5*, 301–309.

Sands, R., Fiscus, E. L. & Reid, C. P. P. 1982. Hydraulic properties of pine and bean roots with varying degrees of suberization, vascular differentation and mycorrhizal infection. *Aust. J. Plant. Physiol. 9*, 559–568.

Sarjala, T. & Kupila-Ahvenniemi, S. 1982. Development of mycorrhizae in seedlings of the Scots pine during the first two growing seasons. *Aquilo Bot. Ser. 18*, 16–26.

Scalabrelli, G., Gouvillon, G. A. & Pokorny, F. A. 1983. Propagation of peach hardwood cuttings in milled pine bark and other media. *Acta Hort. 150*, 459–463.

Schleiff, U. 1986. Water uptake by barley roots as affected by the osmotic and matric potential in the rhizosphere. *Plant and Soil 94*, 143–146.

Shalhevet, J. & Hsiao, Th. C. 1986. Salinity and drought. A comparison of their effects on osmotic adjustment, assimilation, transpiration and growth. *Irrig. Sci. 7*, 249–264.

Seikh, K. H. & Rutter, A. J. 1969. The response of *Molinia caerulea* and *Erica tetralix* to soil aeration and related factors I. Root distribution in relation to soil porosity. *J. Ecol. 57*, 713–726.

Smith, D. L. 1987. *Rockwool in horticulture*. 153 pp. Grower Books, London.

Solbraa, K. 1979. Composting of bark. I. Different bark qualities and their uses in plant production. Norwegian For. Res. Inst. Medd. Norsk Inst. Skogforsk. 34, 281–333.

Solbraa, K. 1986. Bark as growth medium. *Acta Hort. 178*, 129–134.

Spomer, L. A. 1974. Optimizing container soil amendment: The "threshold proportion" and prediction of porosity. *HortSci. 9*, 532–533.

Stenström, E. 1990. Ecology of mycorrhizal *Pinus sylvestris* seedlings—Aspects of colonization and growth. Dr. Thesis. Swedish Univ. Agr. Sci. Dept. For. Myc. Path., Uppsala. 44 pp.

Stolzy, L. H. 1974. Soil atmosphere. In *The plant root and its environment* (ed. Carson, E. W.), pp. 335–361. Univ. of Virginia, Charlottesville.

Tilt, K. M. & Bilderback, T. E. 1987. Physical properties of propagation media and their effects on rooting of three woody ornamentals. *HortSci.* **22,** 245–247.

Tinus, R. W. & McDonald, S. E. 1979. How to grow tree seedlings in containers in greenhouses. Rockey Mountain For. Ran. Exp. Sta. Forest Service, USDA, Gen. Tech. Rep. RM-60, 256 pp.

Topa, M. A. & McLeod, K. W. 1986. Aerenchyma and lenticel formation in pine seedlings: A possible avoidance mechanism to anaerobic growth conditions. *Physiol. Plant. 68*, 540–550.

Topp, G. C., Davis, J. L., Bailey, W. G. & Zebchuk, W. D. 1984. The measurement of soil water content using a portable TDR hand probe. *Can. J. Soil. Sci. 64*, 313–321.

Trochoulias, T., Burton, A. J. & White, E. 1990. The use of bagasse as a potting medium for ornamentals. *Sci. Hort. 42*, 161–167.

Unestam, T. & Stenström, E. 1989. A method for observing and manipulating roots and root associated fungi on plants growing in nonsterile substrates. *Scand. J. For. Res. 4*, 51–58.

Venn, K. 1985. Root dieback of coniferous seedlings in forest nurseries. Norwegian For. Res. Inst. Research Paper 3/85, 11 pp. (In Norwegian with English summary).

Verdonck, O. 1983*a*. New development in the use of graded perlite in horticultural substrates. *Acta Hort. 150*, 575–581.

Verdonck, O. 1983*b*. Reviewing and evaluation of new materials used as substrates. *Acta Hort. 150*, 467–473.

Verdonck, O. & Gabriels, R. 1988. Substrate requirements for plants. *Acta Hort. 221*, 19–23.

Verdonck, O. & Pennick, R. 1986. Air content in horticultural substrates. *Acta Hort. 178*, 101–105.

Verdonck, O., De Vleeschauwer, D. & De Boodt, M. 1980. Growing ornamental plants in inert substrates. *Acta Hort. 99*, 113–118.

Verdonck, O., De Vleeschauwer, D. & De Boodt, M. 1981. The influence of the substrate to plant growth. *Acta Hort. 126*, 251–258.

Verdonck, O., Pennick, R. & De Boodt, M. 1983. The physical properties of different horticultural substances. *Acta Hort. 150*, 155–160.

Verdure, M. 1981. Improvements of physical properties of black peat. *Acta Hort. 126*, 131–142.

Vomocil, J. A. & Flocker, W. J. 1961. Effect of soil compaction on storage and movement of soil air and water. *Trans. Am. Soc. Agr. Eng. 4*, 242–246.

Wang, Y.-T. & Boogher, C. A. 1987. Effect of a medium-incorporated hydrogel on plant growth and water use of two foliage species. *J. Environ. Hort. 5*, 125–127.

Warkentin, B. P. 1984. Physical properties of forest-nursery soils: Relation to seedling growth. In *Forest Nursery Manual: Production of bareroot seedlings* (eds. Duryea, M. L. & Landis, T. D.), pp. 53–61. Martinus/Dr. W. Junk Publishers, The Hague-Boston-Lancaster.

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

White, J. W. 1974. Criteria for selection of growing media for greenhouse crops. *Florists' Rev. 155*, 28–30.

White, J. W. & Mastalerz, J. W. 1966. Soil moisture as related to "container capacity". *J. Am. Soc. Hort. Sci. 89*, 758–765.

Wilson, G. C. S. 1983*a*. The physico-chemical and physical properties of horticultural substrates. *Acta Hort. 150*, 19–32.

Wilson, G. C. S. 1983*b*. Use of vermiculite as a growth medium for tomatoes. *Acta Hort. 150*, 283–288.

II

A Measurement System for Determining Temperature, Water Potential and Aeration of Growth Medium

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Silva Fennica 1992, Vol. 26 N:o 1: 27–35

A measurement system for determining temperature, water potential and aeration of growth medium

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TIIVISTELMÄ: KASVUALUSTAN LÄMPÖTILAN, VESIPOTENTIAALIN JA ILMANVAIHDON MITTAUSJÄRJESTELMÄ

Heiskanen, J. & Laitinen, J. 1992. A measurement system for determining temperature, water potential and aeration of growth medium. Tiivistelmä: Kasvualustan lämpötilan, vesipotentiaalin ja ilmanvaihdon mittausjärjestelmä. Silva Fennica 26(1): 27–35.

A measurement system developed for the parallel and real-time measurement of temperature, matric potential and oxygen diffusion rate (ODR) of a growth medium was assessed. The system consisted of a portable computer, a datalogger, temperature sensors, tensiometers and an ODR-meter with Pt-sensors.

For the measurements, proper sensor contact with the growth medium was needed. For matric potential measurement, appropriate shape and material of the tensiometer tips should be selected for different measurement purposes. The determination of oxygen diffusion rate is based on single, non-continuous measurements. The ODR-measurement required special care with the insertion and handling of the electrodes and selection of the applied voltage. The ODR-measurement of a coarse peat medium was applicable only at matric potentials > –5 kPa. This measurement system was shown to be useful and suitable for accurate determination of thermal-, water- and aeration conditions of a growth medium under greenhouse conditions.

Kasvualustan lämpötilan, matriisipotentiaalin ja hapen diffuusiovirran yhtäaikaista ja viiveetöntä mittaamista tutkittiin tarkoitusta varten rakennetulla sähköisellä mittausjärjestelmällä. Mittausjärjestelmä koostui kannettavasta mikrotietokoneesta, dataloggerista, lämpötila-antureista, tensiometreistä sekä hapendiffuusiomittarista platina-elektrodeineen.

Mittaukset edellyttivät huolellista anturien käsittelyä ja hyvää kontaktia mitattavan kasvualustan kanssa. Tensiometrikärkien materiaalin ja muotoilun tulee olla tarkoituksenmukaiset matriisipotentiaalin mittaamiseen eri sovellutustilanteissa. Hapen diffuusiovirran mittaus perustuu kertamittauksiin ja se vaati erityistä huomiota platinaelektrodien käytössä ja mittausjännitteen valinnassa. Hapen diffuusiovirran mittaus soveltui kasvuturpeelle, kun matriisipotentiaali oli > –5 kPa. Mittaussysteemi todettiin suhteellisen helppokäyttöiseksi, nopeaksi ja tarkaksi kasvihuoneoloissa ja siten soveltuvaksi kasvualustan lämpö-, vesi- ja ilmanvaihto-olojen määrittämiseen.

Keywords: matric potential, oxygen, diffusion, peat, sensors, growing media.
FDC 181.3

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Accepted April 13, 1992

1 Introduction

In a growth medium, the most important physical factors affecting plant growth are the thermal-, water- and aeration conditions. These conditions, and the need for their manipulation, can be evaluated by measuring the values of the variables that affect them. For studying the physical growth conditions in different growth media and managements, such as nursery practices and site preparations, it is crucial to have an easy, fast and accurate system for measuring the values of the physical variables in-situ.

Temperature near the ground surface and in the growth medium can be easily measured by electrical sensors (Taylor and Jackson 1986). The matric potential (in kPa), which is measured by tensiometers, has usually been used as a variable describing the water status in soil (Cassel and Klute 1986). Often tensiometers are still read by vacuum gauges or Hg-manometers, but they more commonly have been integrated into electrical pressure sensors and automatized data-acquisition systems (Long 1984, Cassel and Klute 1986, Lowery et al. 1986, Phene et al. 1989, Saarinen 1989, Nyhan and Drennon 1990). In the case of aeration, the indices and measurements vary more and are also more complex (Mcintyre 1970, Stolzy 1974, Glinski and Stepniewski 1985). However, the best index for soil aeration has been regarded to be the oxygen diffusion rate (ODR, $\mu g/m^2s$), which can be measured electrically with Pt-electrodes (Mcintyre 1970, Glinski and Stepniewski 1985, Mannerkoski 1985).

This paper describes a portable system for parallel and real-time determination of temperature, matric potential and oxygen diffusion rate of a growth medium. The measurement system, which is based on measurement sensors, a personal computer and a datalogger, was tested under greenhouse conditions.

2 Material and methods

2.1 Measurement system

Datalogger

The portable measurement system was integrated on a datalogger Datataker 100F (DT100F) (Fig. 1). The DT100F is a field model that includes 23 differential or 46 single analog and 8 digital input channels. There are 1 analog and 8 digital output channels. The analog input channels can be used for measuring voltage, current, resistance, temperature and frequency. In this study, the sockets of the input channels were connected to the internal amplifiers with wrapping wires so that the input was of the differential voltage type for the sensors used. The analog input channels are autoranging (within ± 25, 250, 2500 mV). The accuracy of the input channels for the voltage is 0.15 % with a resolution of 1 µV. The accuracy and resolution were found to be clearly greater than those of the responses (in mV) of the measurement sensors. The electrical terminals of the sensors were connected with shielded cables to the input channels of the datalogger. The power (12VDC) to the DT100F (operable also on the internal battery) was supplied from a common electrical net via a 220VAC/12VDC adapter. The power (12VDC) to the pressure and temperature sensors was supplied from a common electrical net via a discrete constant voltage source (Mascot, 220VAC/± 12VDC). The supply current was 60 µA for a temperature sensor, 1 mA for a Motorola pressure sensor and 2 mA for the Micro Switch pressure sensors used. The DT100F includes a multiplexer and an A/D-converter.

The datalogger was operated on the software (DECIPHER) delivered with the datalogger. The software was run and the datalogger was programmed from a portable personal computer (Toshiba T3100SX) by entering commands of ASCII-characters via a RS232C-interface. The sensor responses (mV) scanned from the datalogger output were retrieved and stored in files on the hard disk of the computer.

Temperature sensors

Temperature was measured using semiconduc-

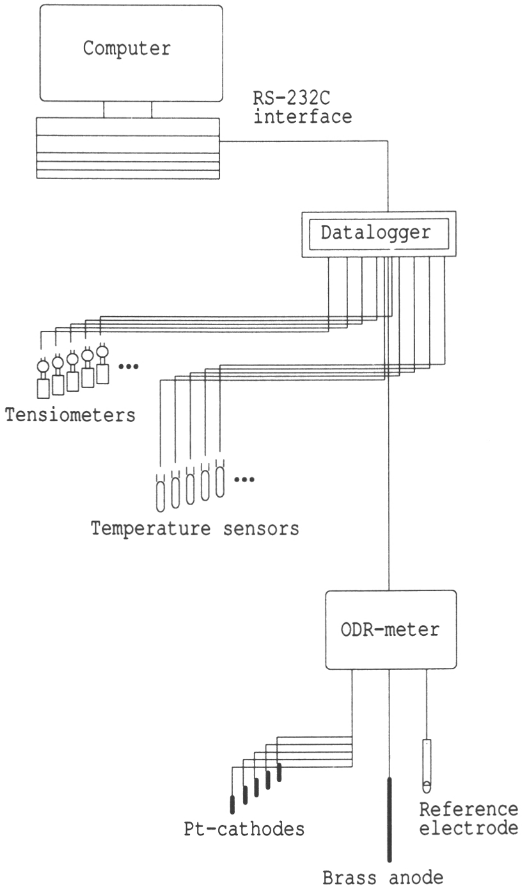

Fig. 1. Schematic diagram of the measurement system.

tor sensors (National LM35DZ). The measurement scale of the sensors is 0 to 100 °C. The sensors were calibrated against a Hg-thermometer (Fuess) at room and electric oven temperatures. In the calibration was included also the fundamental fixed reference points of the melting point of ice (0 °C) and the boiling point of water (100 °C) (Taylor and Jackson 1986).

Matric potential sensors

The matric potential of the growth medium was measured by tensiometers. To test the effect of different tensiometers on the measurement of the growth medium, three different pressure sensors and three differently shaped porous tips were used (Fig. 2). The tip materials in the thin and thick types were ceramics (bubbling pressure 100 kPa, SoilMoisture Equipment Corp.); in the wide type a sintered glass was used (11–16 µm in pore size, corresponding to a bubbling pressure of about 15 kPa, SCHOTT and Gen Mainz.). When a tensiometer is inserted into a growth medium and equilibrium is achieved between the growth medium water and the tensiometer water through the porous tip, the water pressure (in kPa) inside the tensiometer sensed by a pressure sensor (in mV) describes directly the matric potential in the growth medium. To avoid the effects of fluctuations in temperature and atmospheric pressure on the responses of the sensors, differential (temperature- and barometric pressure-compensated) pressure sensors (Micro Switch 16PC15DF and 136PC15G1, Motorola MPX2050GVP) were used. The measurement scale of the Micro Switch sensors is ± 103 kPa and that of the Motorola sensor ± 50 kPa against the ambient pressure. According to the manufacturers, the accuracy of the sensor outputs is within ± 1.5 (Motorola and Micro Switch 136PC) and ± 3.0 mV (Micro Switch 16PC) of the full scale output.

At the high potential range of 5 to –15 kPa, in which the relative reading error is great, each pressure sensor was calibrated. The calibration was done by making direct comparisons (with 10 replicate) between the pressures sensed with a sensor and the hydraulic heads (Cassel and Klute 1986), which were adjusted with the hanging water column in plastic tubing connected to a sensor. The response times of the tensiometers were determined as the time required for the response of a pressure sensor to become constant (± 0.01 mV) when the hydraulic head was rapidly adjusted from 0 to –9.8 kPa.

Oxygen diffusion rate-meter

The oxygen diffusion rate (ODR) was measured using Pt-electrodes (E7.0, Jensen Instruments). The electrodes cannot be connected directly to the datalogger; they need a reference electrode (Ag/AgCl) and a brass anode connected to an appropriate electrical circuit, for which an ODR-meter (Model D, Jensen Instruments) was used. When the electrical voltage is applied to the ODR-meter, the oxygen starts to reduce at the Pt-cathode, which in turn causes a corresponding current. The observed cathode current is proportional to the ODR (Mcintyre 1970, Glinski and Stepniewski 1985). In order to ensure

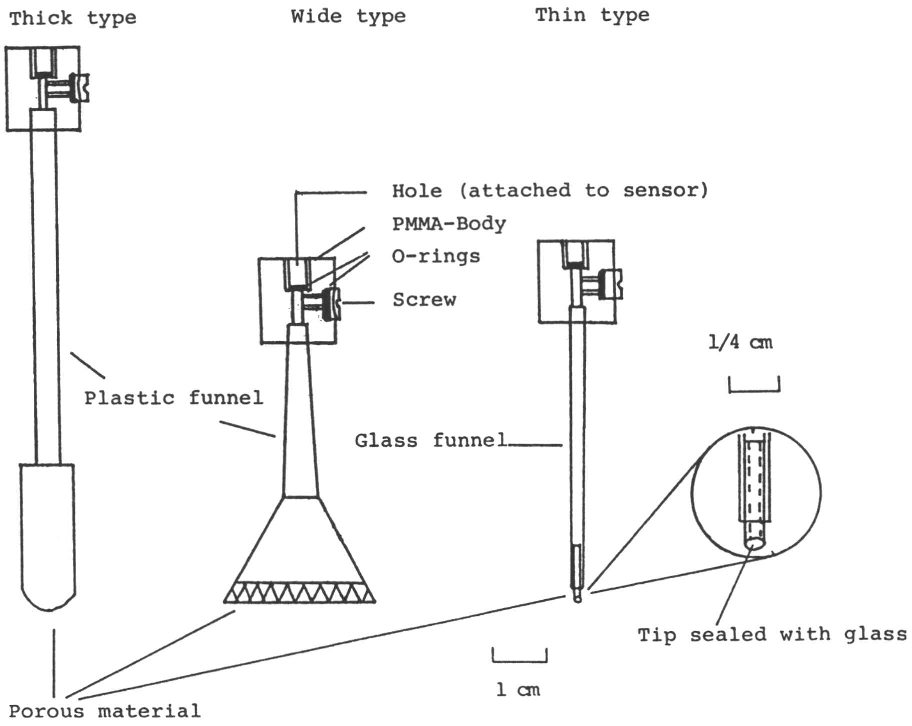

Fig. 2. Schematic diagram showing the construction of the tensiometer tips tested.

oxygen reduction at the electrodes, the electrodes must be covered with a water film while measurements are being taken. The electrode current obtained is affected, in addition to O_2 concentration, by soil structure, pH, salt concentration, moisture and applied voltage (e.g. Mcintyre 1970, Mannerkoski 1985).

When the growth medium was being measured, the distance between each Pt-electrode was at least 1.5 cm. The electrode current was observed each time after 4 minutes stabilizing time from insertion and application of the voltage of –800 mV (Mannerkoski 1985). The current (µA) (surface area of an electrode ~ 0.085 cm²) was converted to the corresponding ODR-value (µg/m²s) by multiplying it by the constant 9.83, which was calculated from Formula 1 (Mcintyre 1970, Glinski and Stepniewski 1985). Between measurements, the electrodes were stored in dry air at room temperature. No appropriate reference methods were available for testing the accuracy of the ODR-meter.

$$ODR = (M\ i)\ (n\ F\ A)^{-1}, \text{ where} \qquad (1)$$

M = molecular mass of O_2 (32 g mol^{-1}),
i = current intensity (µA),
n = number of electrons consumed per mole of O_2 (= 4),
F = the Faraday constant (96500 C mol^{-1}),
A = electrode area (m²).

The ODR-meter system was not yet available with a computer interface; therefore it was not possible to connect the system directly to the datalogger input channels and to have completely automatic data retrieval from all the Pt-electrodes. In addition, ODR could not be recorded continuously, because, due to their 'poisoning' by precipitation of certain compounds, the Pt-electrodes cannot be left in the growth medium for long periods (Mcintyre 1970, Glinski and Stepniewski 1985, cf. Campbell 1980). So far, only one reading at a time can be retrieved from the ODR-meter into the datalogger by connecting the plotter output of the ODR-meter to one datalogger input. This connection was used, when the Pt-electrodes were connected in parallel. The resulting single response (regarded as a value describing the mean response from the bulk growth medium) could be monitored from the datalogger.

2.2 Test measurements

To assess the applicability of the system, a coarse-graded (Puustjärvi 1982) and premix-fertilized Finnish (VAPO D) *Sphagnum* peat growth medium (see Heiskanen 1990) filled into a PVC-plastic sample core (d = 15 cm, h = 12 cm) was used for test measurements. The pH of the growth medium, which was measured from the extracted water, was 4.7–5.0. The measurement sensors were inserted horizontally into the growth medium through small drill holes in the core wall. The tips of the sensors were about 3 cm from the core wall and 6 cm from the surface of the peat. Before the measurements, the desired levels of matric potential were achieved by allowing the growth medium to equilibrate with the respective water (distilled) table levels for two or three days. The measurements were made indoors at temperatures between 20 and 25 °C.

Regression analysis was used to test the responses of the sensors. Statistical and graphical data were analyzed using SYSTAT (v. 5.0) software (SYSTAT... 1990).

3 Results and discussion

3.1 Temperature measurement

The response of the sensor used in relation to a Hg-thermometer was linear ($y = 10.5\ x$, $R^2 = 0.999$) with deviation from the line being < 0.45 °C at temperatures lower than 80 °C (Fig. 3). For more precise measurements, even greater accuracy can be achieved by calibration with a calorimeter. The temperature sensors are calibrated by the manufacturer directly to the linear relation of 10.0 mV/°C, in which the error of the response is typically within ± 0.9 °C over the whole measurement scale. The sensors are small and easy to handle and no difficulties were encountered in measuring the temperature of the growth medium.

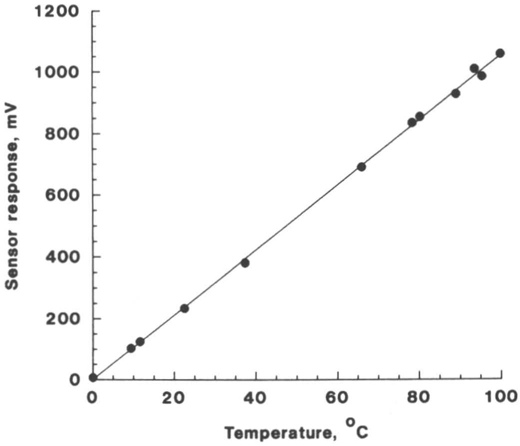

Fig. 3. Calibration line of a National LM35DZ temperature sensor. On the y-axis is the sensor response (mV) and on the x-axis is the temperature read from a Hg-thermometer (°C).

3.2 Matric potential measurement

The responses (mV) of the pressure sensors were linear (Long 1984, Phene et al. 1989) at the matric potential range of 5 to –15 kPa used (Fig. 4, Table 1). The calibration lines passed near the origin, because the responses were achieved from the zero-offset situation (at 0 kPa). The slope of the Motorola sensor line was clearly gentler and the standard deviations somewhat higher than those of the Micro Switch sensors. The standard deviations of the sensor responses (each determined from 10 measurements) were small, less than 0.07 mV. The responses in the vertical and horizontal sensor positions did not differ markedly (Table 1), which indicated that within the potential range used, the differences between the two positions in the hydraulic heads in the adjusting water tubing were small.

When the different types of porous tips were used, the tensiometers responded to a matric potential change (from 0 to –9.8 kPa) in different ways (Fig. 5, Table 2). In particular, the physical dimensions of the porous tips affected the response time. With a large surface area, the contact area between the surrounding water and the tensiometer water was large and equilibrium

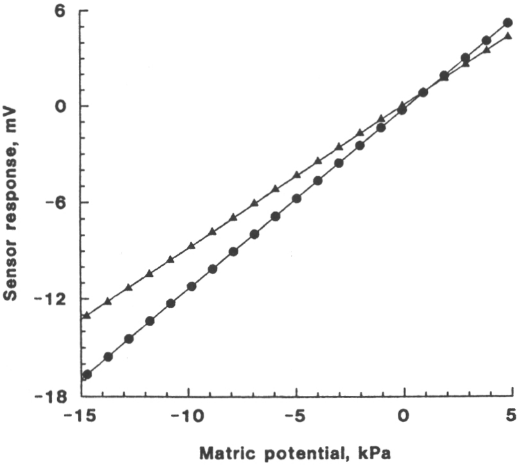

Fig. 4. Calibration line of a Micro Switch 16PC15DF (circles) and a Motorola MPX2050GVP (triangles) pressure sensor placed vertically to the water tubing used for adjustment of hydraulic head. On the y-axis is the sensor response (mV) and on the x-axis is the matric potential (kPa) in the tubing. Standard deviations (from 10 measurements) at different potentials are less than 0.044. (Micro Switch 136PC15G1 response almost the same as 16PC15DF, see Table 1).

Table 1. Parameters of linear regression equations (y = ax) showing the relationship between the matric potential x (kPa) and the electrical output response y (mV) for the three single pressure sensors placed vertically and horizontally to the water tubing in which the hydraulic head was regulated. The response at each matric potential level (between 4.9 and –14.7 kPa) is the mean of ten repeated measurements at desorption. Sensors: A = Micro Switch 16PC15DF, B = Micro Switch 136PC15G1, C = Motorola MPX2050GVP.

Sensor	a	R^2	p	SD*
Vertically				
A	1.1351	0.9994	< 0.00005	0.004–0.020
B	1.1331	0.9998	< 0.00005	0.005–0.044
C	0.8855	0.9999	< 0.00005	0.015–0.036
Horizontally				
A	1.1363	0.9997	< 0.00005	0.005–0.028
B	1.1270	0.9999	< 0.00005	0.007–0.036
C	0.8812	0.9999	< 0.00005	0.032–0.074

* Standard deviations at different matric potentials.

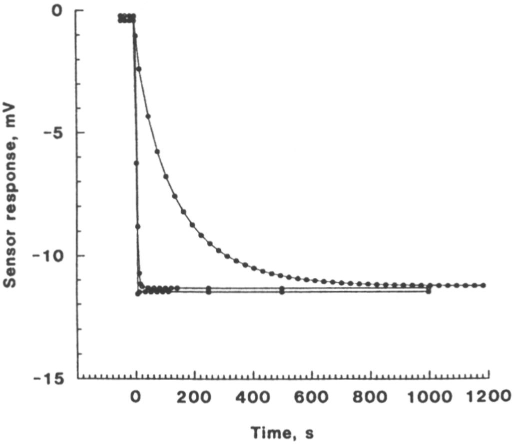

Fig. 5. Sensor response (mV) in time (s) to the matric potential altered from 0 to –9.8 kPa and from a time of 0 s from three tensiometer tips measured with a Micro Switch 16PC15DF sensor. (Curves: upper = thin tip, middle = thick tip and lower = wide tip. See Fig. 2).

Table 2. Characteristics of the three tensiometer tips tested.

Tip type	Wall thickness mm	Surface area (Inner wall) mm^2	Response time* s
Wide	3.7	530	13
Thick	3.5	340	53
Thin	0.3	3	1280 (21.3 min)

* Total time required for sensor output to stabilize (± 0.01 mV) when the matric potential was rapidly altered from 0 to –9.8 kPa.

was achieved rapidly, within tens of seconds (c.f. Nyhan and Drennon 1990). With the thin-type tensiometer the contact area was very small and the response was therefore slow (> 20 minutes). The responses of the tensiometers also differed in the peat growth medium at desorption (Fig. 6). The thick-type tensiometer responded almost linearly ($y = 1.146\ x$, $R^2 = 0.996$), which is close to the calibration line for a single sensor (see Table 1). The slight deviations of the response

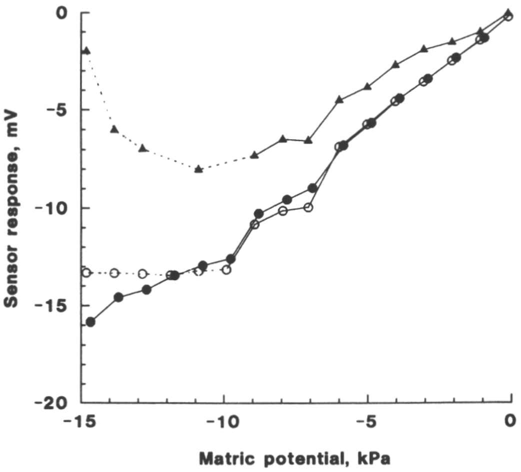

Fig. 6. Sensor responses (mV) of three tensiometers placed horizontally in the peat medium to the decreasing matric potential (kPa) adjusted with a hydraulic head. (Tensiometers are: thick type with a Micro Switch 16PC15DF sensor (solid circles), wide type with a Micro Switch 136PC15G1 sensor (open circles) and thin type with a Motorola MPX2050GVP sensor (solid triangles)). The dotted lines deviate markedly from the response with a single sensor (see Table 1).

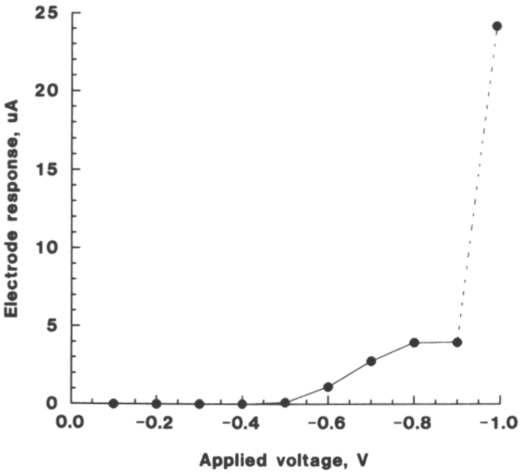

Fig. 7. Response (mA) of five Pt-electrodes to the different applied voltages (V) measured from the peat medium using the D-model ODR-meter (Jensen Instruments). Before each measurement at decreasing applied voltage, the Pt-electrodes were removed from the medium and washed with water. The standard deviations at the different voltages (from 0 to –0.8) are less than 0.2. The matric potential in the peat was 0 kPa. The dotted line shows a drastic, unstable rise in the electrode response.

lines (Fig. 6) from linearity were due to the heterogeneity of the growth medium and, possibly, to incomplete equilibrium of the matric potential. The response of the wide-type tensiometer became almost constant when the matric potential was below –10 kPa, which is close to the bubbling pressure limit of the sintered glass tip. The response of the thin-type tensiometer increased at matric potentials below –9 kPa, which shows that the contact between the ceramic tip and the growth medium has broken. Thus, very small tensiometer tips could be most useful in conditions where the water content fluctuates slowly and when the growth medium samples are small and fine-textured. The porous material used in the tensiometer tips should also be selected so that the bubbling pressure is high enough.

3.3 Oxygen diffusion rate-measurement

Oxygen diffusion rate was measured with one electrode or with several electrodes at a time connected in parallel. The current observed from parallel electrodes can be regarded as a mean response from the growth medium (the current must be divided by the number of parallel electrodes). The ODR-meter, however, was found to be capable of measuring the electrode current only as high as about 85 µA (with the nominal maximum being 50 µA) per electrode or per set of parallel electrodes. Therefore, the parallel connection of electrodes can be used in such measurements where the sum of the electrode currents is less than 85 µA. The current of 85 µA with one electrode suffices for measuring an ODR-value of about 830 µg/m^{2}s or with five parallel electrodes of about 165 µg/m^{2}s.

The ODR of the growth medium was measured using an applied voltage of –0.8 V, which was found to be within the plateau range (–0.75...–0.90 V) of the relationship between the electrode current and the applied voltage (Fig. 7). With voltages higher than –0.5 V, the current was very low (± 0). The applied voltage of –0.99 V gave strong current (with a SD being as high as 17.8), which may indicate that the

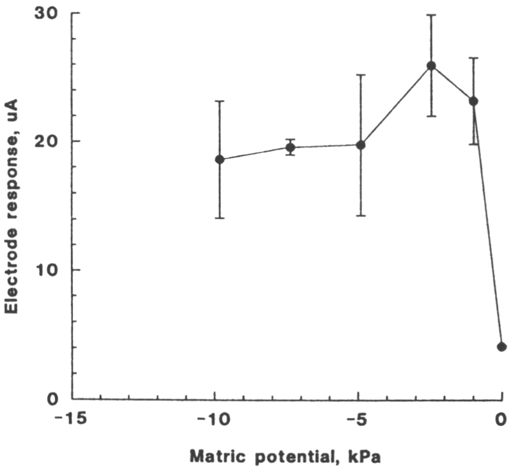

Fig. 8. Mean response of five Pt-electrodes to the decreasing matric potential using the D-model ODR-meter and an applied voltage of –0.8 V. The vertical bars indicate standard deviation (at 0 kPa, the SD is 0.07).

systems does not work stably with such a low voltage. Mannerkoski (1985) also used –0.8 V as the applied voltage for *Sphagnum* peat. However, lower applied voltages have been used both for mineral soils (e.g. Mcintyre 1970, Glinski and Stepniewski 1985) and for organic soils (Campbell 1980). The plateau range measured is also shorter than that usually reported for mineral soils (Mcintyre 1970, Glinski and Stepniewski 1985, Mannerkoski 1985), which may be affected by the acidity (pH < 5.0) of the peat (see Mannerkoski 1985).

When the matric potential of the growth medium was below –2.5 to –5 kPa, the observed electrode current tended to decrease (Fig. 8), despite the fact that the aeration improves during desorption. This was due to drying of the electrode surfaces. Mannerkoski (1985) reported that in peat the observed current decreased when the water table reached 50 cm (~ –5 kPa), which is similar to the result achieved in this study. The variation in ODR was great, however, which is typical of ODR-measurements in general (e.g. Mannerkoski 1985). In mineral soils, ODR can usually be measured at matric potentials from saturation to –50 to –100 kPa (Glinski and Stepniewski 1985). Due to the coarse structure and large pores of the peat, the measured ODR decreased, beginning from higher matric potentials than in fine-textured soils. This is because the air-filled porosity increases more in peat during drying and therefore the water film covering the electrodes also dries earlier in peat than in fine-textured mineral soils. Hence, with peat growth medium the ODR-measurement is applicable when the matric potential is higher than about –5 kPa.

Favourable ODR-values for plant growth are usually above 70 μg/m^{2}s. For most plants the critical ODR-value is about 30 μg/m^{2}s (Glinski and Stepniewski 1985). This critical value corresponds to an electrode current of about 3 μA, which in this study was found to occur in peat growth medium at matric potentials of 0 to –0.5 kPa.

4 Conclusions

The measurement system described was shown to be useful and applicable for determination of thermal-, water- and aeration conditions in growth medium under greenhouse conditions. The measurements can be made rapidly, relatively easily in real-time and in parallel. During the measurements, there must be proper sensor contact with the growth medium. For matric potential measurement, the shape and material of tensiometer tips must be selected to ensure that they are appropriate for different measurement situations. The determination of oxygen diffusion rate is based on single, non-continuous measurements. The ODR-measurement requires special care with the insertion and handling of the electrodes, selection of the applied voltage and interpretation of the results. The ODR-measurement of coarse peat growth media can be applied to matric potentials of > –5 kPa.

Acknowledgements: This study was supported by a grant from the Academy of Finland. Mr. Heiskanen planned the principal construction of the main system, selected the measurement methods, analysed the data and wrote the manuscript. Mr. Laitinen was responsible for technical engineering and construction of the measurement system and for making measurements with the system. The authors wish to thank Prof. H. Mannerkoski, Mr. T. Repo, Lic.Ph., Mr. R. Rikala, M.Sc. and Mr. E. Siivola, M.Sc. for constructive comments, and Dr. J. von Weissenberg for correcting the English language of the manuscript.

References

Campbell, J.A. 1980. Oxygen flux measurement in organic soil. Canadian Journal of Soil Science 60(4): 641–650.

Cassel, D.K. & Klute, A. 1986. Water potential: Tensiometry. In: Klute, A. (ed.). Methods of soil analysis. Part 1. 2nd ed. American Society of Agronomy, Madison, Wisc. p. 563–596.

Glinski, J. & Stepniewski, W. 1985. Soil aeration and its role for plants. CRC Press, Boca Raton, Fla. 250 p.

Heiskanen, J. 1990. Näytelieriön täyttötavan vaikutus kasvuturpeen vedenpidätyskykyyn. Summary: The effect of sample handling on the water retention of growth peat substrate. Suo 41(4–5): 91–96.

Long, F.L. 1984. A field system for automatically measuring soil water potential. Soil Science 137: 227–230.

Lowery, B., Datiri, B.C. & Andraski, B.J. 1986. An electrical readout system for tensiometers. Soil Science Society of America Journal 50: 494–496.

Mannerkoski, H. 1985. Effect of water table fluctuation on the ecology of peat soil. Publications from the Department of Peatland Forestry, Univ. Helsinki 7. 190 p.

Mcintyre, D.S. 1970. The platinum microelectrode method for soil aeration measurement. Advances in Agronomy 22: 235–283.

Nyhan, J.W. & Drennon, B.J. 1990. Tensiometer data acquisition system for hydrologic studies requiring high temporal resolution. Soil Science Society of America Journal 54: 293–296.

Phene, C.J., Allee, C.P. & Pierro, J.D. 1989. Soil matric potential sensor measurements in real-time irrigation scheduling. Agricultural Water Management 16: 173–185.

Puustjärvi, V. 1982. Textural classes of horticultural peat. Peat & Plant Yearbook 1981–1982. p. 28–32.

Saarinen, J. 1989. Automatized measurement of water potential in glasshouse substrates. Acta Horticulturae 238: 57–62.

Stolzy, L.H. 1974. Soil atmosphere. In: Carson, E.W. (ed.). The plant root and its environment. Univ. Virginia, Charlottesville. p. 335–361.

SYSTAT, The system for statistics (four manuals). 1990. SYSTAT Inc, Evanston, IL.

Taylor, S.A. & Jackson, R.D. 1986. Temperature. In: Klute, A. (ed.). Methods of soil analysis. Part 1. 2nd ed. American Society of Agronomy, Madison, Wisc. p. 927–940.

Total of 15 references

III

Variation in Water Retention Characteristics of Peat Growth Media Used in Tree Nurseries

Juha Heiskanen

Silva Fennica 1993, Vol. 27 N:o 2: 77–97

Variation in water retention characteristics of peat growth media used in tree nurseries

Juha Heiskanen

TIIVISTELMÄ: TAIMITARHOILLA KÄYTETTYJEN KASVUTURPEIDEN VEDENPIDÄTYSTUNNUSTEN VAIHTELU

Heiskanen, J. 1993. Variation in water retention characteristics of peat growth media used in tree nurseries. Tiivistelmä: Taimitarhoilla käytettyjen kasvuturpeiden vedenpidätystunnusten vaihtelu. Silva Fennica 27(2): 77–97.

The water retention characteristics and their variation in tree nurseries and related physical properties were determined for commercially produced growth media made of light, low humified *Sphagnum* peat. A total of 100 samples of peat media were collected from filled seedling trays in the greenhouses of four Finnish nurseries in 1990 before seedlings were grown in the trays. In addition, the physical properties were determined from separate samples for two growth media made of compressed peat sheets and chips. The variation in water retention characteristics in nurseries was described using linear models with fixed and random effects. The sources of variation in the mixed linear models were producer, grade, batch (greenhouse) and sample (tray).

The water retention of the peat media at different matric potentials was comparable to that given in the literature for similar peat media. The media shrank an average of 0–16 % during desorption. The peat grades were finer than the Nordic quality standards for peat growth media. Particles < 1 mm increased and particles 1–5 mm decreased the water retention characteristics measured. The greatest total variation in water retention was at –1 kPa. The water retention of the peat media differed least at –5 and –10 kPa. The water retention characteristics of media from different producers usually differed significantly. The grades, on the other hand, did not differ from each other in their water retention characteristics nor were there significant interactions between producer and grade. The batch (greenhouse) effect was marked but was lower than the effect within batches, where the sample (tray) effect was greater than the effect due to random measurement error. At –10 kPa, the measurement error was, however, clearly greater than the sample effect. The random measurement error was comparable to the batch effect. Aeration of the growth medium is dependent on the water content retained between saturation and –1 kPa. The water availability to seedlings at the nursery phase is affected mainly by water retention between –1 and –10 kPa.

Tutkimuksessa selvitettiin kaupallisesti tuotettujen vaaleiden, vähän maatuneiden rahkaturpeiden vedenpidätyskykyä ja sen vaihtelua metsäpuiden taimitarhoilla sekä muita fysikaalisia ominaisuuksia. Turvenäytteitä kerättiin kaikkiaan 100 kpl neljän eri taimitarhan kasvihuoneista valmiiksi täytetyistä taimiarkeista ennen kasvatuksen aloittamista v. 1990. Lisäksi tutkittiin Vapolevy-turpeen ja ruotsalaisen hiutaleturpeen fysikaalisia ominaisuuksia erillisnäytteistä. Vedenpidätyskyvyn vaihtelua taimitarhoilla kuvattiin käyttäen kiinteiden ja satunnaistekijöiden lineaarisia malleja. Lineaarisissa sekamalleissa vaihtelulähteinä olivat turvetuottaja, karkeusaste, turve-erä (kasvihuoneet) ja näyte (taimiarkit).

Turvekasvualustojen vedenpidätyskyky eri matriisipotentiaalitasoilla oli keskimäärin verrattavissa kirjallisuudessa esitettyyn vastaavantyyppisten kasvuturpeiden vedenpidätyskykyyn. Eri kasvuturpeet kutistuivat desorption aikana keskimäärin 0–16 %. Kasvuturpeiden laatuvaatimuksiin nähden kasvuturpeet olivat karkeusasteeltaan liian heinojakoisia. Hiukkaset < 1 mm lisäsivät ja hiukkaset 1–5 mm vähensivät vedenpidätyskykyä. Vedenpidätyskyvyssä suurin kokonaisvaihtelu oli –1 kPa:ssa. Vähäisimmillään erot eri kasvuturpeiden vedenpidätyskyvyn välillä olivat –5 ja –10 kPa:ssa. Eri tuottajien kasvuturpeiden vedenpidätyskyky poikkesi toisistaan merkitsevästi. Karkeusasteet eivät eronneet vedenpidätyskyvyltään toisistaan eikä merkitseviä tuottajan ja karkeusasteen välisiä yhdysvaikutuksia myöskään esiintynyt. Turve-erien (kasvihuoneiden) välinen vaihtelu oli selvä, mutta vähäisempi kuin erien sisäinen vaihtelu. Erien sisällä näytteen (arkin) vaikutus oli suurempi kuin satunnaisen mittausvirheen vaikutus. Kuitenkin mittausvirheellä oli suurempi vaikutus vedenpidätyskykyyn –10 kPa:ssa kuin näytteellä. Satunnainen mittausvirhe oli suuruudeltaan verrattavissa erävaikutukseen. Kasvualustan ilmanvaihto riippuu ennen kaikkea vedenpidätyskyvystä kyllästystilan ja –1 kPa:n välillä. Taimien veden saatavuuteen vaikuttaa taimitarhavaiheessa vedenpidätyskyky lähinnä –1 ja –10 kPa:n välillä.

Keywords: container grown plants, planting stock, production, density, hydraulic conductivity, porosity, physical properties, substrates.
FDC 232.3

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Accepted August 20, 1993

Symbols

A	Area of a sample core, mm^2
Db	Bulk density, $g\ cm^{-3}$
Dp	Particle density, $g\ cm^{-3}$
Dw	Density of water, $g\ cm^{-3}$
Fi	Mass of particles in size class i mm in diameter of total mass, % ($M\ M^{-1}$), e.g. F1–5 = proportion of particles in class 1 to 5 mm
h	Hydraulic head, i.e. height difference between water levels kept on top of a sample core and below the sample core, mm
Il	Loss on ignition (3h/550 °C), % ($M\ M^{-1}$)
Ks	Saturated hydraulic conductivity at 10 °C, $mm\ min^{-1}$
l	Height of a sample core, mm
Mi	Total mass of sample at –i kPa matric potential, g e.g. M1 = total mass at –1 kPa
Ms	Mass of solids i.e. dry mass (24h/105 °C), g
Q	Water volume, mm^3
t	Time interval during which water volume Q has flowed through a sample core, min
Vf	Total porosity, % ($V\ V^{-1}$)
Vi	Sample volume in % at –i kPa in relation to volume at –0.1 kPa, e.g. V1 = relative volume at –1 kPa
θi	Water retained of total volume at –i kPa matric potential, % ($V\ V^{-1}$), e.g. θ1 = water content at –1 kPa, θ1–10 = water content difference between –1 and –10 kPa

1 Introduction

The material used most widely in the Nordic countries as growth medium in container seedling production is light, low humified peat consisting of *Sphagnum* sp. mosses. Material for the manufacture of peat growth medium is harvested from peat bogs and transported to a factory where it is stored in stacks before processing. Sieved and graded peat growth medium is compressed into bales and then delivered to nurseries. Into most peat growth media fertilizers are also incorporated. In the nurseries the peat is finally unpacked and emptied into a filling machine, which loosens, fills and compresses peat into the containers of seedling trays.

In nurseries, the growth of tree seedlings is greatly affected by the availability of water and oxygen to the roots from the growth medium. Water and oxygen availability are determined, in addition to external growth conditions, also by the water retention characteristics of the growth medium, which are strongly dependent on pore size distribution (Hillel 1982). The pore size distribution of the soil is, in turn, affected by particle size distribution, degree of compactness and structure (Hillel 1971,1982, Currie 1984).

In the case of light, low humified (H1–3, von Post scale) peat growth media, the physical properties are determined primarily by the composition of plant species making up the peat and secondarily by particle size distribution (Puustjärvi 1973). The peat growth media used in tree nurseries are usually graded as fine, medium or coarse, as defined by Nordic standards (Puustjärvi 1982a). According to the regulations of the Finnish Ministry of Agriculture and Forestry, the first class light, low humified (H1–3) cultivation peat, which is the peat used in tree nurseries, should contain at least 90 % remains of *Sphagnum* mosses, from which over 80 % should belong to the Acutifolia group. Less than 3 % shrubs and wood remnants and less than 6 % cotton-grass remnants are allowed in the dry mass of the peat (Maa- ja... 1986). The composition of the plant remains affects the surface properties of peat, which, in addition to pore size distribution, have a great effect on water retention characteristics and wettability (Päivänen 1973, Puustjärvi 1973). The surface properties of dry organic materials may even cause water repellency and nonwettability (Hillel 1971, Puustjärvi 1973).

Variation in the physical properties of peat media causes a corresponding change in their water retention characteristics. This may further induce variation in the availability of water and air to the seedlings. Great variation in the water and aeration characteristics of a peat batch may thus cause uneven plant growth within the crop (Puustjärvi 1973, 1975a). In general, the water retention characteristics of peat differ according to bulk density, which changes mainly with the degree of humification (Päivänen 1969, 1973, Puustjärvi 1970). The water retention characteristics of low humified peat growth media are, however, mainly determined either as averages within different peat grades only (e.g. Puustjärvi 1973, Verdonck et al. 1983) or by describing them in terms of few and rather imprecise variables, such as water and air capacity (e.g. Puustjärvi 1969, Folk et al. 1992). Little is therefore known about the actual variation in the water retention characteristics of peat growth media under real growing conditions.

In tree nurseries, a greenhouse or part of a greenhouse is the smallest unit in which irrigation and fertilization can usually be adjusted. The amounts of water and timing of irrigation are usually adjusted by visual and tactile evaluation or by weighing seedling trays and then determining their mass deficit with respect to the mass of a tray in which the target water content is considered to prevail. The availability of water to an individual seedling, however, depends on the actual water and aeration conditions in a container which may differ from the average conditions in the tray. In order to achieve even seedling growth and quality within a crop, irrigation and other growing conditions in greenhouses must be monitored and manipulated effectively. To facilitate these management practices, information is needed about the actual variation in water retention characteristics of different peat products in seedling trays within and between greenhouses. In addition, the manufacture and formulation of peat growth media and mixtures require information on variations in peat properties and the causes of these variations.

The aim of this study was to determine the water retention characteristics and related physical properties of light, low humified peat growth media used in growing container seedlings at tree nurseries and, in particular, the variation in the water retention characteristics of these peat media. Some implications of the determined characteristics for the growth of seedlings and irrigation are further discussed. The differences in water retention characteristics between different peat products and their variation in nurseries were analyzed using linear models with fixed and random effects.

2 Materials and methods

2.1 Peat media

The peat growth media studied here were light, low humified *Sphagnum* peat. The peat grades collected were the coarse and medium grades of two Finnish producers, which account for the major part of the peat medium production in Finland (Vapo and Kekkilä Corp.). The peat grades, specified by the producers, refer to Nordic standards (Puustjärvi 1982a). The peat products of the Vapo Corp. were D1K2 and E1K2 and those of the Kekkilä Corp. ST-400 M6 and PP6 for coarse and medium grades, respectively. Peat was collected from newly filled seedling trays at four tree nurseries (Joroinen, Puupelto, Suonenjoki, Syrjälä) in spring 1990. The peat of a tray was fully emptied onto the ground, from which a gently mixed sample of about 3 dm^3 was placed in a plastic bag. Thus the water content of the peat samples was almost the same as that in the packages delivered from the producers (see Heiskanen 1990). The trays were type TA made of polystyrene (Lännen Corp., Finland).

Each peat sample was collected from a separate, randomly selected seedling tray. The trays had been randomized using random number tables to select the ordinal numbers of the columns and rows of trays in a greenhouse. For each of the 4 producer and grade combinations, 5 groups of 5 randomly selected samples were collected, each from a separate, randomly selected greenhouse. Each group of 5 samples from a greenhouse therefore represented a batch of peat. Peat batches from the same producers were assumed to represent time variable peat batches from the whole production lot of a year. The lots are not expected to vary more between different years than the batches vary within years.

In addition, 10 samples of compressed sheet peat (Vapo Corp.) produced for the Vapo container growing method and 10 samples of Swedish chip peat (Hasselfors Corp.) were randomly collected from a production batch (1–2 packages). The total number of samples studied was thus 120 ($2 \cdot 2 \cdot 5 \cdot 5 + 10 + 10$). Before laboratory determinations, the samples were stored a maximum of 9 months in cold storage (5–10 °C).

2.2 Laboratory determinations

The particle size distribution of each sample of peat medium was determined by dry sieving through standard sieves of 20, 10, 5 and 1 mm hole size (Puustjärvi 1973, Wilson 1983, Kurki 1985). For each main sample collected, a loose, air dried sample of 300 cm^3 was sieved for 2 minutes using a mechanical sieving machine (Retsch Corp., Germany). In order to sieve the sheet peat, it was first moistened and loosened by hand and then air dried.

Loss on ignition, which provides an approximate estimate of organic matter content, was determined by igniting a sample of about 2 g at 550 °C for 3 hours. Particle density was measured using liquid pycnometers with water as the filling liquid and a water bath (Heiskanen 1992). Bulk density was determined as the ratio of dry mass (dried at 105 °C) to saturated volume (volume determinations described later). Total porosity (%) was calculated from particle and bulk densities using Formula 1.

$$Vf = ((Dp - Db) / Dp) \cdot 100. \qquad (1)$$

Saturated hydraulic conductivity was measured by applying the constant head percolation method (Dirksen and Klute 1986, Kretzschmar 1989). Samples were filled into 195 cm^3 cylindrical containers that were 63 mm in height. The top end of the cylinder was open and the base was perforated throughout with 1 mm holes. The samples were compressed from above for 5 seconds with a pressure of 10 g cm^{-2} (Heiskanen 1990) and were then allowed to become saturated in free water for a day. A similar empty cylinder in which the water table was kept constant was then placed tightly on top of the sample cylinder. Before the actual measurement of percolation, tap water was first allowed to percolate through the cylinders overnight. The amount of water that had passed through the sample was then weighed at 30 min intervals. When the water flow had stabilized to almost constant (within a day), this final rate of flow was recorded (see Päivänen 1973). The value of saturated hydraulic conductivity (Ks) was calculated using Formula 2, which is based on the principle of Darcy's law ($l = 63$ mm, $A = 3117$ mm^2, $h = 80–95$ mm).

$$Ks = (Q \cdot l) / (A \cdot h \cdot t). \qquad (2)$$

Because the temperature of the water that flowed through the samples was found to vary between 8 and 18 °C, the effect of varying viscosity on hydraulic conductivity was taken into account by using correction coefficients (Sillanpää 1956, Campbell 1985). The coefficients were determined as the ratio of kinematic viscosity at the observed temperature to that at 10 °C. The corrected values for saturated hydraulic conductivity were considered to estimate the runoff rate of excessive water occurring in seedling containers during cool fall rains on the hardening fields in tree nurseries.

For measurements of bulk density and water retention, peat samples were filled loosely into 250 cm^3 open ended metal cube containers (63 × 63 × 63 mm). The bottoms of the cubes were first sealed with polypropylene netting containg holes 1 mm in diameter. The samples were compressed in the same way as the cylinder samples in the determination of saturated hydraulic conductivity and were then allowed to become saturated for two days in free water, the level of which was kept just below the midlevel of the cubes. To ensure complete saturation, additional water was also sprayed from above occasionally. After saturation, the samples were weighed and their volume was measured with a ruler to a precision of 0.5 mm. This mass was considered to correspond to water retention at the matric potential of –0.1 kPa. The measured volume was used to calculate bulk density.

Water retention characteristics were measured after saturation of the cube samples using a pressure plate apparatus (Soil Moisture Equipment Corp., USA). Matric potentials of –1, –5, –10, –50 and –100 kPa were applied successively over the cube samples until water had ceased flowing from the pressure chambers (about 2 weeks). After rewatering, the same samples were used in all successive applications of decreasing matric potential (Heiskanen 1990). After each matric potential application, samples were weighed and their volume was determined by measuring shrinkage in vertical and horizontal directions with a ruler to a precision of 0.5 mm. The shrinkage of the samples at the applied matric potentials was determined as relative volume to volume at –0.1 kPa. After the masses and volumes of samples at –100 kPa had been determined, the samples were dried at 105 °C until they reached constant mass (24 h), and their dry masses were then weighed.

At –1500 kPa, water retention was measured separately from parallel samples that had been saturated and filled into plastic rings ($d = 50$ mm, $h = 10$ mm). Shallow sample rings were used to ensure contact between the ceramic disk and the samples as well as faster cessation of the slow water flow from the samples. Shrinkage could not be measured. Volumetric water retention (%) at each matric potential was determined using Formula 3 (e.g. Hillel 1971), which gives values in relation to the saturated peat volume (≈ container volume). If needed, water retention can be transformed to a transient peat volume basis at different matric potentials by dividing water retention with the shrunk peat volume (as a proportion of the saturated volume).

$$\theta i = (((Mi - Ms) / Dw) / (Ms/Db)) \cdot 100. \qquad (3)$$

In order to estimate the tray (sample) effect within batches (greenhouses), the random measurement error was estimated using separate data. These data were collected by subsampling main samples randomly from each producer and grade combination (sheet and chip peat excluded). Each combination of subsamples consisted of 6 to 10 samples. Every different combination was collected for each 3 final matric potential level (–1, –10, –100 kPa) to be measured. The samples were handled and measured as described earlier for the main material until the last matric potential to be applied. Then the samples were measured twice after the two successive applications of the last matric potential. The difference between the two measurement values could then be determined. To save time in the laboratory determinations, the subsampling and reduced number of measured matric potentials were used.

2.3 Statistical methods

2.3.1 Estimation of the effects of sources of variation

Variation in the water retention characteristics was analyzed using mixed linear models (Searle 1971, Sokal and Rohlf 1981). The water retention characteristics of peat growth media were assumed to differ according to producers, sieving grades, production batches and individual trays. The effect of the producer is due to peat bogs used for harvesting as well as to all handling and storage specific for a given producer before sieving and packing of the peat. The grade effect is due to the sieving method. The batch effect appears in peat variations between greenhouses in nurseries and is due to differences within production fields and peat storage stacks as well as to differences in handling of peat during production and filling into seedling trays. The tray effect includes variation in peat between trays within batches (greenhouses).

In mixed linear models in general, the effects of specific classes or treatments are regarded as fixed effects. Random effects, on the other hand, are assumed to be random samples from the population of the variable (Searle 1971, Sokal and Rohlf 1981). Therefore, the effects of producer and grade were considered to be fixed and those of batch and tray random. Differences in grades and sieving methods of different producers were estimated using the producer and grade interaction. The effects of batch and tray were nested hierarchically within the higher effects. Tray effect was included into residual effect, which was also expected to include measurement errors. The total variation in an individual tray was thus described using mixed linear Model 4.

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_{ij} + d_{(ij)k} + e_{(ijk)l}, \qquad (4)$$

where

y_{ijkl} = value in an individual tray,
μ = general mean,
α_i = producer effect, (i = 1 Vapo, i = 2 Kekkilä)
β_j = grade effect (j = 1 coarse, j = 2 medium),
γ_{ij} = interaction between producer and grade,
$d_{(ij)k}$ = random batch effect within grade and producer, $E(d_{(ij)k}) = 0$, $var(d_{(ij)k}) = \sigma^2_d$,
$e_{(ijk)l}$ = random residual effect within batch, grade and producer, $E(e_{(ijk)l}) = 0$, $var(e_{(ijk)l}) = \sigma^2_e$, $cov(d_{(ij)k}, e_{(ijk)l}) = 0$.

Variation in the results for measurement of water retention characteristics was increased by random and systematic measurement errors. Systematic errors, however, could not be estimated and were assumed to be negligible. The random measurement errors were included into the residual effect $e_{(ijk)l}$ of Model 4. Hence, in order to estimate the actual tray effect within batches, the random measurement errors should first be estimated and then subtracted from the residual effect. The effect of random measurement error was estimated using the following procedure.

Any value y_1 of a first water retention measurement at a matric potential level was assumed to include a true value z_1 and a random measurement error e_{m1}, i.e. $y_1 = z_1 + e_{m1}$. The second successive value for measurement of the same sample at the same matric potential was expressed correspondingly: $y_2 = z_1 + \delta + e_{m2}$, where δ is an assumed difference between the successive measurement values due to structural changes in the medium during the second application of matric potential and measurement. e_{m1} and e_{m2} were assumed to be uncorrelated and to have equal variances. Therefore, the difference D between the two successive measurements was described by Equation 5.

$$D = y_2 - y_1 = \delta + (e_{m2} - e_{m1}), \qquad (5)$$

where

$E(e_{m2} - e_{m1}) = 0$, $cov(e_{m1}, e_{m2}) = 0$,
$var(e_{m2} - e_{m1}) = var(e_{m1}) + var(e_{m2}) = 2var(e_m)$
$= 2\sigma^2_{em}$.

Structural changes during the second successive measurement were expected to be dependent on the same variation sources as the water retention. Thus, the values of δ depended on producer, grade, batch and tray. Therefore, δ was expressed by Model 6.

$$\delta_{ijkl} = \mu' + \alpha'_i + \beta'_j + \gamma'_{ij} + d'_{(ij)k} + e'_{(ijk)l}, \qquad (6)$$

where the accented letters indicate the same effects as those in the Model 4, $var(e') = \sigma^2_{e'}$.

By combining Models 5 and 6, D was expressed further by Model 7.

$$D_{ijkl} = \mu' + \alpha'_i + \beta'_j + \gamma'_{ijj} + d'_{(ij)k} + \varepsilon_{(ijk)l}, \qquad (7)$$

where

$\varepsilon_{(ijk)l} = e'_{(ijk)l} + e_{m(ijk)l2} - e_{m(ijk)l1}$,
$var(\varepsilon) = \sigma^2_\varepsilon = \sigma^2_{e'} + 2\sigma^2_{em}$.

Variance var(ε) was estimated by computing Model 7 with the separate data for measurement error. Var(e') was considered = 0, when an estimate for the variance of random measurement error was obtained from the equation $\mathrm{var}(e_m) = \mathrm{var}(\varepsilon)/2$. The procedure used yielded an estimate (giving on average overvalues) for the random measurement error in which the effects due to variations in peat material were excluded as far as possible.

General Model 4, which contained the main data, previously yielded the variance of the residual effect within batches var(e), which was the sum of the variances of random measurement error, $\mathrm{var}(e_m)$, and the effect of trays within batches, $\mathrm{var}(e_s)$. Thus, an estimate (giving on average undervalues) of the variation due to trays within batches was determined from Equation 8.

$$\mathrm{var}(e_s) = \mathrm{var}(e) - \mathrm{var}(\varepsilon)/2. \qquad (8)$$

2.3.2 Data analysis

One way analysis of variance and Tukey's test were applied to evaluate the differences between the compared group means. Group means and standard deviations of the variables were calculated for each producer and grade combination from batch means (i.e. trays combined within greenhouses). Batch means were used as independent observations, because trays were dependent on each other within batches (see Model 4). Levene's test was used to test the homogeneity of variances. The F-test and Tukey's pairwise comparisons were also used when variances were unequal, because the obtained significance values were close to those achieved with the Brown-Forsythe test, which does not have the requirement of equal variances.

Mixed effect linear models were used in order to analyze further the sources of variation for the water retention characteristics of the conventionally graded peat media in nurseries (sheet and chip peat excluded). In order to express the effects on the same scale and units as the variables used, the fixed effects were presented as deviations from the general mean and the random effects as standard deviations.

Correlation coefficients were calculated to assess linear relationships between variables ($n = 20$). Stepwise regression analysis was also used to find the best predicting regression equations for the dependent variables. Data were analyzed using BMDP-software (7D, 1R, 2R, 3V, 8V) (BMDP... 1990).

3 Results

3.1 Physical properties of peat media

All the peat media studied were made up mainly of particles in size classes < 1 and 1–5 mm (Table 1). The amount of particles > 20 mm was negligible. The amount of particles 10–20 mm was also scant. Some of the particles > 1 mm were found to be aggregates, most of which were in the class 1–5 mm. In terms of particle size distribution, the grades of Producer 1 (Vapo Corp.) deviated from each other only slightly. The grades of Producer 2 (Kekkilä Corp.) had a more marked difference in particle size distribution. The medium grade contained, on an average, more particles < 1 mm than the coarse grade did. Because they contained more particles < 1 mm, both grades of Producer 1 were clearly finer than those of Producer 2. The grades of Producer 2 also contained, on average, slightly more particles 1–5 mm. For particles < 5 mm, however, the standard deviations of Producer 2 were as much as 4 times greater than those of Producer 1. The sheet peat clearly had the least amount of particles < 1 mm.

The particle density of the peat media did not differ from each other significantly (Table 2). However, the particle density was consistent within both producers of the conventionally graded peat (sheet and chip peat excluded). Particle density tended to increase as the amount of particles 5–10 mm increased (Appendix 1). Bulk density was also relatively consistent within producers (Table 2). The bulk density of chip peat was significantly lower than that of the other peat media. The greater the amount of particles < 1 mm or the less particles 1–5 mm, the greater was the bulk density (Appendix 1). Bulk density was not, however, significantly related to particle density.

Loss on ignition varied only slightly (Table 2).

Table 1. Means and standard deviations (%, M M^{-1}) for particle size (mm) of the peat media calculated from means of five peat batches. Data for sheet and chip peat were calculated from six samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	F < 1	F1–5	F5–10	F10–20	F > 20
Coarse1	62.5±3.4a	28.3±4.7ab	6.7±1.3a	2.2±1.7ab	0.2±0.4a
Medium1	62.6±3.5a	24.3±1.3a	10.0±1.3ab	2.8±2.6ab	0.4±0.6a
Coarse2	38.7±12.2b	44.5±13.0bc	11.2±0.6ab	5.2±1.8a	0.4±1.0a
Medium2	51.8±13.1ab	35.5±13.4abc	10.5±2.1ab	2.2±1.0ab	0.0±0.0a
Sheet	24.0±4.4c	51.8±14.9c	21.2±16.3b	2.9±2.9ab	0.2±0.2a
Chip	38.7±2.3b	52.7±2.6c	8.6±1.2ab	0.0±0.0b	0.0±0.0a
p	< 0.00005	0.0001	0.036	0.009	0.545

Table 2. Means and standard deviations for particle (Dp) and bulk (Db) densities, loss on ignition (Il) and saturated hydraulic conductivity (Ks) of the peat media calculated from means of five peat batches. Data for sheet and chip peat were calculated from six samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	Dp, g cm^{-3}	Db, g cm^{-3}	Il, % M M^{-1}	Ks, mm min^{-1}
Coarse1	1.63±0.03a	0.087±0.005a	94.4±0.3a	0.9±0.4a
Medium1	1.63±0.03a	0.080±0.005ab	95.3±0.6ac	3.1±1.2b
Coarse2	1.67±0.02a	0.072±0.001b	95.6±0.6ac	1.2±0.6ab
Medium2	1.67±0.04a	0.073±0.009b	93.1±0.8b	1.5±0.4ab
Sheet	1.60±0.05a	0.085±0.005a	95.6±0.4c	2.5±1.6ab
Chip	1.66±0.04a	0.057±0.005c	95.4±0.8ac	5.2±1.4c
p	0.052	< 0.00005	< 0.00005	< 0.00005

The lowest loss on ignition was found in the medium grade peat of Producer 2. The loss on ignition (hence also the ash content) was not clearly dependent on particle size or on particle and bulk densities (Appendix 1). Compared to the other variables, saturated hydraulic conductivity had relatively large standard deviations with respect to the means (Table 2). Saturated hydraulic conductivity was significantly higher for chip peat than for the other peat media. There was also a significant difference between the grades of Producer 1. The hydraulic conductivity tended to increase with the water retention at –0.1 to –100 kPa; but it was not highly correlated with particle size distribution or particle and bulk densities (Appendix 1).

The total porosity of the peat media varied relatively little (Table 3, Fig. 1). However, the total porosity of chip peat was clearly the greatest. The highest average water retention at –0.1 kPa matric potential was found in the peat of Producer 1. The sheet peat had significantly the lowest water retention, despite the fact that its standard deviation was the greatest. At –1 kPa matric potential, the peat of Producer 1 continued to retain more water than that of Producer 2. Again, the sheet peat retained the least amount of water. Furthermore, the water retention of the chip peat was further at about the same level as the peat of Producer 2. At –1 kPa, the standard deviations for water retention were relatively large compared to those at the other matric potentials measured.

At –5 kPa, the differences in water retention characteristics between the peat media decreased (Table 3, Fig. 1), and only the sheet and chip peat differed significantly from each other. At –10 kPa, the water retention of all the peat media was very similar and did not differ significantly between media. At –50 kPa, the differences were

Table 3. Means and standard deviations for total porosity (%) and water retention characteristics (%) of the peat media calculated from means of five peat batches. Data for sheet and chip peat were calculated from ten samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	Vf	θ0.1	θ1	θ5	θ10	θ50	θ100	θ1500
Coarse1	94.6±0.4a	91.2±2.2ab	70.3±5.9a	36.9±1.9ab	30.6±1.2a	24.5±0.8ac	24.1±0.9ac	16.4±1.7ab
Medium1	95.1±0.3ab	93.0±1.2a	71.7±3.0a	36.6±1.0ab	31.1±1.0a	25.5±1.0a	24.7±1.0a	14.3±0.5a
Coarse2	95.6±0.1bc	86.8±2.7b	63.3±6.9ac	36.3±3.0ab	29.9±2.5a	20.0±0.9b	19.3±0.8b	13.4±0.5a
Medium2	95.7±0.4c	89.9±2.3ab	63.6±3.5ac	36.2±2.5ab	30.6±1.7a	21.2±2.0bc	20.7±2.2bc	14.6±2.6a
Sheet	94.9±0.3a	78.8±5.2c	42.0±2.6b	34.2±2.2a	31.2±1.7a	29.1±2.6d	27.7±2.1d	18.0±2.7b
Chip	96.7±0.2d	89.6±1.7ab	58.5±9.4c	38.9±2.9b	32.4±2.7a	22.7±2.7b	21.1±2.0b	7.8±0.5c
p	< 0.00005	< 0.00005	< 0.00005	0.007	0.275	< 0.00005	< 0.00005	< 0.00005

again greater. The sheet peat retained significantly greater amount of water than the other media did. The peat of Producer 1 with the chip peat retained, on average, more water than the peat of Producer 2. The water retention of each medium at –100 kPa was only slightly lower than at –50 kPa. At –1500 kPa, the chip peat retained the least water. The sheet peat retained, on average, the most water. No significant differences existed between the conventionally graded peat media.

The amount of water released at –1 kPa matric potential with respect to full saturation (θVf–1) was, on average, lower in the peat of Producer 1 than in that of Producer 2, although the differences were not significant (Table 4). Sheet and chip peat clearly had greater water release, which also differed significantly from the peat of Producer 1. The water retention in the range –1 to –10 kPa (θ1–10) was now greatest in the peat of Producer 1. It did not, however, differ significantly from the peat of Producer 2, but from the sheet and chip peat, which clearly retained the least water. The water retention between –10 and –50 kPa (θ10–50) was markedly lower than in the previous ranges. In this range, the peat of Producer 1 had significantly lower water retention than that of Producer 2. The sheet peat retained water only slightly. In the lowest matric potential range (–50 to –1500 kPa), the water retention was comparable to θ10–50 and the peat of Producer 2 had the lowest average water retention.

The volume of the peat media at desorption was, on average, 0–16 % smaller than at saturation (Table 5). The sheet and chip peat usually shrank significantly less than the conventional peat grades did. After application of the –1 kPa

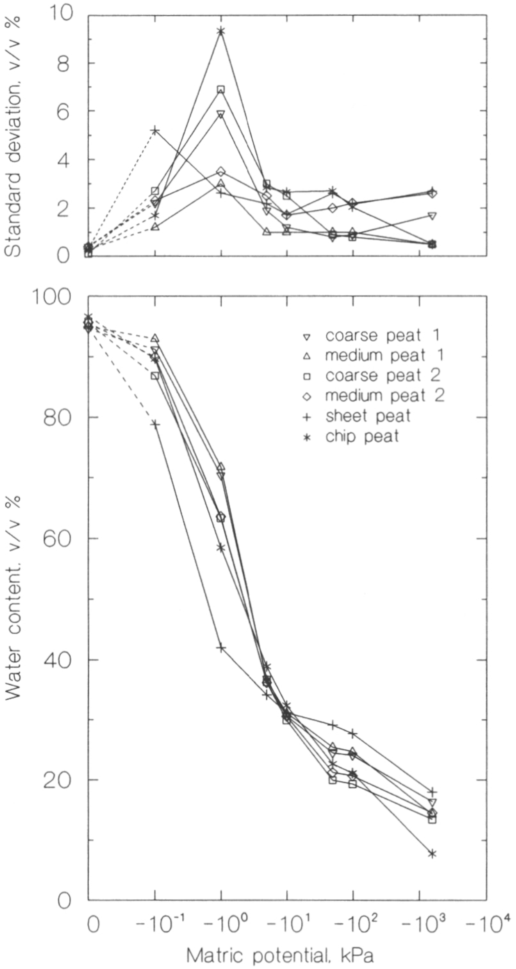

Fig. 1. Mean water retentions and their standard deviations in the peat growth media at different matric potentials at desorption (from Table 3).

Table 4. Means and standard deviations for water retention characteristics (%) of the peat media within selected matric potential ranges calculated from means of five peat batches. Data for sheet and chip peat were calculated from ten samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	Vf–1	θ1–10	θ10–50	θ50–1500
Coarse1	24.3±5.6a	39.7±5.1a	6.2±0.7a	8.1±1.7ab
Medium1	23.3±3.0a	40.6±3.3a	5.7±0.3a	11.2±1.3ac
Coarse2	32.3±7.0ac	33.4±5.5ac	9.9±1.7b	6.5±0.8b
Medium2	32.1±3.7ac	33.0±2.3ac	9.3±1.0b	6.7±0.7b
Sheet	54.0±2.6b	10.9±1.7b	2.1±1.4c	11.1±2.6ac
Chip	43.4±10.4bc	26.1±7.1c	9.7±1.8b	14.3±2.7c
p	< 0.00005	< 0.00005	< 0.00005	< 0.00005

Table 5. Mean shrinkages (%) of the peat media at desorption expressed as relative volumes to volume at –0.1 kPa (= 100%). Values are means and standard deviations calculated from means of five peat batches. Data for sheet and chip peat were calculated from ten samples of a batch. Different letters indicate significant difference ($p < 0.05$, Tukey Studentized range test).

Peat medium	V1	V5	V10	V50	V100
Coarse1	88.2±3.9a	88.6±1.3a	90.1±2.3a	88.2±2.6ac	86.4±1.6ab
Medium1	88.9±2.0a	90.4±1.4a	91.9±1.5ac	89.5±2.1ac	89.7±0.9a
Coarse2	85.8±1.2a	86.7±2.8a	87.0±2.7a	84.9±1.3a	83.5±2.6b
Medium2	86.1±3.3a	88.6±4.6a	87.7±4.5a	86.8±4.6a	86.4±3.5ab
Sheet	98.6±3.4b	97.7±3.3b	99.1±3.5b	98.9±7.1b	99.8±3.5c
Chip	95.4±2.1b	95.1±2.1b	95.4±2.0bc	95.0±2.1bc	95.0±2.5d
p	< 0.00005	< 0.00005	< 0.00005	< 0.00005	< 0.00005

Table 6. Stepwise calculated regression equations, root mean square errors (RMSE) and adjusted coefficients of determination (R^2) describing the relationships between water retention charcateristics and other physical peat properties. Batch means were used as independent observations ($n = 20$).

Variable	Equation	RMSE	R^2
θ0.1	82.62 + 0.1411 (F < 1)	2.47	0.34
θ1	76.14 – 0.5806 (F1–5)	5.37	0.23
θ5	59.40 – 0.2239 (F < 1) – 0.3266 (F1–5)	1.68	0.35
θ10	33.05 – 0.084 (F1–5) + 1.059 (F> 20)	1.19	0.46
θ50	7.03 – 0.1059 (F < 1) + 128.74 (Db)	1.43	0.70
θ100	5.52 – 0.0989 (F < 1) + 145.43 (Db)	1.41	0.71
θ1500	50.99 + 166.64 (Db) – 0.5213 (Il)	1.03	0.68
θVf–1	18.25 + 0.2943 (F1–5)	5.45	0.26
θ1–10	42.84 – 0.1854 (F1–5)	4.95	0.13
θ10–50	–275.43 + 2.9611 (Vf) + 0.3766 (F10–20)	1.31	0.64
θ50–1500	–78.35 + 0.0821 (F < 1) + 0.8671 (Il)	1.82	0.32
Ks	–7.99 – 0.0061 (F1–5) + 0.0877 (Vf)	0.096	0.21

matric potential, the peat volume did not alter greatly during further desorption. The more water was retained, the less was the measured shrinkage in the conventional peat grades (Appendix 1). The more particles < 1 mm or the less particles 1–5 mm there were, the less was the shrinkage.

In general, the greater the amount of particles < 1 mm, the greater was also the water retention at different matric potentials (Appendix 1). The water retention decreased with the amount of 1–5 mm particles. The total porosity decreased with particles < 1 mm and increased with particles 1–5 and 5–10 mm. The air space at –1 kPa (θVf–1) and the amount of water retained between –10 and –50 kPa matric potentials also decreased when the amount of particles < 1 mm increased. Particles 1–5 mm had the opposite effect. Retained water in the matric potential ranges –1 to –10 kPa and –50 to –1500 kPa increased when particles < 1 mm increased or particles 1–5 mm decreased. The increase in loss on ignition (i.e. decrease in ash content) tended to decrease the water retention at –1500 kPa (Appendix 1).

The water retention characteristics could be predicted fairly well from the used physical properties of peat, since the root mean square errors (standard errors of the estimates) of the multiple regression equations were relatively low (Table 6). However, the water retention could be predicted less accurately at high matric potentials than that at lower matric potentials. At high matric potentials, the fine particle size fractions (< 5 mm) predicted best. With decreasing matric potentials, bulk density became more important. Loss on ignition was also a significant factor in predicting water retention at –1500 kPa. The water contents retained within the selected matric potential ranges were more poorly predictable than at the individual potentials. The root mean square errors with respect to the means were over ten times higher than those at the single matric potentials.

3.2 Effects of sources of variation on water retention characteristics

The greatest effect on the water retention characteristics was, in general, the residual effect (variation within batches) (Figs. 2, 3, Appendices 2, 3). At –50 and –100 kPa, the deviation from the general mean due to producer was, however, even greater than the standard deviation of the residual effect. Water retention differed statistically significantly ($p < 0.05$) between producers. The producers did not, however, differ significantly from each other at –5, –10 and –1500 kPa (see also Fig. 1). The grades were also not statistically different nor were there interactions between producer and grade. The batch effect was, however, relatively large at matric potentials between –5 and –1500 kPa. At matric potentials > –5 kPa, the batch effect was relatively less. The greatest variation in water retention was at –1 kPa (see also Table 3, Fig. 1) to which the residual effect contributed most.

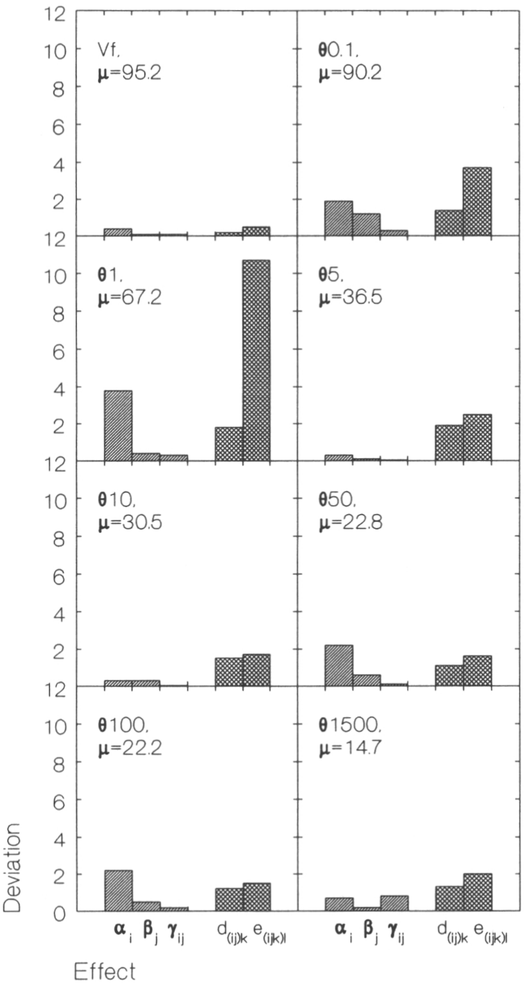

Fig. 2. General means (μ), fixed effects (as absolute values for deviations from the general mean) and random effects (as standard deviations) of water retention characteristics (from Model 4).

Within all the selected matric potential ranges,

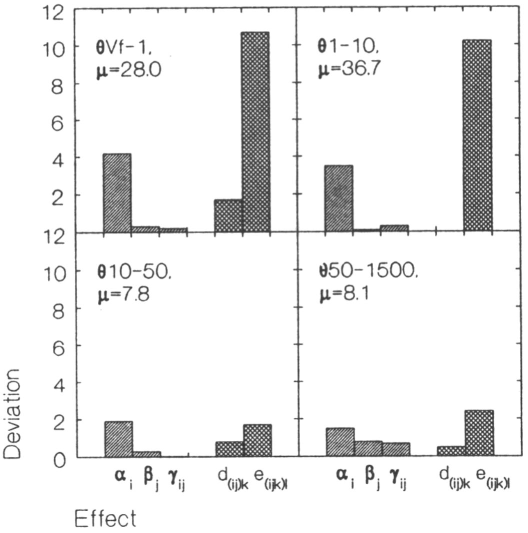

Fig. 3. General means (μ), fixed effects (as absolute values for deviations from the general mean) and random effects (as standard deviations) of water retention characteristics within selected matric potential ranges (from Model 4).

the water retention differed significantly between producers (Fig. 3, Appendix 3). It also differed between grades but only in 50–1500, at which range an interaction also existed between producer and grade. The batch effect was rather small compared with the residual effect.

The residual variation (variation within batches) made up the greatest part of the total variation in water retention at –1 kPa (Figs. 2, 3, Appendices 2, 3). The tray effect within batches was markedly higher than the random measurement error (Table 7), which accounted for a slightly higher effect on the total variation than the batch effect did (Fig 2). At –10 kPa, the greatest source of variation was also the residual effect. However, the measurement error clearly had a greater effect on variation within batches than the tray effect did (Table 7). The measurement error had about as great effect on the total variation as the batch did (Fig. 2). At –100 kPa, the residual variation was relatively less than at –1 and –10 kPa, but was still clear. The greater source of variation within batches was again the tray effect (Table 7). The effect of measurement error was clearly lower than that of batch (Fig. 2). The decrease in the average difference between successive measurements at –1 to –100 kPa indicates that the peat structure was compacted, which caused the amount of retained water to increase during the second measurement (Table 7).

Table 7. Means (μ), mean differences of two successive measurements (diff, % units) and standard deviations (Sd) of measurement error (e_m), tray effect (e_s) and total effect within batches (e) of selected water retention characteristics (from Model 8).

Variable	μ	diff	Sd (e_m)	Sd (e_s)	Sd (e)
θ1	67.2	3.0	2.4	10.4	10.7
θ10	30.5	0.3	1.6	0.6	1.7
θ100	22.2	–0.7	0.6	1.4	1.5

4 Discussion

4.1 Physical properties of peat media

All grades of conventional peat media analyzed in this study were finer than defined by Nordic standards (Puustjärvi 1982a). This may be because the particles comminuted or deaggregated after sieving or because of inappropriate sieving methods used by the producers. Only the sheet peat contained less than 30 % particles < 1 mm and hence only it can be considered coarse. The coarse peat of Producer 2 and the chip peat were medium grade. The rest of the peat media were fine grade since they had less than 70 % but more than 40 % particles < 1 mm. The sheet and chip peat media were coarser than the conventional peat grades. This likely was partly due to the fact that these peat media were taken into the study from packages without comminution or deaggregation with handling at nurseries. In addition, the sheet peat material indeed consisted of rather coarse fibres of cotton-grass and *Sphagnum* mosses and the chip peat consisted of compressed peat aggregates. It is likely that these peat materials do not so easily tend to become finer after manufacture. The sheet peat can be considered to be the coarsest, since it had more particles in size class 5–10 mm than the other media did.

The rather consistent particle density of each producer indicates that the peat material of a given producer had relatively similar density of plant remains due to the specific particle size fractions or moss composition of the bogs from which the peat was harvested. The particle density of the peat media was comparable to the values presented in the literature (Puustjärvi 1969, Heiskanen 1992). The particle density of natural bog peat has been reported to be slightly lower (Päivänen 1973) than that of the peat growth media. The premix-fertilization probably increased the particle density of the peat media. The ashless particle density calculated for the peat growth media was about 1.55 g cm^{-3} (see Heiskanen 1992). The bulk density was comparable to that given in the literature for light peat (Puustjärvi 1969, Päivänen 1969, 1973, Verdonck et al. 1983, Heiskanen 1990). The loss on ignition was somewhat lower than that reported for natural *Sphagnum* peat (Päivänen 1969, 1973). The ash content of the media was probably also increased by fertilizers.

The saturated hydraulic conductivity of the peat media studied was comparable to values reported by Puustjärvi (1982c). The values reported by Korpijaakko and Radforth (1972) and Päivänen (1973) for natural *Sphagnum* peat (H1–3) were also consistent with the present results. However, the quoted results have been determined at higher temperature (≥ 15 °C). The values for saturated hydraulic conductivity may be very close to those for unsaturated (at –4 kPa) hydraulic conductivity (Heiskanen 1993b). At persistent full saturation, the low hydraulic conductivity may be due to low permeability of the pores, because the peat colloids have probably swollen more and hence blocked more of the pores than at desorption just after transient saturation.

The values for total porosity of the peat growth media agreed with values presented in the literature (e.g. Puustjärvi 1969,1973, Verdonck et al. 1983). The sheet and chip peat were coarser than the other media and they thus had clearly greater air filled porosity at –1 kPa. In addition, the lower shrinkage of the sheet and chip peat compared with the other peat media probably contributed to their differing water retention. The water retention of the conventionally graded peat media was comparable to that of similarly compressed and graded peat (Heiskanen 1990) and to that of uncompressed, medium grade peat (Puustjärvi 1973) (Table 8). The water retention of uncompressed, coarse grade peat was, however, lower, which was caused by the fact that the peat media studied here were compressed and finer than the coarse grade defined by Nordic standards (Puustjärvi 1973, 1982a). The water retention of a coarse, uncompressed but compacted, peat growth medium was clearly greater at > –10 kPa (Mannerkoski 1985).

The water retention of the conventionally graded peat was relatively close to that of undisturbed, natural *Sphagnum* bog peat (Päivänen 1973) (Table 8). The standard deviations at different matric potentials were also comparable to those of natural bog peat. The water retention of bog peat at –1500 kPa is, however, somewhat lower than that achieved here. This was probably caused by the presence of more fine particles in the peat growth medium than in undisturbed bog peat. Forest humus layers retained less water at < –1 kPa than the conventionally graded peat growth media did (Heiskanen 1988) (Table 8). The humus material can be considered to be somewhat coarser than the conventional peat grades because of its greater air filled porosity at –1 kPa (θVf–1) (31–50 %). In addition, the humus material is probably more heterogeneous, because the standard deviations in the water retention values were greater than in the peat growth media. Mineral soils and nursery soils based on mineral soils commonly have lower total porosity and retain less water than peat (Päivänen 1973, Westman 1983).

The shrinkage of the peat media at desorption was generally somewhat less than that reported in earlier studies. This may be partly due to the compression that preceded desorption. The volume of relatively dry, loose, low humified *Sphagnum* peat may be up to 25 % lower than when it is wetted (Puustjärvi 1969, 1973, Bunt 1988). Shrinkage of natural *Sphagnum* peat (Db < 0.06) from field moist to oven dry is about 40 % (Päivänen 1982). Shrinkage and compaction tend to decrease the amount of coarse pores and increase that of fine pores, which further affect the water retention and aeration characteristics of peat (Puustjärvi 1973, Langerud 1986, Heiskanen 1990).

It was shown in this study that fine particles (< 1 mm) increased and particles 1–5 mm decreased the water retention characteristics measured. Furthermore, particles < 1 mm decreased and particles 1–5 mm increased the air space at

Table 8. Comparison of bulk density (g cm^{-3}) and water retention characteristics (%) of peat growth media, natural *Sphagnum* bog peat, forest humus layer and open nursery soils.

Reference	Medium	Db	Vf	θ0.1	θ1	θ5	θ10	θ50	θ100	θ1500
	Sphagnum peat media:									
This study	compressed, medium and coarse*	0.07–0.09	95–96	87–93	63–72	36–37	30–31	20–26	19–25	13–16
Puustjärvi 1973	uncompressed, coarse	0.04	97	-	48	23	18	-	-	-
Puustjärvi 1973	uncompressed, medium	0.07	96	-	70	39	29	-	-	-
Mannerkoski 1985	compacted, coarse*	0.07–0.09	-	-	80–90	45–60	35–45	20–25	18–20	-
Heiskanen 1990	compressed, coarse*	0.08–0.09	-	88–93	72–85	-	29–30	-	18–25	-
Päivänen 1973	Natural *Sphagnum* bog peat	0.04–0.07	95–97	92–95	60–91	-	25–49	20–35**	17–30	8–10***
Heiskanen 1988	Forest humus layer	0.09–0.16	91–94	69–83	44–60	-	27–37	-	25–33	14–15
Westman 1983	Nursery soils	0.8–1.4	44–68	-	-	-	21–42	-	-	3–10

*grade specified by manufacturer, ** interpolated, *** extrapolated

–1 kPa. Puustjärvi (1973, 1982b) has also shown that the increase of particles < 1 mm in uncompressed peat growth medium increases water retention at –1 kPa and hence decreases the air space (θVf–1). Particles > 6 mm, on the other hand, clearly increase the air space (Puustjärvi 1973, 1982b). Bulk density of the peat media studied increased water retention more clearly when the matric potential was lower (< –50 kPa). In addition, loss on ignition decreased water retention at –1500 kPa.

The water retention characteristics could be predicted fairly well from the used physical properties of peat, although less accurately at high matric potentials. In addition, the water contents retained within the selected matric potential ranges could be predicted less accurately than at individual matric potentials. The water retention characteristics probably could be predicted more accurately if the heterogeneity of peat material could be measured better. In particular, the particle size fraction classes used in the peat quality standards are rather large and few. The peat particles were found to be concentrated in the finest (< 1 mm) sieving fraction, which is probably due to the fact that peat particles become finer after sieving at the time of manufacture and during transport and handling at nurseries. Hence, the effect of variation in particle size could be better described by also determining fractions finer than 1 mm.

4.2 Sources of variation in water retention characteristics

In general, the water retention characteristics of the conventional peat grades did not differ significantly. However, the peat media of different producers usually differed from each other. The producer and grade interactions were not, in turn, significant, except at –1500 kPa. These observations were due to the fact that the water retention characteristics for the different grades were, on average, about the same for a given producer, but tended to differ between producers. The particle size of the grades also differed between producers. In addition, it is possible that the properties of the peat material were characteristic for each producer due to the specific characteristics of the bogs from which the peat was harvested and due to the manufacturing procedure. The grades were rather similar to each other and were finer than those defined by the Nordic peat quality standards. Peat aggregation or deaggregation and comminution after sieving, compression into containers preceding desorption and shrinkage during desorption probably further decreased the effect of grade on water retention.

Batch clearly affected water retention characteristics at matric potentials < -1 kPa. The variations between peat batches may have been caused by differing peat properties (e.g. composition, humification, compaction) between peat harvesting areas and by variations in peat storage and handling over time. The batch effect was, however, lower than the residual effect within batches, which probably indicates that the peat manufacture within producers and peat handling in nurseries were rather alike over a longer period of time. The clearly greater variation within batches was due to tray effect, because variation within batches due to random measurement error was relatively low. Hence, the clear tray effect was caused mainly by the different properties of the peat before the actual manufacturing process. This may be due to natural variations within peat harvesting areas and changes during storage (e.g. self heating, aggregation, humification).

Although variations within trays were not determined, they may be considerable. To study the actual within tray variations of water retention characteristics, peat sampling from separate containers would be needed. The collection of a large number of sample replications from containers and the physical analyses of such small samples would, however, have been very laborious and difficult or even impossible.

The precision of the water retention measurement was relatively good. The random measurement error was small and had less effect than other sources of variation did. This was due to the relatively great variation in porosity and hence in water retention when the small measurement error did not appear. At -10 kPa, however, the measurement error was significant and was clearly greater than the tray effect. This was probably caused by the relatively low and stable amount of peat pores filled with water around -10 kPa, which further led to low variation in the amounts of water retained. Thus $\theta5\text{–}10$ and $\theta10\text{–}50$ were relatively small. At desorption, the decrease in the water retention curve around -10 kPa was also gentler (see Mannerkoski 1985). Furthermore, at -10 kPa the standard deviations were relatively small. Therefore, the effect of measurement error, which was relatively less at the other matric potentials, became distinct.

Variations in the water retention measurements may have been due to possible differences in initial degree of saturation, possible variations in sample handling and contact area between samples and ceramic disks, and possibly due to too short desorption times, which may have resulted in some incomplete equilibria of water content at different matric potentials. It is also possible that released peat colloids and precipitates, to some extent, blocked the ceramic disks at desorption altering desorption times and affecting the results. The temperature during measurement in the laboratory may have had an effect, but this was probably relatively small (Päivänen 1973).

Differences in measurement techniques may, on the other hand, markedly affect the results when the water retention characteristics of peat growth media are measured and interpreted. For example, sampling and sample handling during measurements have been shown to influence measurement results (Heiskanen 1990). Compression of peat affects porosity, which in turn affects water retention (Puustjärvi 1969, De Kreij and De Bess 1989). A compression of 10 g cm^{-2} may result in up to a 25 % decrease in volume in loose growth media made of *Sphagnum* peat (Heiskanen 1990). Premoistening and wetting methods may also cause differences in water retention (Puustjärvi 1969). Therefore, the results for determination of water retention characteristics may actually be comparable to those achieved by analogous methods (Heiskanen 1990).

4.3 Implications for seedling growth and irrigation

The significance of water retention in different matric potential ranges on the growth of tree seedlings and their irrigation depends on the phase of growth. If the period of controlled growing in greenhouses and the partly uncontrolled (incl. irrigation) hardening phase at the nursery is the main concern, only the water retention at high matric potentials (wet conditions) is of interest. As far as growth phases after the nursery (which may also include drier conditions) are concerned, lower matric potentials than those in the nursery phase must also be taken into consideration (see Heiskanen 1993a).

In wet conditions in particular, a large amount of air space is needed for sufficient aeration. Usually an air space of 20 % has been regarded as adequate for growth of tree seedlings in the open (Warkentin 1984, see also Heiskanen and

Raitio 1991). But in peat media, even 40–50 % has been considered to be favourable for horticultural plants (Puustjärvi 1973, 1975a, Penningsfeld 1974, see also Heiskanen 1993a). About 40 % may thus be assumed to be the minimum air space in peat media for satisfactory seedling growth. Excluding sheet and chip peat, the peat media studied had less air space at –1 kPa than the minimum requirement. If the matric potential is mostly < –3 kPa during growth, however, it cannot be considered that there was lack of air in any of the peat media studied (see Fig. 1).

The favourable matric potential range for tree seedlings can be considered to be –1 to –50 kPa. The best range in light peat media is probably narrower, within a range of about –1 to –10 kPa (Örlander and Due 1986a,b, Heiskanen 1993a). In the favourable range, the greater the amount of available water, the longer is the period before irrigation is needed. Therefore, it would be reasonable to have the easily available water retention (θ1–10) as high as possible, if sufficient oxygen is available. The easily available water retention was rather high in the conventional peat grades studied, but relatively low in the sheet and chip peat. The less easily available water retention (θ10–50) should also be sufficiently high for adequate water availability when this range of matric potential occurs persistently. Within this matric potential range, seedlings in the peat media studied may dry due to the rather low water retention. The harder available water retention (θ50–1500) can be regarded as a water reserve for seedlings in dry conditions such as after outplanting to a forest site. In the media studied this reserve was probably adequate.

Very unequal distribution of water retention into the matric potential ranges studied may cause inadequate water or oxygen to seedlings. Low water retention between saturation and –1 kPa means small air space and yields low aeration. High water retention within high matric potential ranges (i.e. large air space) may, on the other hand, cause low water retention at low matric potentials. For example, the excessive air space of the sheet peat at –1 kPa (54 %) lessened its ability to retain water at lower matric potentials when there was little (2 %) water available in the range of –10 to –50 kPa. A persistent period of matric potential in this range may thus cause seedlings to dry.

The wider the tolerance for regulating amounts of water and timing of irrigation, the easier it is to adjust irrigation. The greater the easily available amount of water and the less the variation in that amount of water, the wider this tolerance will be. Great variations in the water and aeration characteristics of peat have been found to cause variations in plant growth within a crop (Puustjärvi 1973, 1975a). The average amount of irrigation water needed to increase matric potential from –10 to –1 kPa (θ1–10) was 37 % of the volume in the conventionally graded peat media. In a 10 cm thick layer of peat, this irrigation need corresponds to 37 mm water. The time before –10 kPa is again reached in the peat media and irrigation is needed would be about 10 days, because the average rate of evapotranspiration in greenhouses is 2–4 mm a day (Rikala 1985). However, irrigation may be needed even earlier than when –10 kPa is reached, because the peat surface may become too dry to absorb a sufficient amount of water (see Heiskanen 1993b).

The estimated mean drying time of 10 days from –1 to –10 kPa and the corresponding mean amount of irrigation water, 37 mm, are relatively large, when irrigation is, in principle, fairly easily adjustable. However, the standard deviation of θ1–10 within greenhouses was also relatively large, about 10 %-units. This means a corresponding standard deviation of 10 mm in the water content retained in the 10 cm thick peat layer at –1 kPa after application of 37 mm irrigation water at –10 kPa. This relatively high standard deviation may increase the need for more accurate monitoring of irrigation in order to maintain water conditions within the favourable limits in the greenhouse. Large deviations from the average water retention at –1 kPa may hinder aeration in the peat media of seedling trays where the matric potential is higher than –1 kPa due to excessive water. In addition, the risk of hindering aeration may become greater when roots and compaction reduce the amount of coarse pores over time. Thus it may be more reasonable to irrigate less than the whole amount of water at a time and also irrigate more frequently so that aeration limit is not reached in most trays or even in any trays. For example, irrigation at –10 kPa to achieve only –3 to –5 kPa matric potential would not reach the aeration limit in the peat media. The irrigation water needed for the conventionally graded peat media studied here would, for the range –5 to –10 kPa, average about 7 mm with an average irrigation frequency of 3 days at ordinary evaporation rates. Very great variation in water retention within trays may still, however, cause problems in water or oxygen availability to seedlings in separate containers, even though the average irrigation level for trays (within greenhouse) would be determined correctly. Furthermore, different methods of irrigation may have a great effect on the distribution of water into trays and also within trays and containers. In addition, matric potential within an individual container varies vertically, even if the water retention characteristics do not vary (Heiskanen 1993a,b).

Under frequent irrigation in greenhouses and when exposed to rain on hardening fields, aeration may be a more limiting growth factor for seedlings than availability of water. In this case, a large volume of air filled, coarse pores at high matric potentials is needed. Sufficient volume of coarse pores (θVf–1) is especially needed also during growing periods longer than one year, because peat tends to compact and its air space be reduced over time (Puustjärvi 1975b, Langerud 1986, see also Mannerkoski 1982). In this respect, due to its coarse porosity, sheet peat probably best provides sufficient aeration. If irrigation is infrequent, seedlings are not exposed to free rain and the growing period is not longer than one year, a large air space at high matric potentials is not a main consideration. Instead, a large amount of available water in the growth medium, as indeed is for the conventionally graded peat media studied, is more important for seedling growth. The actual methods of irrigation and growth conditions under which seedlings are grown in individual containers are, however, the criteria which finally determine how the properties of media affect growth. Values for those water retention characteristics which are significant for seedling growth and irrigation should thus, in the intrest of accuracy, be determined for each condition separately.

Acknowledgements: In addition to the referees selected by the editor, the manuscript was read by Dr. H. Smolander, R. Rikala, M.Sc., A. Jalkanen, Lic.For, and Prof. H. Mannerkoski. Statistical methods were reviewed by J. Heinonen, M.Sc. and Drs. J. Lappi and H. Henttonen. The English language was revised by Dr. J. von Weissenberg.

References

BMDP Statistical software manual. 1990. Vols. 1–2. Univ. Calif. Press, Berkeley. 1385 p.

Bunt, A.C. 1988. Media and mixes for container-grown plants. 2nd ed. Unwin Hyman, London. 309 p.

Campbell, G.S. 1985. Soil physics with Basic. Transport models for soil-plant systems. Developments in Soil Science 14. Elsevier, Amsterdam. 150 p.

Currie, J.A. 1984. The physical properties in the seedbed. Aspects of Applied Biology 7: 33–54.

De Kreij, C. & De Bess, S.S. 1989. Comparison of physical analysis of peat substrates. Acta Horticulturae 238: 23–36.

Folk, R.S., Timmer, V.R. & Scarratt, J.B. 1992. Evaluating peat as a growing medium for jack pine seedlings. 1. Conventional quality indices. Canadian Journal of Forest Research 22: 945–949.

Heiskanen, J. 1988. Metsämaan vedenpidätyskyvystä ja sen suhteista eräisiin kasvupaikasta mitattuihin tunnuksiin. Lic. For. Thesis. Univ. Helsinki, Dept. Silviculture. 92 p.

— 1990. Näytelieriön täyttötavan vaikutus kasvuturpeen vedenpidätyskykyyn. Summary: The effect of sample handling on the water retention of growth peat substrate. Suo 41(4–5): 91–96.

— 1992. Comparison of three methods for determining the particle density of soil with liquid pycnometers. Communications in Soil Science and Plant Analysis 23(7–8): 841–846.

— 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. Water potential and hydraulic conductivity of peat growth media in containers during drying. Tiivistelmä: Kasvuturpeiden vesipotentiaali ja vedenjohtavuus kuivumisen aikana paakuissa. Silva Fennica 27(1): 1–7.

— & Raitio, H. 1991. Maan vesipotentiaali paljasjuuristen männyntaimien taimitarhakasvatuksessa. Summary: Soil water potential during the production of bare-rooted Scots pine seedlings. Silva Fennica 25(1): 23–36.

Hillel, D. 1971. Soil and water. Physical principles and processes. Academic Press, Orlando. 288 p.

— 1982. Introduction to soil physics. Academic Press, San Diego. 364 p.

Klute, A. & Dirksen, C. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute, A. (ed.). Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agronomy 9. Am. Soc. Agr. Soil Sci. Soc. Am. Publisher, Madison, Wisconsin. p. 687–734.

Korpijaakko, M. & Radforth, N.W. 1972. Studies on the hydraulic conductivity of peat. Proc. 4th Int. Peat Congr. Vol III. p. 323–333.

Kretzschmar, R. 1989. Kulturtechnisch-bodenkundliches Praktikum. Ausgewählte Laboratoriumsmethoden. Eine Einleitung zum selbständigen Arbeiten an Böden. 6. Aufl. Christian-Albrechts

Univ., Kiel. 514 p.

Kurki, L. 1985. Kasvuturpeen laadun merkitys. Turveteollisuus 4: 86–87.

Langerud, B.R. 1986. A simple in situ method for the characterization of porosity in growth media. Plant and Soil 93: 413–425.

Maa- ja metsätalousministeriön päätös eräiden lannoitevalmisteiden laatuvaatimuksista. 1986. Suomen asetuskokoelma n:o 384. Helsinki. p. 885–886.

Mannerkoski, H. 1982. Effect of tree roots on the bulk density of peat. Peat Society Commissions IV and II. Proc. Int. Symp., Minsk. p. 182–188.

— 1985. Effect of water table fluctuation on the ecology of peat soil. Tiivistelmä: Vedenpinnan vaihtelun vaikutus turvemaan ekologiaan. Univ. Helsinki, Publications from the Department of Peatland Forestry 7. 190 p.

Örlander, G. & Due, K. 1986a. Location of hydraulic resistance in the soil-plant pathway in seedlings of Pinus sylvestris L. grown in peat. Canadian Journal of Forest Research 16(1): 115–123.

— 1986b. Water relation of seedlings of Scots pine grown in peat as a function of soil water potential and soil temperature. Studia Forestalia Suecica 175: 1–13.

Päivänen, J. 1969. The bulk density of peat and its determination. Seloste: Turpeen tilavuuspaino ja sen määrittäminen. Silva Fennica 3(1): 1–19.

— 1973. Hydraulic conductivity and water retention in peat soils. Seloste: Turpeen vedenläpäisevyys ja vedenpidätyskyky. Acta Forestalia Fennica 129. 70 p.

— 1982. Physical properties of peat samples in relation to shrinkage upon drying. Seloste: Turvenäytteiden fysikaalisten ominaisuuksien suhde kutistumiseen kuivattaessa. Silva Fennica 16(3): 247–265.

Penningsfeld, F. 1974. Bases of production, examination and use of growth media. Acta Horticulturae 37: 1918–1921.

Puustjärvi, V. 1969. Fixing peat standards. Peat & Plant News 2(1): 3–8.

— 1970. Degree of decomposition. Peat & Plant News 4: 48–52.

— 1973. Kasvuturve ja sen käyttö. Turveteollisuusliitto r.y., Helsinki. 173 p.

— 1975a. Growth disturbances induced by low air space. Peat & Plant Yearbook 1973–1975. p. 17–19.

— 1975b. On the factors contributing to changes in peat structure in greenhouse culture. Peat & Plant Yearbook 1973–1975. p. 11–14.

— 1982a. Textural classes of horticultural peat. Peat & Plant Yearbook 1981–1982. p. 28–32.

— 1982b. The size distribution of peat particles. Peat & Plant Yearbook 1981–1982. p. 33–47.

— 1982c. Turpeen tasoituskastelu I. Puutarha 5: 256–257.

Rikala, R. 1985. Paakkutaimien kastelutarpeen määrittäminen haihdunnan perusteella. Summary: Estimating the water requirements of containerized seedlings on the basis of evaporation. Folia Forestalia 627. 18 p.

Searle, S.R. 1971. Linear models. John Wiley & Sons, New York. 532 p.

Sillanpää, M. 1956. Studies on the hydraulic conductivity of soils and its measurement. Acta Agralia Fennica 87: 1–109.

Sokal, R.R. & Rohlf, F.J. 1981. Biometry. The principles and practice of statistics in biological research. 2nd. ed. Wilt Freeman and Co, New York. 859 p.

Verdonck, O., Pennick, R. & De Boodt, M. 1983. The physical properties of different horticultural substrates. Acta Horticulturae 150: 155–160.

Westman, C.J. 1983. Taimitarhamaiden fysikaalisia ja kemiallisia ominaisuuksia ja niiden suhde orgaanisen aineksen määrään. Summary: Physical and physico-chemical properties of forest tree nursery soils and their relation to the amount of organic matter. Acta Forestalia Fennica 184. 34 p.

Warkentin, B.P. 1984. Physical properties of forest-nursery soils: Relation to seedling growth. In: Duryea, M.L. & Landis, T.D. (eds.). Forest nursery manual: Production of bareroot seedlings. Martinus Nijhoff, Dr. W. Junk Publishers, The Hague–Boston–Lancaster. p. 53–61.

Wilson, G.C.S. 1983. The physico-chemical and physical properties of horticultural substrates. Acta Horticulturae 150: 19–32.

Total of 44 references

Appendix 1. Correlation matrix of the measured variables of the conventionally graded peat. Batch means were used as independent observations (n = 20). In the case of bivariate normality, the smallest significant coefficient is 0.44 ($p < 0.05$).

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1 F < 1	1.00																									
2 F1–5	–0.96	1.00																								
3 F5–10	–0.34	0.12	1.00																							
4 F10–20	–0.46	0.23	0.44	1.00																						
5 F > 20	–0.13	0.02	0.08	0.38	1.00																					
6 Il	–0.10	0.04	–0.01	0.34	0.31	1.00																				
7 Ks	0.38	–0.43	0.16	–0.20	0.26	0.22	1.00																			
8 Dp	–0.34	0.23	0.62	0.17	0.09	–0.30	–0.11	1.00																		
9 Db	0.65	–0.64	–0.38	–0.08	0.03	–0.14	0.02	–0.16	1.00																	
10 Vf	–0.63	0.59	0.50	0.07	0.04	0.01	0.02	0.41	–0.95	1.00																
11 θ0.1	0.61	–0.57	–0.34	–0.28	0.09	0.02	0.51	–0.36	0.33	–0.32	1.00															
12 θ1	0.48	–0.52	–0.14	–0.01	0.26	0.11	0.45	–0.28	0.41	–0.41	0.62	1.00														
13 θ5	0.37	–0.51	0.26	0.18	0.35	0.01	0.27	0.21	0.33	–0.21	0.36	0.61	1.00													
14 θ10	0.49	–0.61	0.22	0.08	0.37	–0.01	0.42	0.15	0.31	–0.18	0.52	0.61	0.96	1.00												
15 θ50	0.80	–0.78	–0.30	–0.30	0.14	0.03	0.51	–0.32	0.75	–0.73	0.72	0.71	0.47	0.56	1.00											
16 θ100	0.80	–0.77	–0.33	–0.32	0.13	–0.02	0.45	–0.33	0.77	–0.76	0.70	0.68	0.46	0.54	0.99	1.00										
17 θ1500	0.60	–0.59	–0.24	–0.15	–0.10	–0.43	–0.11	–0.11	0.78	–0.75	0.09	0.28	0.37	0.34	0.55	0.61	1.00									
18 θVf–1	–0.52	0.55	0.18	0.01	–0.24	–0.11	–0.43	0.30	–0.47	0.47	–0.62	–0.99	–0.60	–0.60	–0.74	–0.72	–0.33	1.00								
19 θ1–10	0.41	–0.42	–0.23	–0.03	0.18	0.13	0.39	–0.37	0.38	–0.41	0.56	0.97	0.41	0.40	0.65	0.62	0.22	–0.97	1.00							
20 θ10–50	–0.59	0.48	0.53	0.42	0.11	–0.05	–0.30	0.50	–0.67	0.73	–0.47	–0.40	0.15	0.08	–0.78	–0.79	–0.41	0.44	–0.48	1.00						
21 θ50–1500	0.44	–0.43	–0.16	–0.23	0.25	0.39	0.69	–0.29	0.24	–0.23	0.77	0.60	0.24	0.38	0.72	0.67	–0.18	–0.60	0.58	–0.59	1.00					
22 V1	0.48	–0.53	0.13	–0.16	0.15	–0.01	0.31	0.09	0.43	–0.36	0.45	0.60	0.53	0.54	0.71	0.70	0.42	–0.60	0.52	–0.44	0.48	1.00				
23 V5	0.42	–0.48	0.29	–0.22	–0.15	–0.29	0.23	0.30	0.56	–0.42	0.14	0.20	0.26	0.29	0.59	0.60	0.54	–0.22	0.14	–0.50	0.25	0.68	1.00			
24 V10	0.56	–0.61	0.11	–0.20	0.17	0.01	0.39	–0.06	0.56	–0.50	0.43	0.46	0.51	0.56	0.76	0.77	0.48	–0.49	0.37	–0.50	0.50	0.75	0.72	1.00		
25 V50	0.54	–0.58	0.16	–0.29	0.07	–0.27	0.30	0.12	0.62	–0.51	0.32	0.41	0.41	0.44	0.72	0.73	0.57	–0.44	0.34	–0.53	0.37	0.81	0.87	0.84	1.00	
26 V100	0.63	–0.68	0.17	–0.26	–0.10	–0.19	0.51	0.06	0.52	–0.43	0.51	0.42	0.38	0.51	0.76	0.76	0.45	–0.44	0.33	–0.53	0.53	0.63	0.83	0.79	0.78	1.00

Appendix 2. General means (μ) and fixed effects (as deviations from the general mean) and standard deviations (Sd) of random effects of water retention characteristics (from Model 4).

Variable	μ	Cell, ij	α_i	β_j	γ_{ij}	$Sd(d_{(ij)k})$	$Sd(e_{(ijk)l})$
Vf	95.2	11	–0.4	–0.1	–0.1	0.2	0.5
		12	–0.4	0.1	0.1	0.2	0.5
		21	0.4	–0.1	0.1	0.2	0.5
		22	0.4	0.1	–0.1	0.2	0.5
θ0.1	90.2	11	1.9	–1.2	0.3	1.4	3.7
		12	1.9	1.2	–0.3	1.4	3.7
		21	–1.9	–1.2	–0.3	1.4	3.7
		22	–1.9	1.2	0.3	1.4	3.7
θ1	67.2	11	3.8	–0.4	–0.3	1.8	10.7
		12	3.8	0.4	0.3	1.8	10.7
		21	–3.8	–0.4	0.3	1.8	10.7
		22	–3.8	0.4	–0.3	1.8	10.7
θ5	36.5	11	0.3	0.1	0.04	1.9	2.5
		12	0.3	–0.1	–0.04	1.9	2.5
		21	–0.3	0.1	–0.04	1.9	2.5
		22	–0.3	–0.1	0.04	1.9	2.5
θ10	30.5	11	0.3	–0.3	0.05	1.5	1.7
		12	0.3	0.3	–0.05	1.5	1.7
		21	–0.3	–0.3	–0.05	1.5	1.7
		22	–0.3	0.3	0.05	1.5	1.7
θ50	22.8	11	2.2	–0.6	0.1	1.1	1.6
		12	2.2	0.6	–0.1	1.1	1.6
		21	–2.2	–0.6	–0.1	1.1	1.6
		22	–2.2	0.6	0.1	1.1	1.6
θ100	22.2	11	2.2	–0.5	0.2	1.2	1.5
		12	2.2	0.5	–0.2	1.2	1.5
		21	–2.2	–0.5	–0.2	1.2	1.5
		22	–2.2	0.5	0.2	1.2	1.5
θ1500	14.7	11	0.7	0.2	0.8	1.3	2.0
		12	0.7	–0.2	–0.8	1.3	2.0
		21	–0.7	0.2	–0.8	1.3	2.0
		22	–0.7	–0.2	0.8	1.3	2.0

Appendix 3. General means (μ) and fixed effects (as deviations from the general mean) and standard deviations (Sd) of random effects of water retention characteristics within selected matric potential ranges (from Model 4).

Variable	μ	Cell, ij	α_i	β_j	γ_{ij}	Sd($d_{(ij)k}$)	Sd($e_{(ijk)l}$)
θVf–1	28.0	11	–4.2	0.3	0.2	1.7	10.7
		12	–4.2	–0.3	–0.2	1.7	10.7
		21	4.2	0.3	–0.2	1.7	10.7
		22	4.2	–0.3	0.2	1.7	10.7
θ1–10	36.7	11	3.5	–0.1	–0.3	≈0	10.2
		12	3.5	0.1	0.3	≈0	10.2
		21	–3.5	–0.1	0.3	≈0	10.2
		22	–3.5	0.1	–0.3	≈0	10.2
θ10–50	7.8	11	–1.9	0.3	–0.02	0.8	1.7
		12	–1.9	–0.3	0.02	0.8	1.7
		21	1.9	0.3	0.02	0.8	1.7
		22	1.9	–0.3	–0.02	0.8	1.7
θ50–1500	8.1	11	1.5	–0.8	–0.7	0.5	2.4
		12	1.5	0.8	0.7	0.5	2.4
		21	–1.5	–0.8	0.7	0.5	2.4
		22	–1.5	0.8	–0.7	0.5	2.4

IV

Water Potential and Hydraulic Conductivity of Peat Growth Media in Containers during Drying

Juha Heiskanen

Silva Fennica 1993, Vol. 27 N:o 1: 1–7

Water potential and hydraulic conductivity of peat growth media in containers during drying

Juha Heiskanen

TIIVISTELMÄ: KASVUTURPEIDEN VESIPOTENTIAALI JA VEDENJOHTAVUUS PAAKUISSA KUIVUMISEN AIKANA

Heiskanen, J. 1993. Water potential and hydraulic conductivity of peat growth media in containers during drying. Tiivistelmä: Kasvuturpeiden vesipotentiaali ja vedenjohtavuus paakuissa kuivumisen aikana. Silva Fennica 27(1): 1–7.

The matric potential and unsaturated hydraulic conductivity of peat based growth media in containers was measured continuously as a function of drying. The particle size distribution and the water retention characteristics of the media were determined from parallel samples. The growth media used were a light, coarse graded *Sphagnum* peat, a medium graded *Sphagnum* peat and a mixture of a perlite and the medium graded *Sphagnum* peat. Containers of two types were packed with the media and allowed to evaporate from saturation. Matric potential was measured automatically using tensiometers during drying.

In both container types, the matric potential of the media was similar down to –10 kPa at each of the three levels measured during drying. Further drying resulted in a large matric potential gradient between the upper and middle levels. During drying, there was also clear shrinkage of the media. When the matric potential at the upper level reached c. –80 kPa, the decrease in height of the media was 5–23 %. The estimated hydraulic conductivity of the media during drying was rather similar. The hydraulic conductivity of the peat-perlite mixture was, however, slightly lower than that of the pure peat media. The hydraulic conductivity decreased linearly on a log-log-scale from c. 10^{-5} to less than 10^{-10} m/s as the matric potential decreased from –3 to –60 kPa. The hydraulic conductivity of the media was comparable to coarse sand at matric potentials below –10 kPa. The decrease in hydraulic conductivity during drying and the possible weakening of soil-root contact due to shrinkage may considerably affect the availability of water to plants.

Turvepohjaisten kasvualustojen vesipotentiaalia ja kyllästymätöntä vedenjohtavuutta mitattiin kuivumisen aikana taimipaakuissa. Edelleen määritettiin rinnakkaisnäytteistä kasvualustojen hiukkaskokojakauma ja vedenpidätyskyky. Kasvualustat olivat karkeaa ja keskikarkeaa vaaleaa rahkaturvetta sekä karkean perliitin ja keskikarkean turpeen seosta. Kasvualustat täytettiin ja tiivistettiin kahteen erityyppiseen paakkuun. Kasvualustojen kuivuessa mitattiin niiden matriisipotentiaalia tensiometrisesti kolmelta paakun vertikaalitasolta kyllästyskosteudesta alkaen kunnes tensiometrien mittausraja saavutettiin.

Kasvualustojen matriisipotentiaali oli kuivumisen edetessä lähes sama aina –10 kPa:iin asti kaikilla mittaustasoilla molemmissa käytetyissä paakkutyypeissä. Kuitenkin kuivumisen edetessä muodostui suuri matriisipotentiaali-gradientti pintakerroksen ja syvemmällä paakussa olevan kasvualustan välille. Kasvualustat myös kutistuivat selvästi kuivumisen aikana. Kasvualustojen kutistuma korkeussuunnassa oli 5–23 %, kun matriisipotentiaali oli n. –80 kPa pintakerroksessa. Kasvualustojen estimoitu vedenjohtavuus aleni matriisipotentiaalin alentuessa suhteellisen yhdenmukaisesti. Turpeen ja perliitin seoksen vedenjohtavuus oli kuitenkin hieman alhaisempi kuin puhtailla turvealustoilla. Vedenjohtavuus aleni log-log-asteikolla lineaarisesti n. 10^{-5}:stä alle 10^{-10}:een m/s, kun matriisipotentiaali aleni –3:stä –60:een kPa. Kasvualustojen vedenjohtavuus oli verrattavissa hiekkaan noin –10 kPa:a alemmilla matriisipotentiaalin arvoilla. Kasvuturpeen kuivuessa vedenjohtavuuden aleneminen sekä kutistumisen mahdollisesti aiheuttama maa-juuri -kontaktin väheneminen voivat heikentää merkittävästi kasvien vedensaatavuutta.

Keywords: matric potential, perlite, shrinkage, substrates, water availability.
FDC 181.3 + 114.1

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Accepted March 17, 1993

1 Introduction

The growth medium most commonly used in containerized plant production in the Nordic countries is light, low humified peat. In nurseries, containerized seedlings are under repeated and variable wetting and drying cycles during which water availability to seedlings may markedly change. Under dry conditions, peat has been reported to provide low water availability to tree seedlings (Örlander and Due 1986ab). Water availability and its dependencies upon the properties of various growth media are essential factors in determining correct nursery management practices (e.g. irrigation, shading, ventilation) and, thus, in promoting the growth and quality of seedlings.

Water uptake by a plant root is greatly affected by the force with which water is retained by the growth medium. This force is measured as the water potential of the growth medium. To evaluate water availability to containerized seedlings and the need for irrigation, it is hence important to monitor the water potential (Heiskanen 1993). Water availability is also dependent on the flow rate of water to the root, which is determined by the hydraulic conductivity and the available total water reservoir. Ideally, the hydraulic conductivity should be high enough to replace the water uptake by the root. However, the variations of water potential and hydraulic conductivity of peat based growth media are poorly known, particularly when used in containers.

The unsaturated hydraulic conductivity of soil depends on the water potential and the physical properties of soil (Hillel 1971). The hydraulic conductivity of mineral soils has been fairly well studied. Conductivity decreases with decreasing water potential and the decrease is generally steeper the coarser the texture. Less is known about the relationships between the unsaturated hydraulic conductivity of various peats and their physical properties. Bartels and Kuntze (1973), Illner and Raasch (1977) and Loxham and Burghardt (1986) give values for some natural peats and Puustjärvi (1991) gives values for a peat growth medium at a few separate matric potentials. However, the hydraulic conductivities of peat and peat based growth media as a function of drying have not been determined.

In this study, the matric potential of peat and a peat-perlite mixture growth medium in containers was measured during drying. The water retention characteristics and unsaturated hydraulic conductivities of the media were also determined. The effect of drying on the hydraulic conductivity of the media and subsequent decreasing water availability to the seedlings are discussed.

2 Materials and methods

Growth media used in this study were 1) Vapo D – a light, low humified, coarse graded *Sphagnum* peat, 2) Vapo E – a medium graded *Sphagnum* peat, and 3) a 1:2 (v/v) mixture of a coarse graded perlite (Nordisk Perlite Corp., Denmark) and Vapo E. Vapo D and Vapo E (Vapo Corp., Finland) are peat media commonly used in Finnish tree nurseries. The particle size distributions of the media were determined from four parallel air dry samples of 300 cm^3 using a mechanical sieving machine (Retsch Corp., Germany) and a shaking time of two minutes (Table 1).

The growth media were packed into two types of open-ended polystyrene containers (TK708 and TA710; Lannen Corp., Finland) according to procedures described by Heiskanen (1990). A piece of polyamide netting (mesh size 1 mm) was first placed in the bottom of each container. The TK708 containers are square in cross section and have a volume of 345 cm^3. The TA710 containers are circular in cross section and have a volume of 285 cm^3. Each medium and container combination were replicated three times. The total number of samples was therefore 18.

Tensiometers, fitted with electrical pressure sensors and connected to an automatic data acquisition system (Heiskanen and Laitinen 1992), were installed at three depths in each container (Fig. 1). The media were then watered abundantly during two days. After the final watering, the media were allowed to freely evaporate in a slowly ventilated fume chamber at 35–40 % relative humidity and 22–25 °C temperature. During the steady, evaporative water flow, the matric potential was recorded at 4 h intervals until the measuring limit of the tensiometers (c. –85 kPa) was achieved (c. 1 month). Evaporation from the bottom and sides of the containers was considered to have a negligible effect on the measured matric potential in the growth media. At the end of the measurement period, the shrinkage of the media was measured in both vertical and horizontal direction using a ruler (± 0.5 mm).

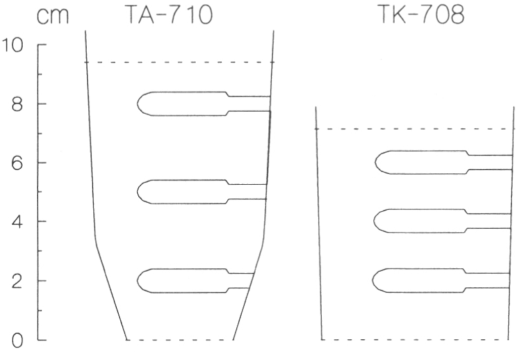

Fig. 1. Container types used and positions of the tensiometers in the containers during the experiment.

Unsaturated hydraulic conductivities were estimated using a method based on that described in detail by Hartge and Horn (1989). First, the desorption water retention characteristics of the growth media were determined from separate, parallel samples (three replicates) using a pressure plate apparatus (Soilmoisture Equipment Corp., USA) and procedures described elsewhere (Heiskanen 1990, Heiskanen and Laitinen 1992). Using the resulting water retention curves (Fig. 2), a water retention value for each calibrated matric potential value measured from the tensiometers (Heiskanen and Laitinen 1992) was then

Table 1. Means and standard deviations of particle size in distribution classes (%, m/m) determined from air dry samples (n = 4) of the growth media.

Medium	Fraction, mm				
	< 1	1–5	5–10	10–20	> 20
Vapo D	45.4±1.3	31.5±1.9	16.8±1.1	6.2±2.41	0.1±0.13
Vapo E	45.5±9.6	36.9±8.3	14.5±2.4	2.9±3.13	0.1±0.08
Perlite	28.8±4.1	70.8±3.9	00.4±0.3	0.0±0.00	0.0±0.00

calculated. Shrinkage during water potential measurement was considered not to markedly affect the water retention characteristics of media between tensiometers with respect to those measured from the separate, parallel samples with the pressure plate apparatus at desorption. Unsaturated hydraulic conductivity values at each tensiometer measurement time interval were estimated for the midpoints between the three tensiometer levels applying the following formula (Weeks and Richards 1967, Hartge and Horn 1989).

$$\partial Q/\partial t = A\ K(\psi m)\ (\partial \psi_m/\partial x + \partial \psi_g/\partial x) \qquad (1)$$

where

$\partial Q/\partial t$ = flow rate (cm³/h) past a given cross-section (between tensiometers) of medium column,

A = cross-section (cm²),

$K(\psi m)$ = hydraulic conductivity (cm/h),

$\partial \psi_m/\partial x$ = matric potential gradient (water-cm/cm) at the cross-section,

$\partial \psi_g/\partial x$ = gravitational potential gradient (water-cm/cm) at the cross-section.

Statistical and graphical data analysis was done using SYSTAT-software (SYSTAT 1990ab).

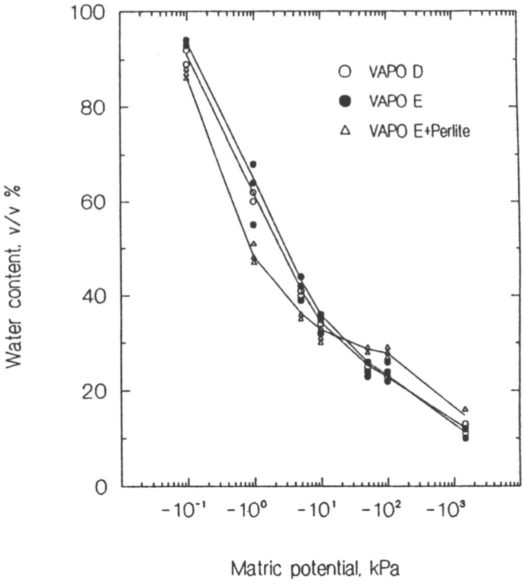

Fig. 2. Water retention characteristics of the growth media.

3 Results and discussion

3.1 Matric potential

For the both container types, the matric potentials of the growth media were similar down to –10 kPa at all the three measurement levels (Fig. 3). Further drying, however, resulted in a considerable matric potential gradient between the uppermost and lower tensiometer levels. When the matric potential at the middle level was –20...–30 kPa, it was about –80 kPa at the uppermost level. At the lowest measurement level, the matric potential was little higher than at the middle level. When the potential at the middle level lowered to –40...–60 kPa, it was –30...–40 kPa at the lowermost level in TA710 containers. Because of the higher surface area to height ratio, the media dried faster in the TK708 containers than in TA710 containers. In addition, differences in seedling transpiration mainly affect the matric potential and water availability in the container. Therefore, at high evapotranspiration rates, it is likely that the need for irrigation during seedling production is greater when using TK708 containers than when using TA710.

Under high evaporative conditions, water availability (see Örlander and Due 1986ab) may also start to rapidly decrease even though the bulk matric potential would be as high as > –20 kPa. If the matric potential at the peat surface is lower than –80 kPa, watering may become difficult due to the water repellency of the dry peat surface. Hence, a water deficit may rapidly follow if the peat cannot absorb sufficient irrigation water to compensate for the water loss.

All the media clearly shrank during drying. When the matric potential at the surface level in the TK708 containers had reached about –80 kPa, the decrease in height of the Vapo D, Vapo E and the peat-perlite mixture was 18–23, 15–20 and 10–15 %, respectively. With the TA710 con-

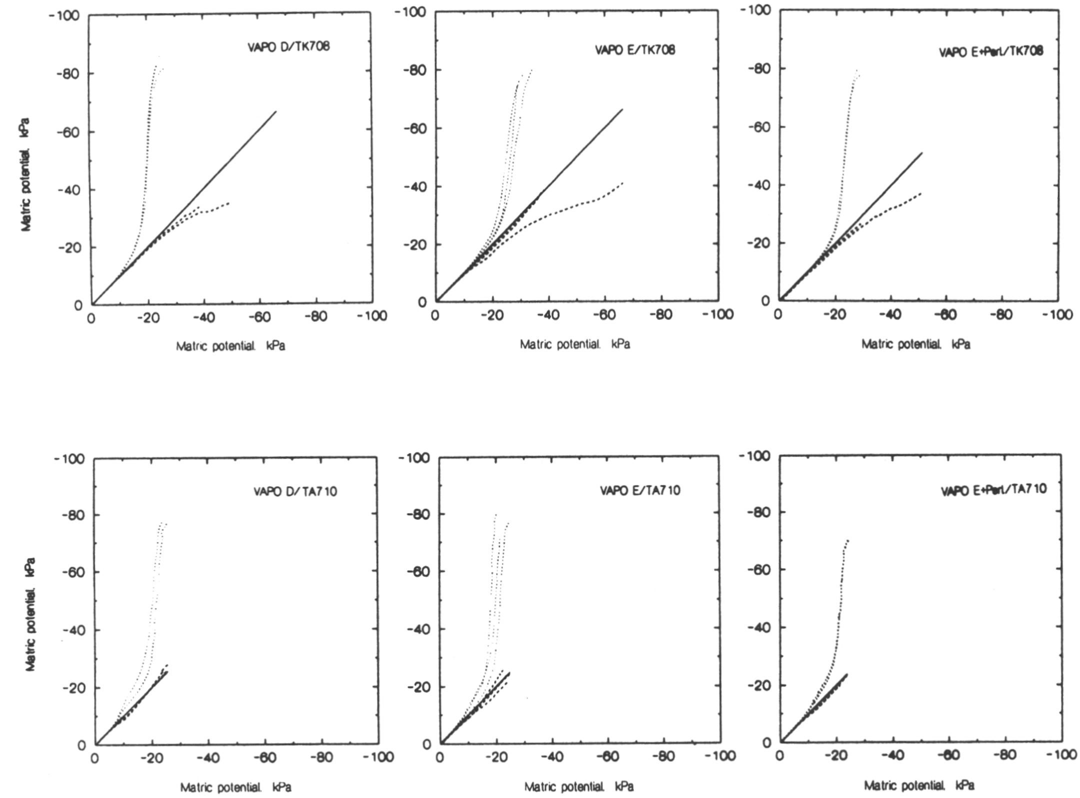

Fig. 3. Matric potential of the growth media at different levels in the containers during drying. Matric potentials are in respect to the matric potential in the middle tensiometer level. (Tensiometer levels: dotted line = upper, solid line = middle, broken line = lower).

tainers, the shrinkage was less; 7–11, 5–7 and 5–10 %, respectively. The mean shrinkage in the horizontal direction was between 4–9 % in all the media.

3.2 Hydraulic conductivity

The particle size distribution and water retention characteristics of both the pure peat media, Vapo D and Vapo E, were rather similar (Table 1, Fig. 2). The water retention characteristics are comparable to those given for medium textured peat media (Heiskanen 1990). The perlite was dominated by particles of 1 to 5 mm diameter and hence the peat-perlite mixture was expected to contain a relatively high proportion of coarse pores. This would explain that the peat-perlite mixture released more water than the pure peats when the matric potential was lowered from saturation to –1 kPa. However, the peat-perlite mixture also retained more water than the peats at potentials < –50 kPa. This is likely to be because perlite contained some very fine particles.

The estimated unsaturated hydraulic conductivities of all three media decreased in a rather uniform way during drying (Fig. 4, Table 2). Hydraulic conductivity decreased almost linearly on a log-log-scale from about 10^{-5} to less than 10^{-10} m/s as the matric potential decreased from –3 to –60 kPa. The pure peat media had very similar hydraulic conductivity. The peat-perlite mixture had, however, somewhat lower hydraulic conductivity, which was due to the very low hydraulic conductivity of perlite (Jackson 1974). For example at –10 and –50 kPa, the average hydraulic conductivity of the peat media was c. 1×10^{-7} and 2×10^{-10} m/s, respectively, while that of the mixture was 3×10^{-8} and 7×10^{-11} m/s, respectively. Hence, the coarse perlite as an

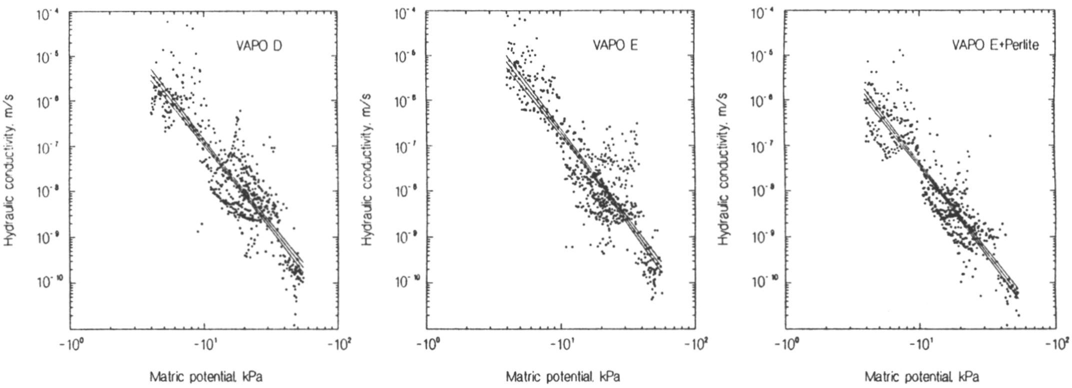

Fig. 4. Scatterplots, fitted regression lines and their 95 % confidence intervals for unsaturated hydraulic conductivity of the growth media during drying. Data were combined from the results of the samples in both container types used.

additive to the peat lowered the hydraulic conductivity compared with that of the pure peat media. The container type was found not to affect the hydraulic conductivity values.

The root mean square errors (RMSE) of the logarithmic hydraulic conductivities of the media were between 0.5 and 0.6 (Table 2). Thus, average deviation in the logarithmic hydraulic conductivity about the regression lines was about an half an order of magnitude (Fig. 4). The deviations of the values from linearity were likely due to the natural heterogeneity of the medium materials and also, possibly, partly to methodological reasons. The water retention characteristics determined from the parallel samples may differ somewhat from the actual characteristics of the media in the containers during drying, for example due to variations in shrinkage and medium materials. In addition, deviations from the stationary water flow during the measurement due to possibly varying evaporation rate and nonisothermal water flow may have caused slight inaccuracy to the hydraulic conductivity values.

The estimated hydraulic conductivity values are relatively similar to those reported in the literature, despite the different measurement techniques used. Bartels and Kuntze (1973) reported the hydraulic conductivity of an undisturbed, low humified (H2-3) peat to decrease from 1.4×10^{-8} to 2.3×10^{-11} m/s when the matric potential decreased from –10 to –100 kPa. Loxham and Burghardt (1986) studied peats from several peatlands and they found a *Sphagnum* bog peat (H2-3) to have the hydraulic conductivity of about 10^{-7}, 10^{-8} and 10^{-9}– 10^{-10} m/s at –3, –10 and –32 kPa, respectively. Rather similar results were also obtained for low humified (H2-4) *Carex* and *Phragmites* peats by Illner and Raasch (1977). According to Puustjärvi (1991), the hydraulic conductivity of a light *Sphagnum* peat growth medium is 2.2×10^{-7} m/s and 5.5×10^{-8} m/s when water content is 50 and 35 %, respectively. These water contents correspond to matric potentials of about –1 and –5...–10 kPa, respectively. The hydraulic conductivity of the studied growth media is comparable to coarse sand at matric potentials < –10 kPa (Bartels and Kuntze 1973, Scheffer and Schachtschabel 1989). At matric potentials > –10 kPa, the hydraulic conductivity of the media is slightly higher than that of coarse sand.

Table 2. Parameters for the regression equations $\log_{10}(y) = a + b \log_{10}|x|$, i.e. ($y = 10^{a} |x|^{b}$) showing the relationships between the hydraulic conductivity (y, m/s) and matric potential (x, kPa) of the growth media. Root mean square errors (RMSE i.e. standard errors of the estimates), regression coefficients (r) and their significances (p) are for $\log_{10}(y)$.

Medium	a	b	RMSE	r	n	p
Vapo D	–3.184	–3.721	0.58	0.88	628	< 0.0005
Vapo E	–2.772	–3.934	0.61	0.87	674	< 0.0005
Vapo E + Perlite	–3.549	–3.863	0.51	0.90	597	< 0.0005

The water availability of a low humified, fine graded peat growth medium to Scots pine seedlings (1-year-old) has been reported to decrease markedly when the matric potential decreases beginning from about –10 kPa (Örlander and Due 1986b). This indicates that either the hydraulic conductivity diminishes or the soil-root contact area becomes less, or both. In this study, the hydraulic conductivity of coarse to medium graded peat growth medium was shown to decrease steeply (logarithmically) in relation to decreasing matric potential. Thus, at matric potentials < –10 kPa, the hydraulic conductivity of peat was indeed low. Shrinkage during drying may result in the formation of air gaps between the roots and peat which are likely to further decrease hydraulic conductivity and hence water availability. Therefore, when considering nursery management, the water potential of peat growth media in containers should not be allowed to frequently fall far below –10 kPa.

Acknowledgements: In addition to the referees selected by the editor, the manuscript has been read and commented on by Prof. H. Mannerkoski, Drs. H. Smolander, M. Starr, T. Karvonen, and R. Rikala, M.Sc. Dr. M. Starr has also revised the English language of the manuscript.

References

Bartels, R. & Kuntze, H. 1973. Torfeigenschaften und ungesättigte hydraulische Leitfähigkeit von Moorböden. Zeitung für Pflanzenernährung und Bodenkunde 134(2): 125–135.

Hartge, K.H. & Horn, R. 1989. Die physikalische Untersuchung von Böden. 2. Aufl. Enke, Stuttgart. 175 p.

Heiskanen, J. 1990. Näytelieriön täyttötavan vaikutus kasvuturpeen vedenpidätyskykyyn. Summary: The effect of sample handling on the water retention of growth peat substrate. Suo 41(4–5): 91–96.

— 1993. Favourable water and aeration conditions for growth media used in containerized tree seedling production: A review. Scandinavian Journal of Forest Research. (In press).

— & Laitinen, J. 1992. A measurement system for determining temperature, water potential and aeration of growth medium. Tiivistelmä: Kasvualustan lämpötilan, vesipotentiaalin ja ilmanvaihdon mittausjärjestelmä. Silva Fennica 26(1): 27–35.

— & Tamminen, P. 1992. Maan fysikaalisten ominaisuuksien määrittäminen. Metsäntutkimuslaitoksen tiedonantoja 424. 32 p.

Hillel, D. 1971. Soil and water. Physical principles and processes. Academic Press, Orlando. 288 p.

Illner, K. & Raasch, H. 1977. Der Einfluss von Torfeigenschaften auf die kapillare Leitfähigkeit in Niedermoorböden. Archiv für Acker- und Pflanzenbau und Bodenkunde 21(10): 753–758.

Jackson, D.K. 1974. Some characteristics of perlite as an experimental growth medium. Plant and Soil 40: 161–167.

Loxham, M. & Burghardt, W. 1986. Saturated and unsaturated permeabilities of North German peats. In: Fuchsman, C.H. (ed.). Peat and water. Aspects of water retention and dewatering in peat. Elsevier, London–New York. p. 37–59.

Örlander, G. & Due, K. 1986a. Location of hydraulic resistance in the soil-plant pathway in seedlings of Pinus sylvestris L. grown in peat. Canadian Journal of Forest Research 16(1): 115–123.

— & Due, K. 1986b. Water relations of seedlings of Scots pine grown in peat as a function of soil water potential and soil temperature. Studia Forestalia Suecica 175. 13 p.

Puustjärvi, V. 1991. Kasvu ja kasvun hallinta kasvihuoneviljelyssä. Kauppapuutarhaliitto ry, Tuotanto-osaston julkaisuja 10. 287 p.

Scheffer, F. & Schachtschabel, P. 1989. Lehrbuch der Bodenkunde. 12. Aufl. Enke, Stuttgart. 491 p.

SYSTAT 1990a. Graphics. Version 5.0. Systat Inc. Evanston, IL, USA. 547 p.

— 1990b. Statistics. Version 5.0. Systat Inc. Evanston, IL, USA. 676 p.

Weeks, L.V. & Richards, S.J. 1967. Soil-water properties computed from transient flow data. Soil Science Society of America Proceedings 31: 721–725.

Total of 17 references

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Physical Properties of Two-Component Growth Media Based on *Sphagnum* Peat and their Implications for Plant-available Water and Aeration

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Physical properties of two-component growth media based on *Sphagnum* peat and their implications for plant-available water and aeration

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Key words: density, hydraulic conductivity, particle size, shrinkage, substrate, water retention

Abstract

The physical properties, in particular the water retention characteristics, of two-component growth media based on low-humified *Sphagnum* peat were studied. The high water retention of pure peat, which is further increased by shrinkage of the medium at desorption, yielded low air-filled porosity at high matric potentials (≥ –1 kPa). The addition of coarse perlite to peat decreased the shrinkage markedly and also tended to increase the low saturated hydraulic conductivity of peat, which had initially been rather low. In all media studied, the amount of water that is easily available to plants (water content retained between –1 and –10 kPa matric potential) was relatively high. In peat that contained half repellent rockwool or hydrogel, this water retention was, however, markedly lower. Between –10 and –50 kPa matric potential, water retention was rather low in all media (<10 %). Within the lowest matric potential range studied (–50 to –1500 kPa), water retention was considerably elevated in peat that contained half hydrogel. The implications of the physical properties of the media for plant-available water and aeration in the media are discussed.

Introduction

One of the growth media used most widely throughout the world for culturing containerized plants is peat, especially light, low-humified *Sphagnum* peat (Bunt, 1988; Heiskanen, 1993a; Landis et al., 1990; Puustjärvi, 1977). However, the physical properties of pure peat may not provide optimal water and aeration conditions under all management regimes and growth phases of various species (Heiskanen, 1993a; Puustjärvi, 1977). Therefore, to manipulate the properties of the peat growth medium and also to save peat material, in many countries peat-based mixtures are used as growth media (Bunt, 1988; Landis et al., 1990).

Water availability to plants and aeration in the growth medium is evaluated mainly according to physical criteria derived from the physical properties, especially water retention characteristics, of the growth medium (e.g. De Boodt and Verdonck, 1972; Heiskanen, 1993a, b; Puustjärvi, 1977). The hydraulic conductivity of the growth medium as a function of matric potential may also be determined when more accurate evaluation of water availability is required (Heiskanen, 1993a, c; da Silva et al., 1993). In order to manipulate these physical properties of peat, suitable additive materials should be selected. In principle, by mixing materials of coarse textural grade into peat, the amount of coarse pores and thus the aeration of the growth medium can be increased. Addition of fine grade materials tends, in turn, to increase water retention. Although many studies and guides on the properties of various growth media are available (e.g. Bunt, 1988; Landis et al., 1990), there is little information on the properties of peat-based media mixtures or on how these properties affect water and aeration conditions in the growth medium.

The aims of the present study were to determine the physical properties, in particular the water retention characteristics, of various binary growth media based on low-humified *Sphagnum* peat and to evaluate the implications of these properties for the availability of water and oxygen to plant roots.

Materials and methods

The growth media studied were two-component mixtures based on commercially produced light, low-humified, medium textural grade and premix-fertilized *Sphagnum* peat (Vapo E1K2, Vapo Corp., Finland), which is commonly used in Finland to produce containerized forest tree seedlings. The additive materials in peat were coarse (cPr) and fine perlite (fPr) (type 05-60 and 00-10, Nordisk Perlite Corp., Denmark), loose, nongranulated water-repellent rockwool (rRw) and granulated water-absorbent rockwool (aRw) (type BU-20 and 012-519, Grodania Corp., Denmark) and hydrogel (Gel) (Waterworks America Corp., USA). The volumetric proportions of the additives in the loose mixtures were 10, 25 and 50 %. In the following text, the mixtures used are referred to using codes consisting of abbreviations for the additives and their proportions. The first letters of a mixture code indicate the additive and the following number is the proportion of the additive in the mixture. For example, rRw25 denotes a mixture of peat (75%) and repellent rockwool (25%).

The mixtures were prepared in the early spring of 1992 by mixing the component materials by hand. The mixtures were then stored in plastic bags in cold storage (+ 5 °C) for 1 to 8 months before the laboratory determinations were made. Hydrogel was mixed into peat as dry grains with a ratio of 1 g of hydrogel to 0.75 dm^3 of peat to achieve 25 % hydrogel in moist mixture samples, because 1 g of dry hydrogel was found to absorb water to an average volume of about 0.25 dm^3. This absorption ratio was used to calculate the respective mixing ratios for the other hydrogel proportions (10, 50 %) to be added to peat. For containerized plants, the rate of application recommended by the producer for hydrogel is 0.6–1.75 g dm^{-3}.

The gravimetric (M M^{-1}) particle size distributions of pure peat and pure additive materials were determined with a mechanical sieve by dry sieving the media through standard sieves with hole sizes of 20, 10, 5, 1 and 0.06 mm (Heiskanen, 1993b). In pure peat and fPr, most of the particles were smaller than 1 mm, while cPr clearly contained the most particles 1–5 mm in diameter (Fig. 1). Almost half of the particles in aRw were 5–10 mm in diameter, while most of the particles in rRw were larger than 20 mm. Since the particle size distribution differed between media and the particles of peat (organic cells and fibers), perlites (mineral cells) and rockwools (mineral fibers) possess a different structure even within the same fractions, variation also in the other physical properties of the media can be expected (Handreck, 1983).

Bulk density was determined as the ratio of dry mass (dried at 105 °C) to volume at –0.1 kPa matric potential (volume determinations described later). The particle densities of peat and aRw were meas-

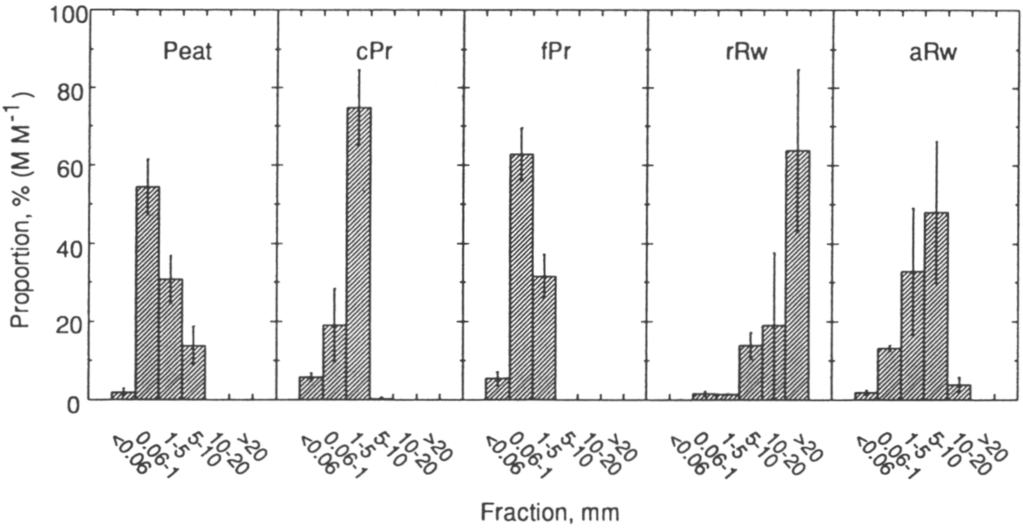

Fig. 1. Particle size (mm) distribution (%, M M^{-1}) of pure peat and pure additive materials. Bars indicate means and vertical lines indicate standard deviations.

Table 1. Means and standard deviations measured or estimated for particle (Ds) and bulk density (Db), total porosity (Vf = (Ds – Db) Ds^{-1}), loss on ignition (Il) and saturated hydraulic conductivity (Ks) of pure peat (n = 10) and pure additive materials (n = 5).

Medium	Ds, g cm^{-3}	Db, g cm^{-3}	Vf, % (V V^{-1})	Il, % (M M^{-1})	Ks, cm min^{-1}
Peat	1.61±0.04	0.074±0.004	95.5±0.22	94.7±0.45	0.095±0.05
cPr	2.10[a]	0.098±0.002	95.3±0.11[a]	1.0±0.10	2.79±0.45
fPr	2.10[a]	0.044±0.002	97.9±0.10[a]	1.5±0.16	1.88±0.04
rRw	2.82±0.09[b]	0.073±0.006	97.4±0.21[b]	2.7±0.18	0.23±0.03
aRw	2.82±0.09	0.153±0.010	94.6±0.34	0.1±0.11	1.72±0.26

[a] Estimated from Vf in Verdonck (1983), [b] from Ds of aRw100.

ured using liquid pycnometers with water as the filling liquid and a water bath (Heiskanen, 1992). Due to the differing degrees of non-wettability of the other materials, their particle densities were not measured. Loss on ignition of pure materials (Gel excluded) was determined by igniting a sample of about 2 g at 550 °C for 3 hours. The saturated hydraulic conductivity of each media was measured by applying the constant-head method (Heiskanen, 1993b; Klute and Dirksen, 1986).

Because peat is an organic material, its particle density was much lower and its loss on ignition was significantly higher than those of the pure additive materials ($p<0.05$, Tukey's test, Table 1). Compared with other materials, aRw had significantly the highest bulk density. Nevertheless, the total porosity was high and was rather similar in all media. The saturated hydraulic conductivity of pure peat was, however, significantly lower than that of pure cPr, fPr and aRw, but was similar to that of rRw.

Before measuring water retention charcteristics, the media were loosely filled into open-ended metal cubes and compressed with a pressure of 10 g cm^{-2}. Volumetric (V V^{-1}) water retention characteristics of the media were determined at desorption (from –0.1 to –1500 kPa) using a pressure plate apparatus (Soilmoisture Equipment Corp., USA) and procedures described in detail by Heiskanen (1993b). The volumetric water retention of the media at different matric potentials was calculated in relation to the initial wet sample volume at –0.1 kPa matric potential. This volume can be regarded as corresponding to the volume of the medium in containers newly filled in nurseries. Volumetric shrinkage was also measured at desorption (Heiskanen, 1993b). Water retention was transformed to a transient sample volume basis at different matric potentials by dividing water retention by the volume of the shrunk sample (when expressed as a proportion of the initial volume). For pure peat and for each mixture in the water retention measurement, 10 sample replicates were used. Five sample replicates were used for pure additive materials (rRw and Gel excluded). Thus, a total of 175 samples were measured. Due to the fragile consistency and poor manageability during measurement, the water retention characteristics of pure hydrogel were not measured. Due to total water repellency, these characteristics of pure repellent rockwool were not measured either.

At matric potentials > –10 kPa, pure peat retained significantly more water than the pure additive materials (Fig. 2). At matric potentials < –50 kPa, both perlites retained more water than peat. aRw retained an amount of water comparable to that of perlites at

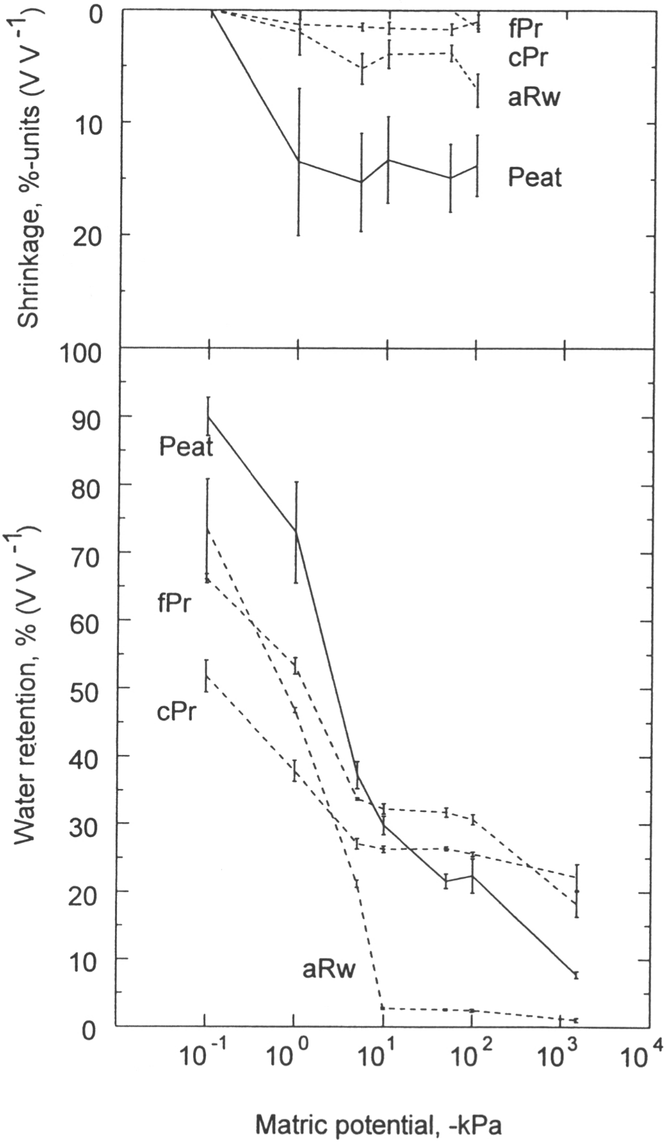

Fig. 2. Desorption water-retention characteristics (% of total sample volume at –0.1 kPa, V V^{-1}) and shrinkage of the volume (%-units, V V^{-1}) of pure peat and pure additive materials. Shrinkage is defined as the difference between volume at –0.1 kPa (=100 %) and that at each matric potential (kPa). Vertical lines indicate standard deviations.

> –5 kPa, but at lower matric potentials it retained very little water (< 3 %). (Due to its water repellency, pure rRw retained no water.) Pure peat also shrank most at desorption. aRw shrank somewhat, but less than peat, while perlites shrank only a little (< 2 %-units of initial volume).

Means and standard deviations of the variables were calculated for the groups of media that were compared. Levene's test was used to test the homogeneity of the variances. To test the differences of the means between groups, one-way analysis of variance (ANOVA) and Tukey's test were also used. These tests were also used when variances were unequal, because the significance levels obtained were similar to those achieved with the Brown-Forsythe test, which does not require equal variances. Multivariate analysis of variance (MANOVA) was used to test the designs of repeated measurements.

Results

The bulk densities of the media mixtures were relatively similar, averaging 0.04–0.10 g cm^{-3} (Fig. 3). Due to the high bulk density of pure aRw, however, the bulk density of aRw25–50 mixtures were significantly higher ($p<0.05$ Tukey's test). Addition of rRw and cPr

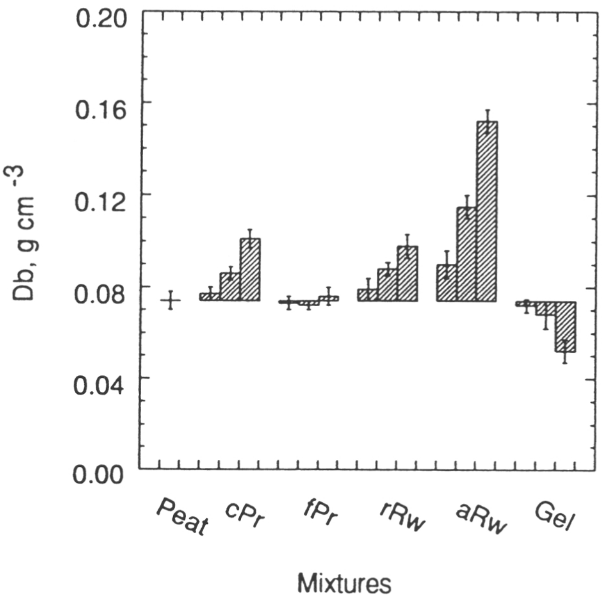

Fig. 3. Bulk density (Db, g cm^{-3}) of pure peat and media mixtures. Bars indicate means and vertical lines indicate standard deviations. The reference level is the Db of pure peat. The different bars for a given additive indicate the different volumetric proportions (10, 25 and 50 %, respectively) of the additive in the mixture.

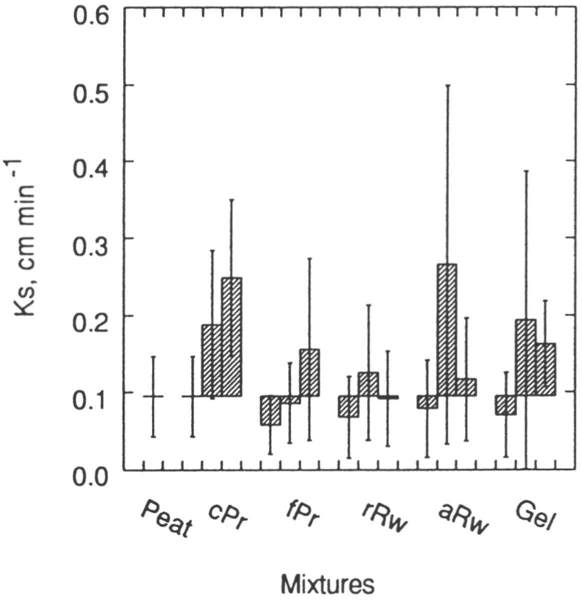

Fig. 4. Saturated hydraulic conductivity (Ks, cm min $^{-1}$) of pure peat and media mixtures. Bars indicate means and vertical lines indicate standard deviations. The reference level is the Ks of pure peat. The different bars for a given additive indicate different volumetric proportions (10, 25 and 50 %, respectively) of the additive in the mixture.

to peat also tended to increase bulk density, while addition of Gel tended to decrease it slightly. The saturated hydraulic conductivity of media mixtures was usually lower than 0.3 cm min $^{-1}$ (Fig. 4). Increased addition of cPr to peat tended to increase hydraulic conductivity most clearly. With other additives, the effect on hydraulic conductivity of adding them to peat was rather variable.

Water retention as well as the volume of the media at desorption differed significantly between media ($p<0.01$ for the interaction of different media and matric potentials by several statistics; MANOVA with e.g. Wilks' lambda and Hotelling-Lawley trace tests). With increased proportions of additives in peat, the water retention at a matric potential of –0.1 kPa tended to remain fairly constant or to decrease slightly (Fig. 5). However, the water retention of cPr50 and rRw50 was significantly lower than that of all other media ($p<0.01$ Tukey's test). At a matric potential of –1 kPa, the variation in water retention was high compared with that at other matric potentials. At matric potentials ≤ –5 kPa, rRw and aRw tended to decrease and Gel to increase water retention as the proportion added to peat increased. However, at the wilting point (–1500 kPa) all media retained water rather similarly.

The volume of all media mixtures shrank markedly at desorption (5–25 %-units of the initial volume, Fig. 6). In general, the shrink-

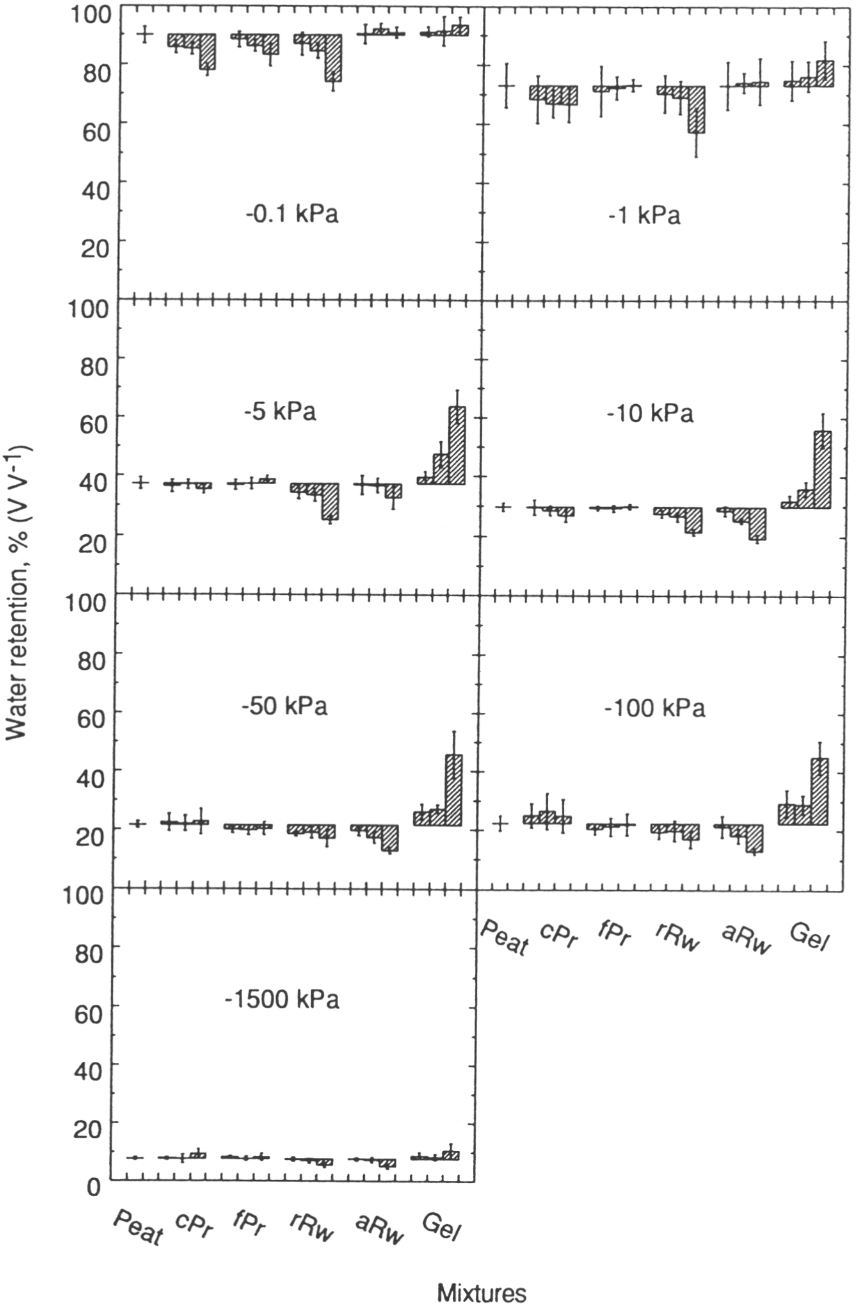

Fig. 5. Desorption water-retention characteristics (% of volume at –0.1 kPa, V V^{-1}) of pure peat and media mixtures. Bars indicate means and vertical lines indicate standard deviations at each matric potential (kPa). The reference level at each matric potential is the water content of pure peat. The different bars for a given additive indicate different volumetric proportions (10, 25 and 50 %, respectively) of the additive in the mixture.

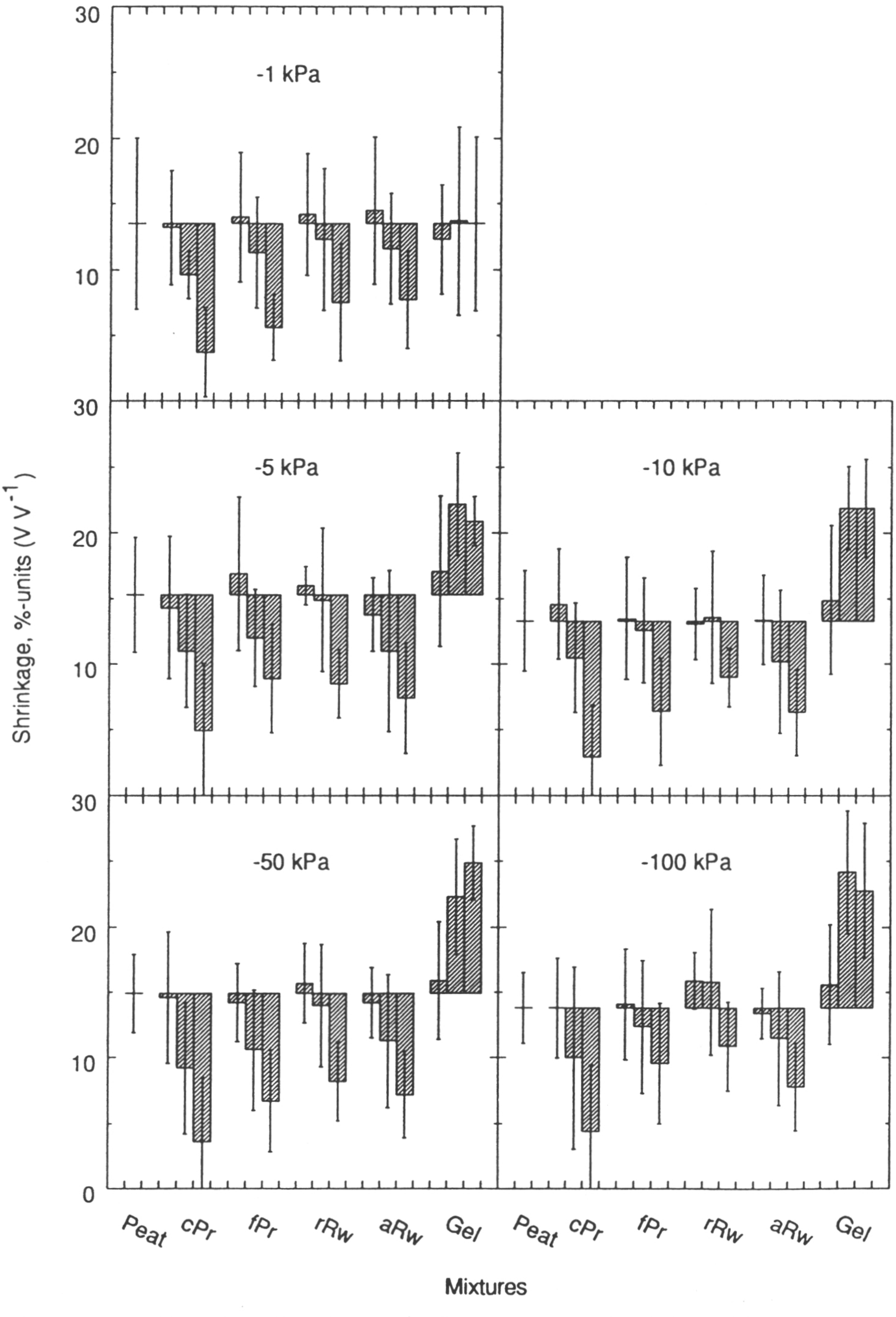

Fig. 6. Shrinkage of the volume (%-units, V V^{-1}) of pure peat and media mixtures at desorption. Shrinkage is defined as the difference between the volume at –0.1 kPa (=100 %) and that at each matric potential (kPa). Bars indicate means and vertical lines indicate standard deviations. The reference level at each matric potential is the shrinkage of pure peat. The different bars for a given additive indicate different volumetric proportions (10, 25 and 50 %, respectively) of the additive in the mixture.

age of the media did not alter much after –1 kPa matric potential at desorption. Compared with the other additive materials, cPr most clearly decreased the shrinkage of the growth medium as the proportion added to peat increased. The addition of fPr, rRw and aRw to peat also tended to decrease shrinkage at whole desorption, while the addition of Gel to peat tended to increase it at matric potentials <–1 kPa.

Since the water retention at a matric potential of –1 kPa tended to increase with the addition of Gel, water retention between 0 and –1 kPa was thus even lower in peat containing Gel than in pure peat. Between –1 and –10 kPa matric potential, water retention was markedly decreased in rRw50 and Gel50 compared with other media (Fig. 7). Increasing addition of aRw to peat tended to increase this water retention slightly. Between –10 and –50 kPa matric potential, water retention by all media was greatly decreased compared with that within the previous matric potential range, and no marked differences were found between media. Between –50 and –1500 kPa matric potential, addition of Gel to peat tended to increase water retention strongly.

Due to the marked shrinkage of the media at desorption, their water retention was greater when expressed per volume of shrunk medium than per initial saturated volume (Fig. 6). Between 0 and –1 kPa matric potential, water retention for pure peat was 22 % per initial volume of peat but only 13 % per shrunk volume. Because the shrinkage did not alter much after –1 kPa during desorption, water retention was thus increased only slightly within the selected matric potential ranges and increased most within the range of –1 to –10 kPa (<10 %-units). In media containing Gel, within –50 and –1500 kPa there was also a marked increase in water retention due to shrinkage, because in these media the shrinkage increased slightly after –1 kPa (Fig. 6).

Discussion

The particle size distribution, bulk density, loss on ignition and saturated hydraulic conductivity of pure peat were rather similar to what had been reported previously for the same type of peat growth medium (Heiskanen, 1993b; Puustjärvi, 1977). The saturated hydraulic conductivity of the media mixtures did not, however, differ markedly from each other, although increased additions of coarse perlite to peat clearly tended to increase it. Probably as a result of a lower amount of fine fraction, the saturated hydraulic conductivity of both pure perlites was higher than reported by Chen et al. (1980) for a few types of perlite. Jenkins and Jarrell (1989), however, reported a higher conductivity for perlite of a medium textural grade.

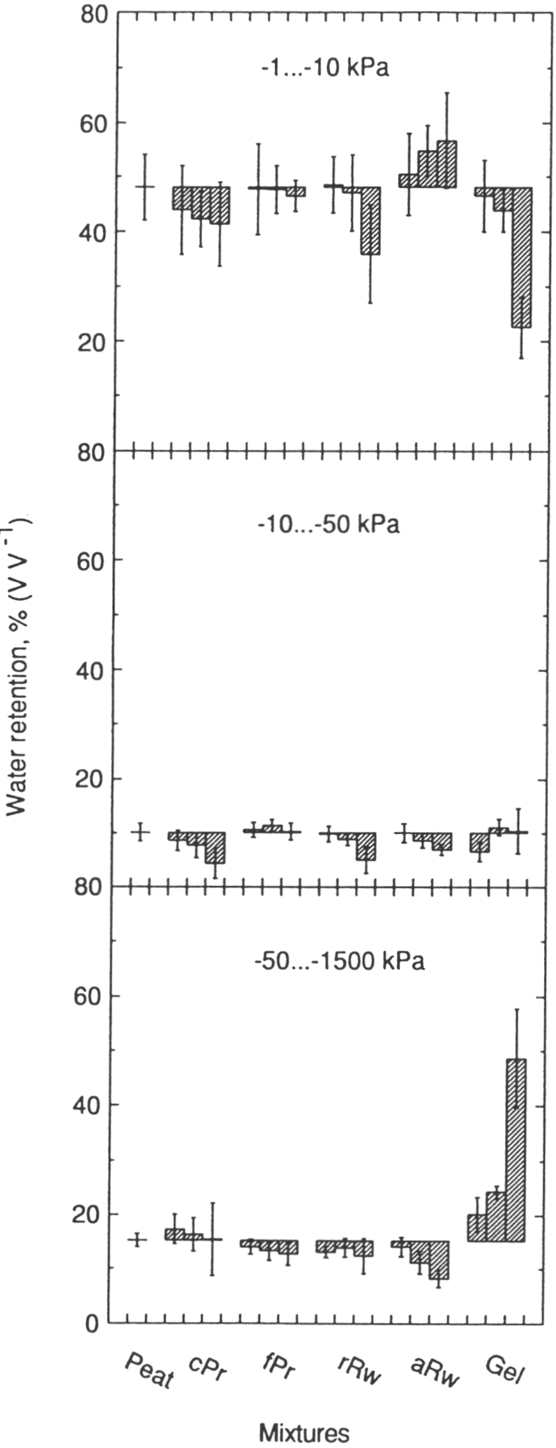

Fig. 7. Water retention (% of volume at each matric potential, V V^{-1}) of pure peat and media mixtures within selected matric potential ranges (kPa). Bars indicate means and vertical lines indicate standard deviations. The reference level at each matric potential range is the water content of pure peat. The sample volume at –1500 kPa was considered to be the same as that at –100 kPa. The different bars for a given additive indicate different volumetric proportions (10, 25 and 50 %, respectively) of the additive in the mixture.

The slight differences in hydraulic conductivity between peat mixtures are probably due partly to the constant-head method used, which required long-term saturation (1–2 days) of the samples. In organic media, long-term saturation is likely to cause swelling and compaction, which in turn tend to block pores, thus reducing the differences in the hydraulic conductivity of peat of different structures (Heiskanen, 1993b). Saturation of a shorter duration has been shown to give higher hydraulic conductivity values even for mineral soils (Sillanpää, 1956). Therefore, if the initial water content is lower and the saturation time after irrigation or precipitation is shorter in nurseries, the actual saturated hydraulic conductivity of peat growth media is most likely higher than that achieved here with the constant-head method. Consequently, in nurseries additions of perlite to peat are also likely to give a more marked increase in the actual saturated hydraulic conductivity.

During water retention measurements, especially when the surface of the medium was dry, the wettability of the medium was observed to be higher in media containing perlite than in other media. Addition of perlite as well as vermiculite and mineral soils has also previously been reported to increase the wettability of growth media mixtures (Bunt, 1988; Heiskanen, 1994a, c).

The desorption water-retention characteristics of pure peat were similar to those reported earlier for the same type of peat (Heiskanen, 1993a, b; Puustjärvi, 1977). In addition, *Sphagnum* peat-perlite mixtures have been shown to retain less water than pure peat, at least at matric potentials down to about –50 kPa (Heiskanen, 1993c, 1994c; Verdonck, 1983). The water retention characteristics of the pure perlites studied here were intermediate to those reported previously for perlite of various textural grades (Chen et al., 1990; Haynes and Goh, 1978; Handreck, 1983; Jackson, 1974; Verdonck, 1983; Verdonck et al., 1983). Furthermore, as shown here, pure absorbent rockwools retain almost as much water as peat but release it almost totally at matric potentials < –5 kPa at desorption and with small (<50 %) additions usually do not markedly alter the water retention characteristics of the growth media mixtures (Fonteno and Nelson, 1990; Nelson and Fonteno, 1991; Scagel and Davis, 1988). However, addition of water-repellent rockwool to peat tends to decrease water retention at desorption (Langerud, 1986; Scagel and Davis, 1988).

The water content that is easily available to plants (water content retained between –1 and –10 kPa matric potential) grown in the growth media studied was very high (Fig. 7) (see De Boodt and Verdonck, 1972; Heiskanen, 1993b). In rRw50 and Gel50, this water retention was, however, markedly lower, which may restrict the availability of water compared with the other media. The available water between matric potentials of –10 and –50 kPa, which can be considered to be a water reserve for plants growing under slightly suboptimal moisture conditions, was rather low in all media (<10

%). Thus, growth may be reduced in plants persistently exposed to these conditions. In peat which contained half hydrogel, the most slowly available water reserve within the driest matric potential range studied (–50 to –1500 kPa) was markedly elevated. This indicates that the hydrogel used retains mostly water, which is released and is thus available to plants only at low matric potentials (< –50 kPa). Therefore, growth media that contain hydrogel provide a means of storing water for plants grown under dry conditions (Gehring and Lewis, 1980; Eikhof et al., 1973; Johnson, 1984; Taylor and Halfacre, 1986; Woodhouse and Johnson, 1991). Especially at high transpiration rates, however, the unsaturated hydraulic conductivity of the growth medium (see Heiskanen, 1993c) may still be too low to supply all the water lost by transpiration rapidly enough.

On the other hand, at high matric potentials, aeration of the growth medium may be restricted due to high water retention. In organic growth media, even more than 40 % air-filled porosity may be required for adequate aeration to roots (Heiskanen, 1993a, 1994a, b; Puustjärvi, 1977). In the present study, air-filled porosity at –1 kPa matric potential (at about container capacity) (i.e. water retention between 0 and –1 kPa matric potential) was clearly lower than 40 % in pure peat and even lower in peat to which hydrogel had been added. Due to high water retention in wet conditions, reduced aeration in pure peat (Heiskanen, 1994b; Puustjärvi, 1977), and especially in growth media containing various hydrogels (Flannery and Busscher, 1982; Heiskanen, 1994a; Lennox and Lumis, 1987; Tripepi et al., 1991), has also been indicated in other studies. Due to increasing air-filled porosity at –1 kPa matric potential, coarse perlite (Verdonck, 1983) and water-repellent rockwool (Langerud, 1986; Scagel and Davis, 1988) added to peat increase aeration of the growth medium.

At desorption the shrinkage of the media studied was marked but was considerably lower in the mixtures containing perlite and also somewhat lower in those containing rockwool. The shrinkage reported for peat growth media used in tree nurseries has been similar to that found for pure peat in this study (Heiskanen, 1993b). Lowered shrinkage of the growth medium at desorption has also been shown previously in peat medium containing coarse perlite (Heiskanen, 1994c). The shrinkage of the media did not much affect water retention within the matric potential ranges studied. Thus the water availability to plants grown in these media is also not likely to be markedly affected by the shrinkage. Nevertheless, the shrinkage of the medium tends to increase bulk density, thus increasing the water retention expressed per apparent, shrunk volume of the medium at a specific matric potential compared with those expressed for the initial saturated volume. Therefore shrinkage correspondingly decreases both total and air-filled porosities. Because the media studied did not shrink much further after –1 kPa matric potential at desorption, the strongest decrease in air-filled porosity had thus occurred between matric potentials –0.1 and –1 kPa. Therefore, shrinkage reduces aeration in the growth medium and may even elevate the risk of waterlogging and hypoxia for plants grown in those media, that possess high water retention and are persistently kept near container capacity (Heiskanen, 1994b; Richard et al., 1958). Moreover, in long-term plant culturing, shrinkage due to compaction over time may further decrease aeration in the growth medium (Langerud, 1986; Puustjärvi, 1977).

Conclusions

It was shown that when added to low-humified *Sphagnum* peat in a proportion of less than 50%, the additives studied did not markedly alter the water retention characteristics of peat. Addition of hydrogel or repellent rockwool to peat in proportions higher than 25 % tended, however, to decrease the retention of water that is easily available to plants. Thus, no marked advantages in terms of water availability to plants can be seen in plant culturing with the use of peat-based binary growth media compared with pure peat. In dry conditions, however, addition of hydrogel to peat was shown to increase the amount of plant-available water considerably. Furthermore, especially with containerized plants subjected to long-term culturing and heavy irrigation or precipitation, the low saturated hydraulic conductivity and the high water retention of pure peat, which are further increased by shrinkage at desorption, may yield such a low air-filled porosity that the media become waterlogged. Therefore, in order to prevent inadequate aeration, increased percolation of excess water may be required, which can be achieved e.g. by addition of coarse perlite to peat. On the other hand, addition of perlite was also found to increase the wettability of dry peat, which in nurseries can facilitate absorption of irrigation water by the growth medium. Adequate aeration under wet conditions together with high availability of water also under dry conditions may be possibly achieved with appropriate peat-based ternary or multi-component growth media. This suggestion, however, remains to be verified in further research.

Acknowledgements

In addition to the referees selected by the editor, the manuscript was reviewed by Drs. H. Smolander and P. Aphalo and by R. Rikala, M.Sc. Dr. J. von Weissenberg revised the English language of the manuscript.

References

Bunt A C 1988 Media and mixes for container-grown plants. A manual on the preparation and use of growing media for pot plants. 2nd ed. Unwin Hyman, London. 309 p.

Chen Y, Banin A and Ataman Y 1980 Characterization of particles and pores, hydraulic properties and water-air ratios of artificial growth media and soils. Proc. 5th Int. Congr. Soilless Culture. May 18–24. pp. 63–82. ISOSC, Wageningen.

De Boodt M and Verdonck O 1972 The physical properties of the substrates in horticulture. Acta Hort. 26, 37–44.

Eikhof R H, King P A and Moline S W 1973 The influence of a hydrophilic polymer on the water requirements and shelf life of container grown plants. Nat. Agric. Plastics Assoc. Conf. Proc. 11, 117–126.

Flannery R L and Busscher W J 1982 Use of a synthetic polymer in potting soils to improve water holding capacity. Commun. Soil Sci. Plant Anal. 13, 103–111.

Fonteno W C and Nelson P V 1990 Physical properties of and plant responses to rockwool-amended media. J. Amer. Soc. Hort. Sci. 115, 375–381.

Gehring J M and Lewis A J 1980 Effect of hydrogel on wilting and moisture stress of bedding plants. J. Amer. Soc. Hort. Sci. 105, 511–513.

Handreck K A 1983 Particle size and the physical properties of growing media for containers. Commun. Soil Sci. Plant Anal. 14, 209–222.

Haynes R J and Goh K M 1978 Evaluation of potting media for commercial nursery production of container-grown plants. N. Z. J. Agric. Res. 21, 449–456.

Heiskanen J 1992 Comparison of three methods for determining the particle density of soil with liquid pycnometers. Commun. Soil Sci. Plant Anal. 23, 841–846.

Heiskanen J 1993a Favourable water and aeration conditions for growth media used in containerized tree seedling production: A review. Scand. J. For. Res. 8, 337–358.

Heiskanen J 1993b Variation in water retention characteristics of peat growth media used in tree nurseries. Silva Fenn. 27, 77–97.

Heiskanen J 1993c Water potential and hydraulic conductivity of peat growth media in containers during drying. Silva Fenn. 27, 1–7.

Heiskanen J 1994a Effect of peat-based two-component growth media on the growth of containerized Scots pine seedlings. Suo 45, 17–29.

Heiskanen J 1994b Irrigation regime affects water and aeration conditions in peat growth medium and the growth of containerized Scots pine seedlings. New For. (In press).

Heiskanen J 1994c Water status of *Sphagnum* peat and a peat-perlite mixture in containers subjected to different irrigation regimes. HortScience. (In press).

Jackson D K 1974 Some characteristics of perlite as an experimental growth medium. Plant and Soil 40, 161–167.

Jenkins J R and Jarrell W M 1989 Predicting physical and chemical properties of container mixtures. HortScience 24, 292–295.

Johnson M S 1984 Effect of soluble salts on water absorption by gel-forming soil conditioners. J. Sci. Food. Agric. 35, 1063–1066.

Klute A and Dirksen C 1986 Hydraulic conductivity and diffusivity: Laboratory methods. *In* Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Agronomy 9. Am. Soc. Agr. Ed. A Klute. pp. 687–734. Soil Sci. Soc. Am. Publisher, Madison, Wisconsin.

Landis T D, Tinus R W, McDonald S E and Barnett J P 1990 Containers and growing media. The container tree nursery manual. Vol 2. USDA, Forest Service, Washinghton DC. Agric handbook 674. 87 p.

Langerud B R 1986 A simple *in situ* method for the characterization of porosity in growth media. Plant and Soil 93, 413–425.

Lennox T L and Lumis G P 1987 Evaluation of physical properties of several growing media for use in aerial seedling containers. Can. J. For. Res. 17, 165–173.

Nelson P V and Fonteno W C 1991 Physical analysis of rockwool slabs and effects of fiber orientation, irrigation frequency and production technique on *Chrysanthemum* production. J. Plant Nutr. 14, 835–866.

Puustjärvi V 1977 Peat and its use in horticulture. Turveteollisuuslitto ry. Publication 3. Liikekirjapaino, Helsinki. 160 p.

Richard F, Chausson J-S and Surber E 1958 The influence of soil moisture tension and soil structure on the growth of young spruce seedlings. Mitt. Schweiz. Anst. forstl. Versuchsw. 34, 1–34. (In German with English summary).

Scagel R K and Davis G A 1988 Recommendations and alternative growing media for use in containerized nursery production of conifers: Some physical and chemical properties of media and amendments. USDA, For. Serv. Rocky Mountain Experiment Station. Gen. Tech. Rep. RM-167, 60–65.

Sillanpää M 1956 Studies on the hydraulic conductivity of soils and its measurement. Acta Agr. Fenn. 87, 1–109.

da Silva F F, Wallach R and Chen Y 1993 Hydraulic properties of *Sphagnum* peat moss and tuff (scoria) and their potential effects on water availability. Plant and Soil 154, 119–126.

Taylor K C and Halfacre R G 1986 The effect of hydrophilic polymer on media water retention and nutrient availability to *Ligustum lucidum*. HortScience 21, 1159–1161.

Tripepi R R, George M W, Dumroese R K and Wenny D L 1991 Birch seedling response to irrigation frequency and a hydrophilic polymer amendment in a container medium. J. Environ. Hort. 9, 119–123.

Verdonck O 1983 New developments in the use of graded perlite in horticultural substrates. Acta Hort. 150, 575–581.

Verdonck O, Pennick R and De Boodt M 1983 The physical properties of different horticultural substrates. Acta Hort. 150, 155–160.

Woodhouse J and Johnson M S 1991 Water storing soil polymers and the growth of trees. Arboric. J. 15, 27–35.

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ISBN 951-40-1391-3
ISSN 0358-4283