Chapter 68
Physical Properties of Organic Soils and Growing Media: Water and Air Storage and Flow Dynamics

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68.1 INTRODUCTION

Along with their particle-size distribution and degree of decomposition, the specific properties of growing media and peat substrates require the development of characterization methods specific to their use and behavior. The low wettability of dry peats is a fundamental characteristic that needs to be characterized when assessing peat properties for horticultural use. Other physical properties of peat soils are measured in a similar way to that of mineral soils, but methods developed for mineral soils have been modified to facilitate the standardization of peat materials. This is also the case for growing media, but with even more specificity. Methods have been developed for characterizing growing media because of the importance of disturbance on the analytical results as well as the specific contexts linked to their use: pot configuration, irrigation devices, and type of culture.

When analyzing organic soils and growing media, apart from sample disturbance, careful attention should be paid to wettability and hysteresis effects. Wettability can be dealt with by carefully rewetting the sample using hot water, a wetting agent, or prewetting well ahead of the final sample preparation. Hysteresis refers to the fact that properties measured during drainage may differ from those measured on rewetting. Some growing media are well known to be hysteretic, and hence particular properties linked to gas diffusivity, water retention, air content, and unsaturated hydraulic conductivity should be performed under rewetting or drainage, depending on sample use (greenhouse or nursery), along with the range of water potentials representative of such use and any other specific conditions (container geometry, irrigation devices, etc.). This chapter presents methods to characterize the physical properties of growing media and organic soils, adapted to reduce disturbance, and acknowledging wettability and hysteretic issues.

68.2 WETTABILITY (OR WATER REPELLENCY)

Peat is well known and is used for its capability of storing large amounts of water. Despite this aspect, air-dried peat is also well known for its hydrophobicity and the nature of this peculiar behavior had been studied extensively (Fuchsman 1986). Commercially, it is overcome by the extensive use of a surfactant or by the addition of mineral components (Michel 1998). However, the wettability of peat-based substrates should be assessed before its use to decide whether or not a wetting agent should be added to the medium.

Organic matter is one constituent affecting the soil's hydrophilicity or hydrophobicity, and thus its behavior during rewetting (Jouany et al. 1992; Dekker et al. 2000; Michel et al. 2001). Water repellency can cause problems because, after drying out, organic soils or growing media show a high heterogeneity in water flow rates, thus requiring a long rewetting time as their physical properties are impaired (Valat et al. 1991; Michel 1998).

Wettability is the ability of a liquid to spread over a surface (Letey et al. 1962). A drop of liquid placed on a solid surface configures itself in a way that depends on the interaction between solid and liquid. The Young (1805) equation describes this system at equilibrium

$$\gamma_{\mathrm{L}} \cos \varepsilon = \gamma_{\mathrm{S}} - \gamma_{\mathrm{SL}} \qquad (68.1)$$

where γ_{S}, γ_{SL}, γ_{L} are the surface tension of the solid, the interfacial tension between the liquid and the solid, and the surface tension of the liquid, respectively, and ε is the contact angle at the solid–liquid–vapor interface.

Wettability can then be estimated from contact angle measurements, knowing that the wettability is high when ε approaches zero (see Data Analysis, p. 888). Most of the time, simple and rapid tests such as the "water drop penetration time" (WDPT) (Letey 1969; McGhie and Posner 1980; Dekker and Ritsema 2000), the "molarity of an ethanol droplet" (King 1981; De Jonge et al. 1999), etc. are used to estimate the wettability of materials, which provide only a primary (qualitative) evaluation of wettability. However, measurements of the solid–liquid contact angle are the best techniques to precisely evaluate the wettability of materials.

68.2.1 THE WATER DROP PENETRATION TIME METHOD

Materials and Reagents

1. Syringe (2 mL maximum) and distilled water
2. Dry surface of soil or substrate

TABLE 68.1 Classification of Soil/Substrate Water Repellency Related to the Water Drop Penetration Time (WDPT)

WDPT	<5 s	5–60 s	60–600 s	600 s–1 h	>1 h
Surface state	Hydrophilic	Weakly hydrophobic	Highly hydrophobic	Severely hydrophobic	Extremely hydrophobic

Source: From Dekker, L.W., Ritsema, C.J., and Oostindie, K. in L. Rochefort and J.-Y. Daigle (Eds.), *Proceedings of the 11th International Peat Congress*, Vol. 2., Edmonton, AB, Canada, 2000, 566–574.

Procedure

1. Apply 10 to 15 drops of distilled water (10 μL each) onto the soil or growing media surface using a syringe.
2. Measure the time for the complete penetration of the drop into the material.
3. Characterize the surface state in relation to the time of penetration, found in Table 68.1.

Comments

Large variations in the measurements can be observed in relation to the roughness and structure of the materials, and also to the heterogeneity of the composition of materials.

68.2.2 DIRECT CONTACT ANGLE MEASUREMENT: THE DROPLET METHOD

The direct droplet method is by far the most common, and consists of measuring the contact angle between a liquid and a solid surface.

Materials and Reagents

1. Goniometer
2. Hydraulic press for compacting soil or growing media
3. A few grams of air-dried soil or growing media (~1–5 g, depending on the density of material tested)

Procedure

1. Prepare a smooth, planar, homogenous, isotropic surface (Busscher et al. 1984) by compacting the sample of soil or growing media with a hydraulic press at 75 MPa (Valat et al. 1991) or by drying the soil or growing medium liquid suspension on a thin slide.
2. Place a drop of water (10 μL) with a syringe on the material.

3 Measure the contact angle either directly from the profile of the volume of the droplet using an optical goniometer or from the measurement of the geometrical dimensions: volume, height, and length (Letey et al. 1962; Chassin 1979; Good 1979).

Data Analysis

Conventionally, a material can be considered hydrophilic when the contact angle with water is less than 90°, and hydrophobic when the contact angle is more than 90°. The smaller the contact angle, the higher the wettability.

Comments

The necessity of having a smooth and planar surface makes it impossible to measure the wettability of materials related to the water content due to changes in the rugosity (roughness factor) of the surface and the contact angles can only be measured on dried materials.

68.2.3 INDIRECT CONTACT MEASUREMENT: CAPILLARY RISE METHOD

Because of the aforementioned constraints, and contrary to the droplet method, the capillary rise method, already used to measure the rewetting time of soils (Letey et al. 1962; Watson and Letey 1970), also can be used to measure contact angles on noncompacted materials, as well as the wettability of materials at different water contents (Michel et al. 2001).

The contact angle is calculated from the modified Washburn (1921) equation, which defines the flow of a liquid through a capillary column by considering that a material can be described as a bundle of capillaries:

$$\frac{l^2}{t} = \frac{\gamma_L(\tau \cdot r)\cos\varepsilon}{2\eta} \tag{68.2}$$

where l represents the height of the wetting front (cm), t is the time (s), η and γ_L are the viscosity (mPa · s) and the surface tension of the liquid (mJ m^{-2}), respectively, r and τ represent the mean radius (cm) and the tortuosity constant (to approximate the tortuosity of the capillaries), respectively, and ε is the contact angle (°).

By replacing the height of the wetting front l by the increase in weight m due to the penetration of the liquid through a bundle of capillaries, the Washburn equation becomes

$$\cos\varepsilon = \left(\frac{m^2}{t}\right)\left(\frac{\eta}{\rho^2\gamma_L c}\right) \tag{68.3}$$

in which

$$c = \frac{1}{2}\Pi^2(\tau r)^5 n^2 \tag{68.4}$$

where m is the mass of the adsorbed liquid (g), ρ is the density of the liquid (g cm^{-3}), and n is the number of capillaries. The term c (cm^5) corresponds to an empirical constant of the porosity and tortuosity of capillaries, which depends on particle size and degree of packing.

Materials and Reagents

1. Glass tube with a porous glass base (around 1 cm diameter 4 cm in height).
2. Microbalance (precision at the millimetric scale).
3. Tensiometer (apparatus for measuring the surface properties of liquid or solid, e.g., surface energy and surface tension). Note: not the tensiometer that measures water potential in soil.
4. Liquids: hexane (extra pure) and distilled water.
5. A few grams of soil or growing media equilibrated at different water contents (~1–5 g, depending on the density of material tested and its water content).

Procedure

The experiment consists of following the capillary rise on a column of soil or growing media with various liquids.

1. Place a sample of soil or growing medium in the glass tube (with a porous glass base).
2. Fix the tube to the microbalance.
3. Place the tube in contact with a receptacle containing a liquid with a very low surface tension (i.e., hexane), which completely wets the sample ($\varepsilon = 0$).
4. Measure automatically the speed of capillary rise, translated by the increase in weight in the sample, in relation to time by a computer.
5. Repeat steps 1 to 4 several times with hexane.
6. Assess the parameter c from the Washburn equation (Equation 68.3).
7. Repeat steps 1 to 4 several times with distilled water.
8. Then, compute the contact angle with water from the above equations.

Comments

The main sources of error come from variations in porosity and permeability of materials, and from the assumption that the geometry of the pores is not affected by wetting, which is not the case for unstable materials. But the most important limitation of the capillary rise method is the inability to measure angles greater than 90° (since there is no capillary rise for a hydrophobic material), and hence the degree of hydrophobicity. It is also impossible to measure the wettability at very high water potentials (>−10 kPa) because of the absence of capillary rise for quasisaturated materials, but this is of minor importance because materials at water potentials >−100 kPa are already highly hydrophilic (Michel 1998).

68.3 BULK DENSITY

Bulk density (BD) is an easily measured property correlated with many other peat properties and is used for trade and characterization purposes. In organic soils, it is simply determined in the same way as for mineral soils using a cylinder of known volume forced into the soil, then air dried and weighed. Special sampler shapes have been proposed (Sheppard et al. 1993). A cylinder with a sharpened edge can also be used. However, the bottom surface contact area of the core should be very large, as small cores (5 cm diameter and less) can compact the organic soil easily on a ratio of 5, 6, or even 7 to 1 (against about 1.2 to 1 for mineral soil with the same instrument).

For peat-based substrates (as well as other organic growing media), specific methods have been developed to prevent any disturbance, because of their sensitivity to settling and loosening. Therefore, a reliable methodology to prepare samples and measure bulk densities is of great importance. Also, because of this sensitivity, sample preparation should yield BD values close to those obtained under cultivation. Worldwide, two groups of standardized methods exist. The first group uses large-volume samples (20 L) prepared without compaction and have been designed and are used mainly for trade purposes (e.g., CEN method, 12580; Morel et al. 1999). A second group of methods uses smaller volumes (usually less than 1 L), which are naturally drained after saturation or onto which an external pressure is applied in addition to overburden pressure (Hidding 1999). These methods attempt to mimic natural settling conditions in a potted substrate under cultivation and are mainly used for characterization purposes. Additional details on these two groups can be found in Caron and Rivière (2003).

68.3.1 BULK DENSITY WITH CORES (FOR ORGANIC SOILS OR LOOSE SUBSTRATES)

This method is commonly used with organic soils or on cores filled with loose substrates.

Materials and Reagents

1. Core samplers or McCauley sampler and sharpened knife
2. Forced-air oven

Procedure

1. For organic soils, trim a core of undisturbed peat with a sharpened knife to fit roughly into the core sampler. A core sample can also be extracted with a McCauley sampler.
2. Alternatively, for peat substrates, they should be loosely packed into cores (as described below for the water desorption curves, using the CEN/TC 223 method). Samples should be prepared as for the water desorption procedure with the above part of the cylinder removed (see water desorption), and the

sample wetted from underneath and then saturated again. Then the substrates should be drained on a tension table (see below) at a tension of −1 kPa.

3 Dry samples at 105°C or 70°C, then compute the BD from

$$\mathrm{BD} = \frac{\mathrm{SDW}}{V} \tag{68.5}$$

where BD is bulk density (mass per unit volume), SDW is the sample dry weight, and V is the core volume.

Comments

Care should be taken in order to minimize peat compression by the cylinder when sampling. The BD of peat materials is affected by water content. Preequilibration of the substrate at −5 kPa before core filling is therefore now a standard practice in Europe (Verdonck and Gabriels 1992). The correlation between BD and ash content is high (Grigal et al. 1989). BD is also highly correlated to the degree of decomposition (Silc and Stanek 1977). The above method, as well as other methods using the oven-dry weight at 105°C (see below), might slightly overestimate the water content of peat, since peat drying at a temperature exceeding 85°C can result in some loss of organic matter (Macfarlane 1969). Hence, drying at 70°C may be preferred. Prior checks should be made with the type of material in order to set a reference drying temperature.

68.3.2 BULK DENSITY *IN SITU*

Techniques have also been developed to measure BD directly in the potted substrates without any substrate manipulation (Paquet et al. 1993). After the compaction process, either natural or artificial, BD is determined using time domain reflectometry (TDR) (Topp et al. 1980) and is calculated from the total porosity (water content at saturation) determination measured on soil cores or cylinders using TDR. The same technique can be used at a saturated depth in the profile (see Section 68.4.2).

68.4 WATER AND AIR STORAGE

68.4.1 TOTAL POROSITY

Total porosity is the first point of the water desorption curve since it gives the total volume available for water and air storage. It is one of the important parameters in assessing the quality of commercial growing media (Hidding 1999). It can be measured directly *in situ* for potted growing media or directly in the field for organic soils. Alternatively, it can be measured on soil or substrate cores. For loosely filled substrate cores, samples are prepared the same way as for the water desorption curve (see below).

68.4.2 TOTAL POROSITY *IN SITU*

The approach is based on the volumetric water content determination on cores or potted substrates slowly rewetted from underneath, and assumes no air entrapment. The same technique can be used at a saturated depth in the profile.

Materials

1 Samples in a pot or in cores or alternatively a saturated depth in the profile.

2 A water bath for slow rewetting from underneath (for pots or cores).

3 Distilled or deionized water.

4 TDR probes of the length equivalent to the desired volume to be sampled.

5 A time domain reflectometer. Alternatively, CS-615 or any other time domain, frequency domain, or capacitive probe could be used, but they tend to be less accurate.

6 An appropriate calibration curve for the probe, if necessary.

Procedure

1 Rewet a sample in a pot or core from underneath by gradual elevation of the water level and immersion for 24 h, with the water level about 1 cm below the top of the substrate. This achieves full saturation of the substrate, without having significant changes in total porosity as a result of the release of the overburden pressure.

2 Insert the TDR probe into the sample. As the TDR technique represents the average water content along the sampling probe, the probe should be made to sample the total pot height (for a vertical sample), desired soil depth (for sampling in peat bogs), or the pot diameter (for horizontal sampling). The probe should be fully inserted into the substrate, or its full length and should sample the whole depth. Additional measurements could be taken, if necessary, by reinserting the probes at other locations within the sample. The TDR apparatus determines the apparent dielectric constant of the medium, from which volumetric water content is derived. The apparatus must be calibrated a priori against volumetric water content determined from weighing, as equations relating the apparent dielectric constant to volumetric water content derived for mineral soils do not apply to organic soils (Paquet et al. 1993). Paquet et al. (1993), Anisko et al. (1994), and Da Sylva et al. (1998) have published different calibration equations for various organic–mineral soil mixtures.

Calculations

Calculate volumetric water content from the dielectric constant measurement. Total porosity is then assumed to be equal to the volumetric water content. BD can be deduced from total porosity estimates, obtained by measuring water content after complete rewetting of the substrate and from particle density (PD) estimates (see next section).

Comments

It is critical with this approach to resaturate slowly (resaturation by slowly raising the water level in the bath to reach full saturation of the sample). This procedure is frequently used for well-moist blonde peat (Caron et al. 2002), but may lead to serious errors with air-dried white or black peat materials (Wever 1995), and therefore the period of rewetting should be prolonged if necessary. One way to check is to monitor, over a long period of time, the readings obtained with TDR to make sure they do not increase and to deaerate the sample if needed by putting the core in a chamber or the pot within a cell (Nemati et al. 2002). Potted plants, recently cut, with many roots, have been suspected of generating lot of gases, and care should be taken to apply a vacuum when resaturating the sample to avoid any gas entrapment. Gas entrapment (methane) may also occur in field samples (Buttler et al. 1991).

68.4.3 TOTAL POROSITY BY CALCULATION

Physical parameters, such as total pore (TP) space, can be calculated from knowing the BD and ash content, after determining the BD obtained on soil cores (see above).

Calculations

Total porosity can be calculated from BD and PD. Particle density is estimated from ash content (Paquet et al. 1993), assuming a PD of 1.55 for the organic fraction (OM) and 2.65 for the mineral fraction (Verdonck et al. 1978):

$$\%\mathrm{OM} = 100\% - \%\mathrm{ash} \tag{68.6}$$

$$\mathrm{PD} = \frac{1}{\frac{F}{1.55} + \frac{1-F}{2.65}} \tag{68.7}$$

where

$$F = \frac{\%\mathrm{OM}}{\%\mathrm{solids}}. \tag{68.8}$$

$$\mathrm{TP} = 1 - \frac{\mathrm{BD}}{\mathrm{PD}} \tag{68.9}$$

Alternatively, PD can be measured on samples using kerosene or ethanol and a pycnometer using the classical mineral soil approach (Blake and Hartge 1986).

Comments

Macfarlane (1969) reported that estimates of PD calculated from ash content can deviate up to 18% from the actual value.

68.4.4 WATER DESORPTION CURVE ON CORES

This method is widely used in Europe and has been adopted by the International Society of Horticultural Science to characterize growing media used in nurseries and greenhouses (Verdonck and Gabriels 1992; Hidding 1999). It provides estimates of the volumetric water content (sometimes referred to as water-holding capacity) at different potentials.

When characterizing peat material, past literature and common use have referred to the water-holding capacity of peat as one characteristic, often obtained by the soak and drain method (Parent and Caron 1993), where water in saturated peat is extracted by gravity. However, since the water potential at which the water-holding capacity is measured is equal to half the height of the peat sample, the value of water-holding capacity is inaccurate as the method does not provide information on the height of the cylinder at which the water content is measured. Hence, much more complete information is provided by the water desorption curve, and this characterization is recommended for obtaining information on the water-holding capacity of materials.

Materials

1. Double rings (5 cm height and 10 cm i.d.) as well as fixing collars made of temperature-resistant polypropylene should be used. Fix the collar at the periphery of the bottom ring of known volume V_R (2 cm high, glued at a height of 1.5 cm on the lower ring, and hence overlapping 0.5 cm on the upper ring).
2. Nylon gauze fitting the bottom of the rings.
3. A sand box or a tension table (Topp and Zebchuk 1979).
4. Large plastic containers, perforated at the bottom.
5. Steel frame and nylon cloth about 30 × 60 cm.
6. A large plastic water bath (about 5 L or more).

Procedures

1. Transfer around 10 L of material in several containers.
2. Cover the pot with a nylon cloth.
3. Place the pot on a steel frame into the water bath.
4. Fill the bath slowly up to 1 cm under the top of the substrate.
5. Stand overnight.
6. Remove the pot and leave 48 h on the sandbox, applying a potential of −5 kPa pressure head measured from the bottom of the plastic pot.
7. Then fill the assembled rings (with a cheese cloth or very coarse nylon cloth secured at the bottom of the lower ring) with the material using a large spoon in increments of about 100 mL without causing compaction (filling the hollow spaces though) of the removable rings.
8. Cover the upper ring with a nylon cloth to prevent substrate from floating.
9. Transfer the filled double rings to the bath.

10 Flood slowly to 1 cm from the top of the upper ring.

11 Saturate for 24 h.

12 Transfer to the tension table.

13 Cover the table and the sample with a cloth.

14 Apply a pressure head of −1 kPa (10 cm of suction), calculated from the middle of the lower ring.

15 Equilibrate for 48 h.

16 Remove the sample from the table and then the upper ring slowly, exposing the uppermost part to the material.

17 Strike off the excess material keeping a flat surface using a sharp knife without causing compaction. This is a delicate operation that should be performed as precisely as possible. Very fibrous material should be cut with large scissors.

18 Determine the weight of the sample present in the lower ring (W_R).

19 Return the sample for other potential determinations (−2, −5, −10 kPa), leaving them at least 24 h between each measurement. Check for equilibrium (constant weight) at a given potential before applying a new potential.

20 Dry the sample in the oven at 105°C to estimate dry BD and volumetric water content at each corresponding potential. For shrinking material, measurement of height of the substrate within the ring may be useful to correct the volumetric water content by adjusting V_R accordingly. Adjust for cheese cloth weight.

Calculations

1 Volumetric water content at −1 kPa, θ_1, is determined as

$$\theta_1 = \frac{W_1 - W_R}{V_R} \qquad (68.10)$$

where W_R is the dry weight of the lower ring and V_R the ring volume. The volumetric water content for other potentials is then determined accordingly by replacing W_1 with the weight corresponding to the potential applied.

2 Air volume (AFP for air-filled porosity) is determined from the difference between total porosity (TP) and θ_1:

$$\text{AFP} = \frac{\text{TP} - \theta_1}{V_R} \qquad (68.11)$$

3 Easily available water (EAW) is the water volume between −1 and −5 kPa and is calculated from

$$\mathrm{EAW} = \frac{\theta_1 - \theta_5}{V_\mathrm{R}} \tag{68.12}$$

4 Available water (AW) is the water volume between −1 and −10 kPa, and is calculated from

$$\mathrm{AW} = \frac{\theta_1 - \theta_{10}}{V_\mathrm{R}} \tag{68.13}$$

5 Buffer capacity (BC) is the water volume between −5 and −10 kPa and is calculated as

$$\mathrm{BC} = \frac{\theta_5 - \theta_{10}}{V_\mathrm{R}} \tag{68.14}$$

Comments

Because of pronounced hysteretic effects, the measurements should be performed at different potentials upon rewetting. This is particularly relevant when the substrates are used with subirrigation devices (ebb and flow, gullies, capillary mats) to be more representative of growing conditions.

68.4.5 WATER DESORPTION OF POTTED SUBSTRATES

For diagnostic purposes, in research facilities, nurseries, or greenhouses, attempts have been made to infer properties existing in pots from the water desorption curves measured on independent samples. Paquet et al. (1993) have shown that substrate disturbance alters these properties and Fonteno (1989) exemplified the effects that container size and geometry may have on existing water and air contents in containers. It is also our experience that once potted, substrate physical properties will evolve significantly, as a result of settling and compaction, decomposition, particle reorganization, and root activity (Allaire-Leung et al. 1999). Hence, measurements taken directly in the pot before and during plant growth are advisable for accurate diagnosis and proper characterization.

Materials

1 Potted substrates with the containers open at the bottom

2 TDR apparatus and probe or a weighing scale

3 Polyethylene sheets, a screen or nylon gauze

4 Tension table apparatus (Topp and Zebchuk 1979)

Procedure

1 When using potted substrates with growing plants, first cut off the top part of the plant.

2 Resaturate the substrate from below by slowly increasing the water content to saturate the sample, measuring water content with a vertically inserted probe.

3 Bring the water level up overnight, and finish raising it up to 1 cm below the top of the substrate.

4 Measure the water content during the day to make sure it reaches a constant value. Drift may suggest a high level of entrapped air. Flush trapped air with carbon dioxide if necessary, and then resaturate with deaerated water or put the sample into a vacuum chamber.

5 Determine water content at saturation (it then equals TP).

6 Let the sample drain for about 1.5 to 2 h, and then measure the TDR values vertically at regular intervals during drainage to make sure they have reached a constant value, i.e., the volumetric water content at container capacity, which may differ from that at -1 kPa, since the equivalent applied potential, due to the weight of water, varies with container height (Fonteno 1989). Alternatively, the container can be weighed (in absence of TDR measurements).

7 AFP can then be calculated from the difference between volumetric water content at saturation and that after saturation and drainage (θ_c) using

$$\mathrm{AFP} = \mathrm{TP} - \theta_c \tag{68.15}$$

8 Cover the substrate top surface with a plastic sheet to restrict evaporation.

9 Take a second measurement with a horizontally inserted probe and note the height of the probe to estimate the corresponding potential.

10 Put the substrate in contact with the tension table (Figure 68.1). Make sure a good contact is established between the sample and the tension table by making a slurry if necessary, or by making additional holes at the bottom of the pot and fixing a screen or a gauze, if necessary, to retain the substrate.

11 Apply a series of water potentials, the most common being $-1, -2, -5$, and -10 kPa, by lowering the opening of the drainage tube of the tension table to a fixed distance (10, 20 cm, etc.) from the probe height. Equilibrate for 24 h between each potential point, measuring the volumetric water content or weigh the pot between each point. For each measurement, record the water content and the corresponding height. Using TDR instead of a weighing balance has the advantage of accuracy at a known height and prevents removal of the potted substrate from the tension table.

12 Measurements should be performed on rewetting and on drainage, as the properties clearly differ because of hysteresis, which affects air content and AW.

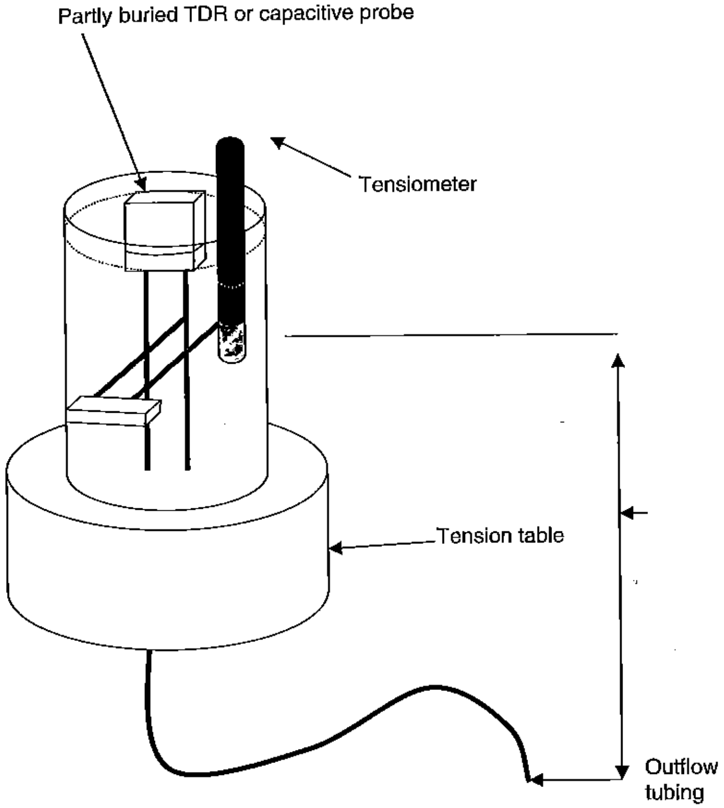

FIGURE 68.1. The system to measure the soil water desorption curve on potted substrates or in cylinders showing horizontally or vertically installed TDR probes. The plant should be cut before putting the pot onto the tension table.

13 Draw the water desorption curves and calculate the parameter as mentioned above (Equation 68.11 through Equation 68.15). In the absence of a TDR, TP should be calculated from the bulk and particle densities, which requires determination of the whole container weight at 105°C for use in the calculation of AFP in Equation 68.15.

Comments

The entrapment of air can be a problem with the tension table method, and care should be taken to avoid breaking the water column. The above procedure has been described in more detail elsewhere for pots (Paquet et al. 1993).

68.4.6 POINT OF AIR ENTRY

Measurement of point of air entry is critical if an indirect assessment of the gas diffusivity is desired (Caron and Nkongolo 2004). It may also be used for modeling purposes and in the design of growing systems for identifying the height of the water-saturated zone at the bottom of containers, which then may result in oxygen-deficient zones. Caron et al. (2002) and Nemati et al. (2002) carried out a comparison of different approaches to identify the air-entry value, and the one based on the water desorption curve is presented here (Nemati et al. 2002) for determination of air entry at the bottom of the pot. Nemati et al. (2002) have also proposed and validated another approach based on pressure transducer measurements, which can be automated. Other approaches have been proposed and tested but have yielded inaccurate estimates for a large number of growing media (Caron et al. 2002).

Materials

1 Substrates potted in PVC cylinders or in greenhouse or nursery containers, loosely filled or taken directly from the production area should be used. The walls of cylinders or pots should be perforated with two tapped holes: one for the TDR probe to monitor water content and the other for the tensiometer to monitor matric potential.

2 A TDR probe consisting of three 145-mm long stainless steel rods, 2 mm diameter and spaced 15 mm apart, forming a plane.

3 Minitensiometers approximately 80 mm long × 8 mm outside diameter.

4 A fast-response tension table, an Erlenmeyer flask, and a metal stand (see Figure 1 in Nemati et al. 2002).

Procedure

1 Before starting the measurements, evaluate the zone of influence of the TDR probe. It can be determined by immersing horizontal probes in water and measuring at what distance from the horizontal position of the probes any changes in water content can be accurately detected.

2 Prepare the substrates in cylinders as mentioned above (see Section 68.4.5) or obtain the containers from the production area.

3 Saturate the sample from the bottom, slowly raising the water level overnight. Bring the water level to about 1 cm from the top of the substrate.

4 Slowly drain the substrate and put the cylinder in contact with the tension table.

5 Insert the TDR probe (30 mm from the bottom of the pot) and the tensiometers horizontally at the precise height corresponding to the top zone of influence of the probe (Nemati et al. 2002), and apply a potential of +0.2 kPa to the table (i.e., with a 20 mm height of water on the surface of the tension table).

6 Cover the cylinders or pots to restrict evaporation, but leave small holes to allow air to enter at the surface.

7 Monitor water content and matric potential of the substrates daily after each decrease of water level at the rate of 10 mm per day. This step can be fast or slow depending on the hydrodynamics of the system. An assessment of the dynamics of equilibrium should be performed first by checking (after potential changes) the pace at which the water content changes, by monitoring the water content with the TDR probes at different times.

8 Adjust the matric potential data for the height of the water column in the tensiometer as well as for the distance between the tensiometer and the TDR probe.

9 Plot water content as a function of water potential $\theta(\psi)$. It will result in a curve with at least two distinct zones: an initial zone showing nearly constant water content with decreasing water potential and a second zone showing sharp decrease in water content with water potential (in some cases followed by a third zone of lesser decrease). The air-entry value is estimated from the intersection of the fitted lines for the first two zones as illustrated by Nemati et al. (2002).

68.5 WATER AND GAS MOVEMENT

68.5.1 Saturated Hydraulic Conductivity on Cores or in the Field

This method is preferably used with organic soils and substrate-filled cores. Hydraulic conductivity of organic soils is determined in the same manner as mineral soils (Klute and Dirksen, 1986). One should be aware that organic soils are composed of rather loose materials and that, consequently, the walls of auger holes may be unstable while measuring hydraulic conductivity or the infiltration rate of water in the field. However, measurements *in situ* are obviously more preferable than measurements performed on disturbed cores because of the high sensitivity of the structure. Measurements of saturated hydraulic conductivity (K_s) by the constant-head or the falling-head method may be invalidated by the presence of large particles in the peat sample. Also, mathematical models developed especially to estimate saturated hydraulic conductivity from field measurements might not apply to organic soils (Hemond and Goldman 1985). Verification of the applicability of Darcy's law in peat substrates has however led to the conclusion that low flow is laminar and Darcy's approach applies (Allaire et al. 1994). If so, then measurements made directly in the field using the Guelph permeameter are possible above the water table but may require an independent estimation of α (a parameter used to characterize the unsaturated hydraulic conductivity). Organic soils in our studies have yielded estimates of α of about 9 m^{-1} on internal drainage tests (J. Caron, unpublished data). These values are comparable to that of some peat substrates (about 7–9 m^{-1}) (Caron et al. 1998; Jobin et al. 2004), but may be higher. Saturated hydraulic conductivity values sometimes are comparable to that of sandy loam or loam soils, which is surprising, but may be linked to their low pore effectiveness (Caron and Nkongolo 2004). Readers are referred to K_s measurement procedures for mineral soils (see Section ''Soil Water Analyses'') for further details on K_s determinations, either in the field or in the laboratory (if the decision is made to use cores).

68.5.2 Saturated Hydraulic Conductivity of Potted Growing Media

The particularly sensitive structure of growing media makes it highly advisable to measure the saturated hydraulic conductivity on undisturbed substrates. The measurement is sometimes performed with plants present, which incorporate changes in the structure of decomposition, reorganization, settling, and root enmeshment, all of which are known to affect K_s determinations (Allaire-Leung et al. 1999). The procedure uses constant-head permeameter devices to establish steady-state conditions and obtains flow measurements in a container (Figure 68.2). Since these flow measurements are affected by the container geometry and hole distribution (a 3-D process), the flow is corrected to provide an estimate of the equivalent saturated hydraulic conductivity from Darcy's law as if it was a 1-D process measured in a cylinder. Performing these measurements in a cylinder may be problematic

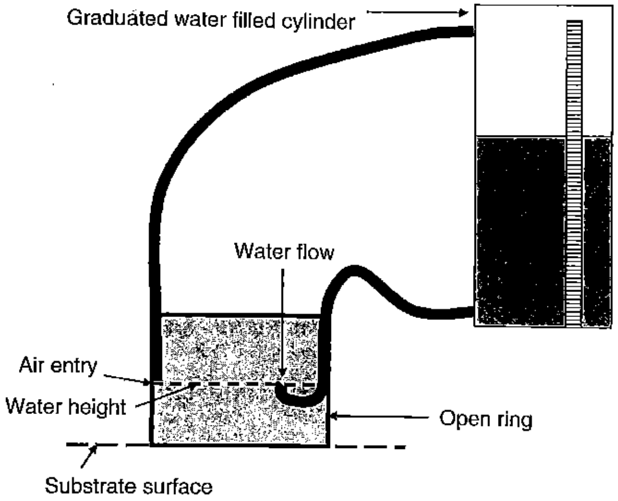

FIGURE 68.2. Schematic representation of the special head of the Côté's infiltrometer to measure saturated hydraulic conductivity.

because of the very sensitive structure, and important deformations affecting the K_s determination have been observed. Allaire et al. (1994) have instead proposed correcting the flow from the measurement performed directly in the pot and have shown this approach to be appropriate. Obviously, the container geometry, hole distribution, and hydraulic gradient affect the correction factor. If no correction factor is available, Allaire et al. (1994) describe an experimental procedure on how to derive it from solving Laplace's equation in 3-D.

Materials

1. A constant-head permeameter (Côté's infiltrometer, Figure 68.2), with a special head that can be moved directly onto a pot surface (Banton et al. 1991)
2. An interpretation chart for different container heights and pot-hole distributions (Allaire et al. 1994)
3. A ruler
4. A substrate field container, with or without the actively growing plant
5. A water pail

Procedure

1. Immerse containers in a distilled-water or tap-water filled bath for 24 h by slowly rewetting the sample from underneath. A prewetting period may be necessary if hydrophobicity is suspected.
2. Take the container slowly off the bath and put it onto a metal stand having a perforated surface.

3 If there is an empty space between the container side and the substrate, fill the gap with bentonite to avoid preferential flow.

4 Cover the substrate surface with a screen or a porous pad (scouring pad) to prevent particles from floating and plugging the opening of the infiltrometer or to reduce particle displacement.

5 Establish steady state when maintaining a known height of water above the substrate surface using the infiltrometer.

6 Measure the water drop in the permeameter as a function of time.

7 Calculate flux after reaching steady-state conditions (Q).

8 Determine the known height of water above the substrate surface (h).

9 Determine the final height after running the experiment (L).

10 Calculate the substrate surface area (A).

11 Find the flux reduction ratio obtained from Figure 5 in Allaire et al. (1994). For 1 L pots with multiple holes (type Ultra) commonly found in greenhouses, we determined that the R_f value is equal to 1.66 with a substrate height of 7 and 3 cm of water head.

12 Calculate the saturated hydraulic conductivity K_s from

$$K_s = \frac{QLR_f}{A(h+L)} \tag{68.16}$$

68.5.3 UNSATURATED HYDRAULIC CONDUCTIVITY ON SOIL CORES AND POTTED SUBSTRATES

Instantaneous profile methods (Watson 1966; Wind 1969; Hillel et al. 1972; Vachaud and Dane 2002) have successfully been used in the field at different depths for characterizing the whole-unsaturated hydraulic conductivity curve on both drainage and rewetting. The approach has been used for potted substrates and on soil cores (Naasz et al. 2005) and is presented here. The method is highly variable, close to saturation (−1 to 0 kPa) (Caron and Elrick 2005; Naasz et al. 2005), but provides useful and rapid estimates in the range of water availability (−1 to −20 kPa) in this kind of substrate. Unsaturated hydraulic conductivity (using constant-head methods) is not accurate enough for an adequate characterization at potentials lower than −2 kPa, and therefore is not presented herein.

Materials

1 Two large PVC cylinders (14 cm diameter and 14 cm height).

2 Small PVC cylinders (10 cm diameter and 12 cm height, $V = 942\ \text{cm}^3$).

3 A TDR system: two TDR miniprobes (three wires, 80 mm long, with 4-mm uncoated stainless steel rods and a spacing of 10 mm). The probes are connected to a Tektronix 1502C system (Tektronix, Beaverton, OR) via a multiplexer run by WINTDR software (Time Domain Reflectometry Soil Sample Analysis Program V. 6.1, Utah State University, Logan, Utah).

4 A tensiometer system: two minitensiometers (2.2 mm diameter and 20 mm length, ceramic cell, SDEC 220 [Société Développement et Commercialization, Reignac, France]) are connected to pressure transducers (differential pressure sensors, precision: ±0.03%, response time: 10^{-3} s) monitored by a real-time multitasking computer to control the measurement and to collect data.

5 Small ventilators to impose top-surface sample evaporation.

6 A Mariotte bottle to maintain a constant-head bottom infiltration.

Procedure

1 Since the physical properties of organic substrates are largely influenced by preparation and, more precisely, by the packing of materials, the procedure of substrates preparation is standardized: manually fill with substrate (but without packing) two large PVC cylinders (14 cm diameter and 14 cm height). Slowly wet cylinders (30 min) from the bottom, saturate with distilled water for 24 h, and allow samples to equilibrate for 48 h to a water potential of −5 kPa (on a tension table). Empty cylinders, homogenize substrate, and fill small PVC cylinders (10 cm diameter and 12 cm height) with substrate without packing. Finally, slowly saturate material from the bottom for 24 h.

2 Horizontally insert (at an angle of 90°) the two pairs of sensors (TDR probes and minitensiometers to determine volumetric water content θ and the water potential ψ, respectively) at two levels, h_1 and h_2, from the bottom of the small PVC cylinder ($h_1 = 9$ cm and $h_2 = 3$ cm, Figure 68.3).

3 Seal the bottom of the column to prevent water loss and then slowly saturate the substrate from the bottom with the Mariotte bottle.

4 When readings (TDR and tensiometers) indicate that the core is in hydrostatic equilibrium (after about 30 min), the evaporation experiment could begin.

5 Impose controlled top-surface sample evaporation with the small ventilators.

6 The evaporation experiment is terminated when the uppermost tensiometer in the substrate core reaches a suction level of approximately −30 kPa.

7 The sample is then subjected to infiltration. During the infiltration experiment, impose three pressure levels (stepwise increases): −15, −5, 0 kPa.

8 The drying–wetting cycle lasts for approximately 1 month and represents ~8000 sets of water content/water potential data (measurements were taken every 5 min).

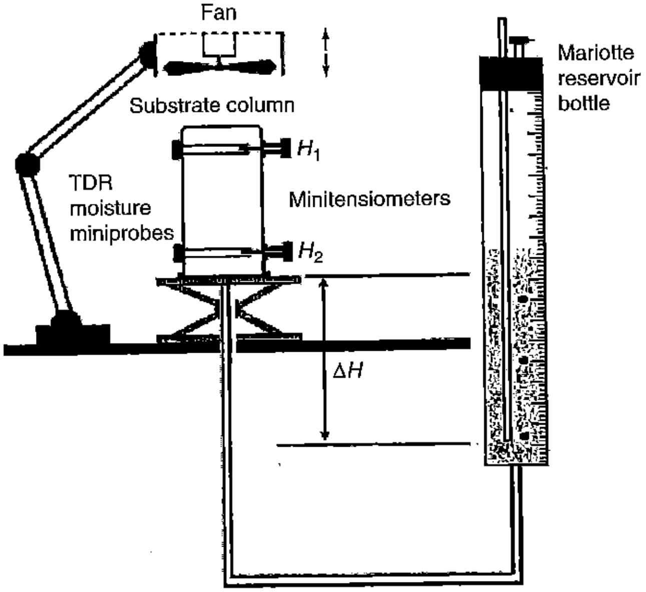

FIGURE 68.3. Schematic representation of the experimental design for measuring the unsaturated hydraulic conductivity in cores. (Redrawn from Naasz, R., Michel, J.-C., and Charpentier, S., *Soil Sci. Soc. Am. J.*, 69, 13, 2005.)

Calculations

Calculate the unsaturated hydraulic conductivity by direct measurement from water content and water pressure data obtained during evaporation and infiltration experiments with the Darcy equation. First, calculate the water flow through the column q from the temporal changes (Δt) in water storage at two depths (h_1 and h_2) as follows:

$$q = -\frac{\Delta\theta_{h_1} - \Delta\theta_{h_2}}{\Delta t} \tag{68.17}$$

where $\Delta t = t_2 - t_1$ is the time interval; t_1 is time 1 and t_2 is time 2. The unsaturated hydraulic conductivity $k(\psi)$ is then obtained by dividing the flux density calculated above with the matric head differences ($\mathrm{d}\psi$) at the same positions ($\mathrm{d}z = h_1 - h_2$) and times as follows:

$$k(\psi) = \frac{-q}{\left(\frac{\mathrm{d}\psi}{\mathrm{d}z} - 1\right)} \tag{68.18}$$

Comments

The introduction of TDR miniprobes and minitensiometers in the substrate column could possibly lead to a small change in the structure of materials and, as a result, in the hydraulic properties. The volume occupied by all sensors in the column has been calculated and only represents <1% of the whole substrate core volume.

68.5.4 UNSATURATED HYDRAULIC CONDUCTIVITY *IN SITU*

Organic growing media are almost exclusively used in greenhouse and nursery production and are watered either from above (overhead sprinklers, mist, nozzles) or from below (capillary mats, ebb and flow, gully systems). For subirrigation systems in nurseries, the shape of the unsaturated hydraulic conductivity curve is a very critical factor in assessing their performances (Caron et al. 2005). However, this characterization should be performed *in situ* (in the pot) upon rewetting and very close to saturation. The instantaneous profile (see previous sections) cannot be used in this range. Instead, Caron and Elrick (2005) have proposed a procedure specifically developed for porous media that have a large proportion of macropores, such as organic substrates. It uses a simple tension disk apparatus. At saturation, the procedure also measures the saturated hydraulic conductivity.

Materials

1. A tension disk with a membrane (e.g., nylon fiber) having an air-entry value of approximately −5 kPa of water head (−50 cm).
2. A cylindrical container (e.g., a commercial pot) having a height of at least 15 cm. The bottom should have several holes (for 1-D flow) and a coarse screen used if necessary to contain the substrate (Figure 68.4).
3. A clear container (e.g., acrylic) large enough to contain the substrate-filled container mentioned in step 2.

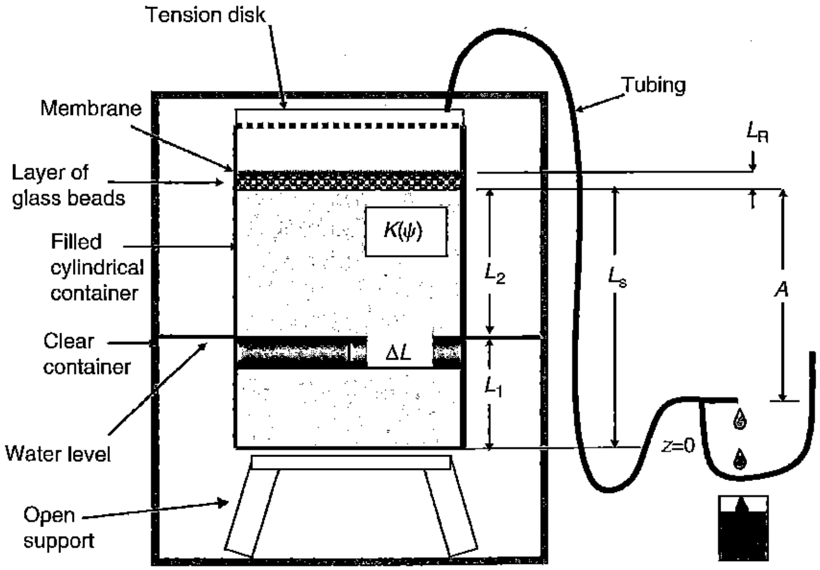

FIGURE 68.4. Schematic of the Laval tension disc for measuring unsaturated hydraulic conductivity upon rewetting on a potted substrate. (Redrawn from Caron, J. and Elrick, D.E., *Soil Sci. Soc. Am. J.*, 69, 794, 2005.)

4 A Mariotte bottle to maintain a constant head.

5 Glass beads (average diameter of 180–120 μm).

6 Plastic tubing and a graduated cylinder to measure the volume of water collected.

Procedure

1 Pack the cylindrical container (pot) as uniformly as possible. Wet the pot from below so that free water is on the surface, then drain and rewet two or more times to obtain a more stable volume. The top of the substrate can be sprayed with water if wetting appears to be a problem. L_s is the depth of the substrate. The substrate can also be taken directly from the production area, but the top part of the plant should be cut first.

2 Put the pot in the larger acrylic box (see Figure 68.4), placing the pot on a support that allows unrestricted flow to the bottom of the pot.

3 A thin layer of glass beads (air-entry value of about −2.5 kPa) should be applied to the surface.

4 The tension disk should be carefully placed on the surface of the substrate (the disk should be slightly smaller in diameter than the inside diameter of the pot). Leave overnight to equilibrate. Note that L_R, the thickness of the membrane system, is $\ll L_s$ (Figure 68.4).

5 Add water to the acrylic box so that the level of the water is about 1 cm above the bottom of the pot. L_1 is the water level in the box measured from the bottom of the pot and L_2 is the distance from the water level in the box to the top of the substrate.

6 Apply suction to the tension disk by lowering the bottom end of the plastic tubing (top end connected to the tension disc) so that the water exiting from the tube is about 2 cm below the water level in the box. Measure the distance between the water level in the container and the exit end of the plastic tube ($A-L_2$). ΔL in Figure 68.4 is the head loss due to Darcy flow in the saturated zone.

7 When steady flow is attained (after about three measurements), record the flow rate in $\text{cm}^3\ \text{min}^{-1}$ (other units can be used).

8 Raise the water level in the box by about 2 cm; raise the lower end of the plastic tubing about 2 cm; measure the distance between the water level in the container and the exit end of the plastic tube, and then record the steady-state flow rate.

9 Repeat step 8 until the water surface is within 2 cm of the surface and record the steady flow rate.

10 The last step is to raise the water level around the pot to about 1 cm above the substrate level in the pot. The substrate should be saturated. Measure the saturated hydraulic conductivity using Darcy's law for saturated flow.

11 This series of measurements can generally be carried out within 2–3 h.

Calculations

Calculate the saturated hydraulic conductivity, K_s. It may be necessary to correct for the resistance of the tension disk membrane and glass bead system, particularly at high water contents near saturation. Use the formula below to calculate K_s:

$$K_s = \frac{L_s}{\frac{(\Delta H)_T}{J_T} - R_R} \tag{68.19}$$

where L_s is the thickness of the substrate, $(\Delta H)_T = (A - L_2)$ is the measured head drop across the substrate plus the disk system (the combined system), J_T is the measured flux through the combined system, and R_R is the independently measured resistance to flow through the disk system only (Caron and Elrick 2005).

Calculating the unsaturated hydraulic conductivity, $K(\psi)$, where ψ is the soil water pressure head, requires numerical procedures and can best be carried out using a computer program. An Excel program can be used for this purpose and some details are presented by Caron and Elrick (2005).

Comments

This procedure was developed specifically to measure the unsaturated hydraulic conductivity upon rewetting in the high water potential range, for example −2 to 0 kPa of pressure head, which is the range of interest when characterizing organic substrates packed into pots used with subirrigation devices (ebb and flow, capillary mats). It may be useful for Histosols where subirrigation systems are extensively used. The procedure can be applied to high-conductivity mineral soils such as sands or highly structured mineral soils. It can also be used for sand bed systems used in nurseries, or in cranberry production where field subirrigation systems are used. The theoretical justification of the proposed methodology has been presented elsewhere and validated for growing media and sand (Caron and Elrick 2005). The estimates obtained from such an approach have been shown to adequately predict the behavior of the capillary process in soil columns and pot plant production on capillary mats (Caron et al. 2005).

68.5.5 GAS DIFFUSIVITY

Gas diffusion is critical for diagnosing aeration problems in growing media as shown in many studies (Allaire et al. 1996; Nkongolo 1996; Nkongolo and Caron 1999; Caron et al. 2001; Caron 2004), and therefore numerous attempts have been made to characterize it. A classical method, used with peat by King and Smith (1987), was presented by Rolston (1986) and the reader is referred to it for greater details. Again, it is important to reemphasize the need for performing this measurement at more than one water content, as this substrate property is volumetric water content dependent. The chosen water content (or potential) should correspond as closely as possible to the container situation if the gas diffusivity is used as an index to assess plant performance.

In quality control of growing media, the water desorption curve and the saturated hydraulic conductivity are measured. It is thus possible to predict gas diffusivity (and pore connectivity) from the shape of the water desorption curve and the saturated hydraulic conductivity. The approach has been shown to be unbiased for peat substrates and to provide estimates consistent with previously published gas diffusivity data, but it is based on assumptions valid for peat and organic growing media only. This approach appears invalid for mineral soils (Caron and Nkongolo 2004).

Methods

1 Use the results of the saturated hydraulic conductivity measured *in situ* (K_s), the water desorption curve, and the point of air entry, measured as highlighted above, on the same sample, with potted substrates in containers of cylindrical shapes if possible.

2 Commercially available software (capable of handling nonlinear equations) for calculating the different parameters.

Procedure

Fit the water desorption data points, to obtain the value of α, b, and n relationship using the function adapted to horticultural substrates by Milks et al. (1989):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\psi)^n]^b} \tag{68.20}$$

where θ is the volumetric water content, θ_s is the mean volumetric water content of the soil at saturation (total porosity), θ_r is the mean volumetric water content at asymptotic residual, ψ is the water potential (kPa), and b, n, and α are empirically fitted parameters.

1 Calculate the dimensionless water content

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{68.21}$$

2 Calculate pore tortuosity from the following equation, using any commercially available software

$$\tau_w = \frac{0.00028\rho g}{\eta K_s} \int_{\theta_r}^{\theta_{ea}} \alpha^2 \left(\Theta^{-1/b} - 1\right)^{-2/n} \mathrm{d}\theta \tag{68.22}$$

where the upper limit of the integral is calculated from the volumetric water content at the point of air entry, θ_{ea}, as this upper limit will correspond to the radius of the largest pore involved in water flow. The lower limit, θ_r, is calculated from the residual water content at a water potential of −10 kPa. Although the lower limit should theoretically be 0, the contribution to K_s of pores retaining water at water potentials lower than −10 kPa in peat substrates is so small that it is considered to be negligible and can be disregarded for τ_w calculations.

3 Once τ_w is obtained, calculate the pore effective coefficient (γ) from

$$\gamma = \frac{1}{\tau_w} \tag{68.23}$$

Obtain θ_a determined on the same core or potted sample. King and Smith (1987) showed that in peat substrates, the relationship between gas diffusivity (D_s), the proportion of the total volume occupied by air (called AFP, θ_a), and gas diffusivity in the air (D_0) can be expressed as

$$D_s = D_0 \gamma \theta_a \tag{68.24}$$

4. The results of this calculation yield values for tortuosity (or pore efficiency) as well as for gas diffusivity, which can be multiplied by volumetric water content to provide estimates for gas diffusivity across a wide range of water contents based on Equation 68.24.

68.6 INTERPRETATION CHART FOR THE QUALITY OF GROWING MEDIA

Table 68.2 was derived for growers for a wide range of growth problems in the field and when observing the operation of subirrigation systems in greenhouse and nursery experiments. It complements existing data used in the industry for diagnostic purposes and has been obtained from numerous experiments summarized by Caron (2004). It represents values found with best-performing substrates under specific experimental conditions and should therefore be considered indicative only.

TABLE 68.2 Norms for Physical Properties of Growing Media Linked to Gas and Water Storage and Exchange

Properties	**Aeration processes**			**Liquid water transfers**		
Parameters	**Air-filled porosity (AFP) (–1 kPa)**	**Gas relative diffusivity (–0.8 kPa)**	**Easily available water (EAW)**	K_s	**Unsaturated hydraulic conductivity**	
Units	$cm^3\ cm^{-3}$	—	$cm^3\ cm^{-3}$	$cm\ s^{-1}$	α_1 kPa^{-1}	ψ_b kPa
Norms	0.15–0.30[a,b]	0.010–0.015[c]	0.20–0.30[b]	0.08[d]	9.6[e]	−0.5[e]

Sources: From [a]Wever, G., *Acta Hort.*, 294, 41, 1991, [b]De Boodt, M. and Verdonck, O., *Acta Hort.*, 26, 37, 1972, [c]Allaire, S., Caron, J., Duchesne, I., Parent, L.E., and Rioux, J.A., *J. Am. Soc. Hort. Sci.*, 121, 236, 1996, [d]Mustin, M., in *Le Compost*, Dubusc, Paris, France, 1987, [e]Caron, J. and Elrick, D.E., *Soil Sci. Soc. Am. J.*, 69, 794, 2005.

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