From Forest Nursery Notes, Summer 2008

190. Defining critical capillary rise properties for growing media: model and methodology. Caron, J. and Elrick, D. E. Acta Horticulturae 779:149-153. 2008.

Defining Critical Capillary Rise Properties for Growing Media: Model and Methodology

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Keywords: peat substrates, bark, air-filled porosity, aeration capillary rise, nursery

Abstract

Efficient use of irrigation water is becoming an important issue in nursery and greenhouse production across the world. Different water conserving systems have been proposed with some relying on good substrate capillary rise properties. However, little is known about the appropriate capillary properties of various substrates. Hence, this paper summarizes the different steps that were followed in order to identify the appropriate capillary rise properties for proper plant growth in nurseries. A first step was to develop a model of capillary rise based on the unsaturated hydraulic conductivity curve, the models developed in a second step, and then the models were validated against field data in a third step. Therefore, this conceptual framework is proposed by the authors for assessing the suitability of substrates for plant growth by characterizing the substrate, using the evapotranspirative demand as input, and a model to predict the substrate performance under nursery or greenhouse conditions. Alternatively, a comparison of the unsaturated hydraulic conductivity curve with a chart is proposed as a simpler but less accurate way of assessing the behaviour of substrates prior to nursery use.

INTRODUCTION

The efficient use of irrigation water is becoming a major issue in nursery and greenhouse production. Inefficient use results in an increased risk of a water shortage during drought periods, and limited water supplies under non-drought conditions, both of which can lead to restrictions on irrigation. Hence, in many parts of the world, there is increasing pressure to design closed and semi-closed irrigation systems and to implement more severe environmental regulations. Different systems to conserve water have been proposed for nurseries and greenhouses over the years. Gullies, catchment basins, ebb and flow, capillary mats and microirrigation, among other systems, appear to be sound procedures for conserving water. For some irrigation systems such as gullies, sand beds, ebb and flow and capillary mats, good substrate capillary rise properties are needed, but standards for such properties are lacking. Recently, a new capillary mat system designed for saving water in nursery production was tested and appears to offer an efficient way of conserving water (Caron et al., 2002). However, with the introduction of this system, as with other subirrigation devices like ebb and flow and sand beds, it rapidly became apparent that substrate properties were extremely important. Best performances in nurseries with such a system were obtained with substrates containing at least 60% sphagnum peat, while substrates dominated by coarse bark showed an important drying of the top substrate surface (Fig. 1), with the top part of the container experiencing dry conditions with potentials lower than the threshold level of water availability.

Extensive outdoor experiments carried out to assess substrate performances were both time and resource consuming. It was therefore of interest to investigate whether the drying behaviour could have been predicted from basic soil properties, instead of carrying out the field experiments. Therefore, a modeling approach was proposed as a first step to assess the possible performance of a growing medium using subirrigation. A first

Proc. IS on Growing Media
Ed.: J.-C. Michel
Acta Hort. 779, ISHS 2008

objective of the project was therefore to develop a model of capillary rise to predict the behaviour observed with different growing media on a capillary mat system.

Common substrates used with overhead irrigation systems have very high air-filled porosities and fast drainage, but low amounts of available water. Therefore, their performance in ebb and flow and capillary rise systems will be related to a proper movement of water from the bottom to the top of the substrate, through a capillary rise mechanism linked to their unsaturated hydraulic conductivity properties. However, there was no suitable technique available which would measure the unsaturated hydraulic conductivity very close to saturation, particularly under rewetting. Hence, a second objective of the study was to derive a method to perform such characterization.

Combining the properties into the model could then yield results that then should be validated in order to see how well they predict the shape of a drying profile. Thus a third objective of the project was to validate the model against actual data. The predicted values from such models will, however, depend on the evapotranspirative demand and hence, require such parameters as a model input, on top of the hydraulic properties of the media. Hence, a fourth and last objective of the project was to propose comparative norms of substrate parameters, where only the unsaturated hydraulic conductivity is used for a first evaluation.

DERIVING A MODEL

We proposed a theoretical model of capillary rise using the hydraulic characteristics of growing media to predict the suitability of various substrates. The model assumes steady state and solves Richards equation (with a source term for plant uptake and surface evaporation) using the Kirchoff transform, and assumes a piecewise exponential function of the unsaturated hydraulic conductivity curve, a shape found to well represent the hydraulic properties under rewetting. Such an equation generates a solution of the soil water potential as a function of depth (Caron et al., 2005) of the form of:

$$\psi_2(z) = \frac{1}{\alpha_2} \ln \left[\frac{\left[K_b - \left(J_b + \frac{P}{\alpha_2} \right) \right] \exp[-\alpha_2 (z_b - z)] + J_b - P z_b + \frac{P}{\alpha_2}(\alpha_2 z + 1)}{K_b} \right] + \psi_b$$

where ψ (negative in unsaturated soil), is the soil water potential (expressed as water head) and z the substrate depth, for a constant evapotranspirative flux density J_b at the pot surface and a plant uptake equals to P. This solution is valid for the interval $0 \leq z \leq z_b$ over which a new α value must be introduced (see Caron et al., 2005 for details). K_b, α_2 and ψ_b are obtained from the unsaturated hydraulic conductivity curve. K_b is the unsaturated hydraulic conductivity at the breakpoint pressure head, ψ_b and α_2 is a fitting parameter for the unsaturated hydraulic conductivity curve below the breakpoint pressure head (see Caron and Elrick, 2005). Hence, this model can be used, along with the characteristics of the curve, to predict either a drying profile in a container or a wet one, close to hydrostatic equilibrium for different values of P.

CHARACTERIZING THE HYDRAULIC CONDUCTIVITY

The method of characterization, while being required to provide input model parameters, may be use for mineral soils (sand) and soils having unsaturated hydraulic conductivity functions showing either a single (SEA) or piecewise exponential (PEA) relationship between the unsaturated hydraulic conductivity and the soil water potential. The proposed method (Caron and Elrick, 2005) allows measurement of this function in the pot, on the undisturbed sample (Fig. 2), as indeed containers are put in contact with a free water source at the bottom and a tension disc put in contact with its upper surface. The proposed method solved the steady state unsaturated flow equation for a piecewise unsaturated hydraulic conductivity function upon rewetting and is very rapid (4–8 hours to get the full -15 cm to 0 potential range). The proposed method was tested and validated for a sand and a peat-bark mix (Caron and Elrick, 2005). The results indicate that the unsaturated hydraulic conductivity curve may be obtained from water flux measurements using a specifically designed tension disc placed on top of the substrate, and that the estimates on rewetting are much more accurate, particularly at water contents close to saturation, than those obtained using the instantaneous profile method. Moreover, the proposed procedure is easy to carry out, requires only an inexpensive tension disc and is based on a sound physical representation of the rewetting process. Results indicated that the PEA is appropriate for most substrates and that the SEA can be considered as a special case of the PEA if only one exponential "piece" is required for the entire range (e.g., sand).

VALIDATING THE APPROACH

The proposed theoretical model with the peat-bark mix showed drying curves data consistent with the earlier observations. In their study, Caron et al. (2002) used the same α_1, α_2, ψ_b and K_s parameters of their bark dominated substrate and the theoretical model above and compared the output with a lab experiment under steady state conditions, in which a much finer resolution of the matric head profile was obtained (Fig. 1). Both the observed and predicted potential profiles demonstrated the same drying pattern. However, differences in the predicted height of drying were reported, and possibly attributed to the variability between replicated measurements. Indeed, the curve in Fig. 1 was generated from average values but about one third of the data showed higher α_1 values, which, when used produced predicted values closer to the observed one (see Caron et al., 2005). The authors consequently recommended measuring these properties on replicated samples, because of this variability issue.

DERIVING NORMS FOR UNSATURATED HYDRAULIC CONDUCTIVITY

Norms were derived by using the above equation and by running simulation models. Such results are exemplified by Caron et al. (2005). However, using the above model requires an assessment of the evapotranspirative demand, and running the model. Numerous experiments were carried out over years under different evapotranspirative demands, with which we were able to identify zones of poor and good performances in capillary rise for substrates with contrasting unsaturated hydraulic conductivity curves (Fig. 3). Hence, users can derive the appropriate hydraulic conductivity relationship using the tension disc method and can then compare the outcome of their measurement with the chart. This procedure then gives a first indication of its suitability for subirrigation.

CONCLUSION

The wide acceptance of coarse media used in nurseries is based on trial and error type experiments in Mediterranean countries or the Southeast United States, where heavy rainfall can create waterlogged conditions detrimental to crop growth. However, our data suggest that the proportion of the fine fraction in nursery mixes should be increased to improve capillary rise, a growth limiting factor.

Our work also suggests that the unsaturated hydraulic conductivity curve is worth characterizing in subirrigation studies and can be used to assess the quality of the substrate and either used in a predictive model or compared with proposed preliminary norms.

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Figures

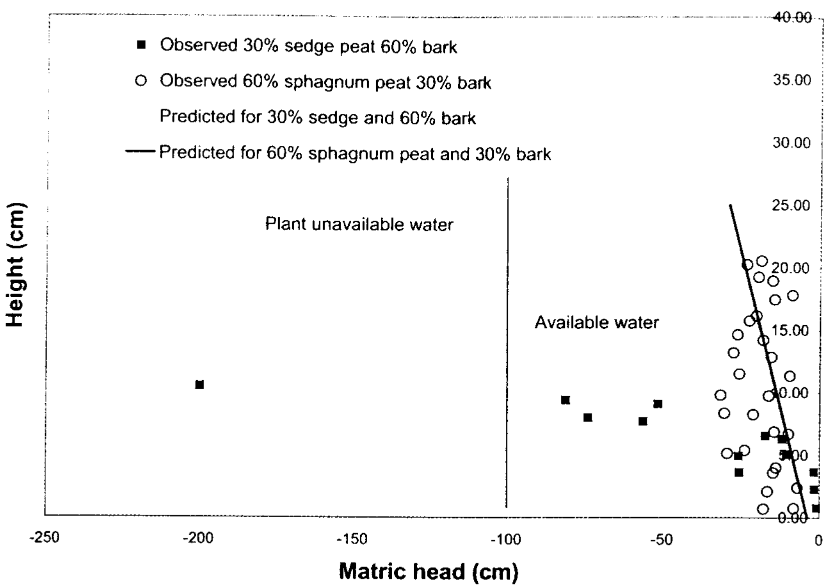

Fig. 1. Observed and predicted head profiles for two different substrates in capillary rise.

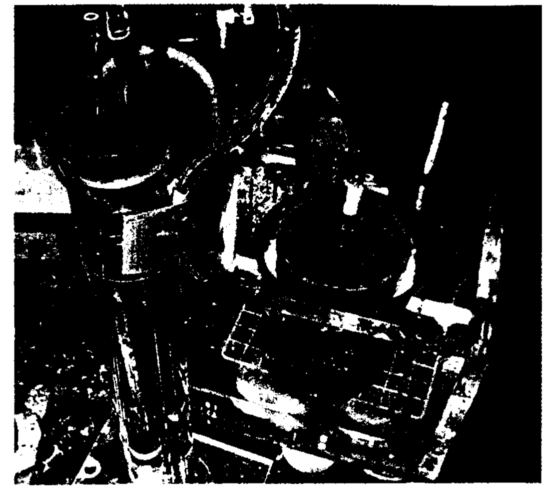

Fig. 2. Photograph of the Laval tension disc for measuring unsaturated hydraulic conductivity upon rewetting on a potted substrate.

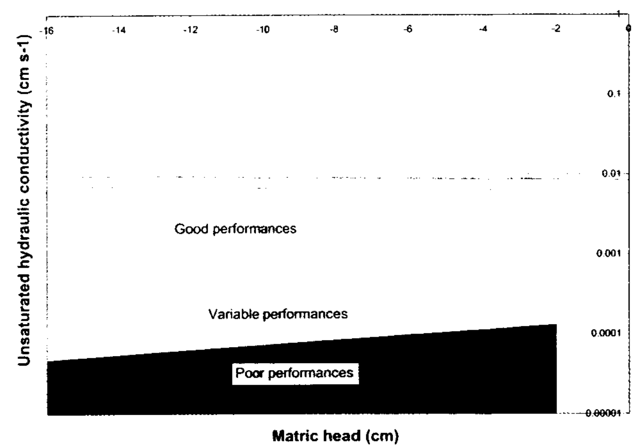

Fig. 3. Comparative chart for substrate quality using the unsaturated hydraulic conductivity curve measured on rewetting.

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PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON GROWING MEDIA

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Acta Horticulturae 779
January 2008