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Hydrology of Horticultural Substrates: II. Predicting Physical Properties of Media in Containers

Robert R. Milks[1], William C. Fonteno[2], and Roy A. Larson[3]
Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695-7609

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Abstract. **Handling and preparing growing media can have pronounced effects on the "intensity variables" bulk density and equilibrium volume wetness through changes in pore size distribution. These changes in turn affect the container "capacity variables": the absolute amounts of medium, air, and water in a container. A nonlinear moisture retention function was combined with container geometry in an equilibrium capacity variable (ECV) model that provided accurate predictions of total porosity, container capacity, air space, unavailable water, available water,and solid fraction for several container-medium combinations.**

Many researchers have noted the limitations of growing plants in small containers and various problems associated with media used in these containers (1–10, 15, 17, 20, 24, 26).

The water and air phases have been difficult to quantify. White and Mastalerz (27) introduced the concept of container capacity (CC), i.e., that amount of water retained in a containerized substrate system after drainage from saturation, but before evaporation. They noted difficulty in relating measured CC to a soil characteristic or moisture retention (MT) curve [a function of volume wetness (Θ) vs. MT]. This was later determined to be because CC is a function of both medium and container (13). Total porosity (TP), the volume of the medium not occupied by the solid fraction, can be quantified by measuring the amount of water held at saturation. Air space (AS) is defined as the difference between TP and CC. A simple method for measuring these capacity variables has been used for classroom demonstration (19).

Tilt (23) used a method proposed by Fonteno and Bilderback (9) that predicted CC and AS in containers using soil characteristic data collected at MT from 0 to 30 kPa. A cubic function was developed by regression to describe the data. The curve was then applied to the geometry of the containers. Karlovich and Fonteno (12) also used this system to predict the capacity variables CC and AS. They further extended it to predict the amount of water in containers at different moisture tensions.

The cubic polynomial has inherent problems in accurately describing moisture retention data. This is especially evident when it is applied to shallow containers (23). The more sophisticated nonlinear function developed by van Genuchten and Nielsen (25) was found to provide a more accurate model (16).

Water held at MT >1500 kPa is often considered unavailable water (UW) (23). The difference between CC and UW is thus the amount of water available for plant growth (AW). While 1500 kPa may represent an endpoint for plant survival, the endpoint for optimal plant growth is at a much lower MT. These five "state" variables can be influenced by cultural practices, by changing certain "intensity" variables such as bulk density and altering pore size distributions (22).

Proposed is an equilibrium capacity variable (ECV) model that combines the nonlinear moisture retention function of Van Genuchten and Nielsen (25) with container geometry. This research examines the model's predictions of total porosity, container capacity, air space, unavailable water, available water, and solid fraction for several container–medium combinations.

Materials and Methods

Eight replications of five media were packed in aluminum cylinders, 7.6 cm in diameter by 7.6 cm in height, using procedures of Bilderback et al. (3). Samples were placed in Buchner funnels with porous plates that, when saturated, had an air-entry pressure > 40 kPa. After slowly saturating over 2 days, volumetric moisture retained was determined at pressures of 0, 0.4, 1, 2, 4, 5, 7.5, 10, 20, and 30 kPa, using Karlovich and Fonteno's (12) adaptation of Fonteno et al. (8).

Media descriptions are in Table 1. Cecil clay loam (medium 1) was used as a representative of mineral soils, media 2, 3, and 4 were peat-based, bark-based, and soil-based container mixtures, respectively, and phenolic foam (medium 5) was used as a type of artificial medium with monodisperse pore size distribution.

A nonlinear, five-parameter function developed by Van Gen-

Table 1. Description of growing media.

Medium No.	Medium Description	Bulk density ($g\cdot cm^{-3}$)	Maximum particle diam (cm)
1	Cecil clay loam	1.00	0.200
2	1 peat[z] : 1 vermiculite[y]	0.15	0.635 : 0.635
3	3 bark[x] : 1 peat : 1 sand[w]	0.41	1.270 : 0.200
4	1 soil[v] : 1 peat : 1 sand	1.11	0.200 : 0.200 : 0.635
5	Phenolic foam[u]	0.01	Matrix

[z] Canadian sphagnum peat.
[y] Horticultural vermiculite #2.
[x] Pine bark humus.
[w] Builder's grade sand.
[v] Wagram sandy loam.
[u] Oasis Rootcube (Smithers Oasis Co., Kent, Ohio).

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[1] Former graduate research assistant. Current address: Winstrip, Inc. Rt. 2, Jeffress Road, Fletcher, NC 28732.

[2] Associate professor.

[3] Professor.

Table 2. Mean observed water content with their mean SEs, predicted percent water volume and equilibrium capacity variable model (ECV) predictions for a 7.6-cm (height, diameter) container for five substrates at four tensions.

Model	0	0.4	5	30
	kPa			
	Percent by volume			
	Cecil clay loam			
Observed	60.5	50.1	30.3	24.0
Mean SE	0.6	0.8	0.4	0.2
Predicted[y]	60.5	51.0	29.9	25.0
ECV	60.5	51.0	29.1	24.6
	1 peat : 1 vermiculite			
Observed	86.9	76.2	39.9	31.9
Mean SE	0.7	0.5	0.1	0.2
Predicted	86.9	75.6	38.9	33.7
ECV	86.9	74.7	37.9	33.2
	3 bark : 1 peat : 1 sand			
Observed	70.5	58.7	28.8	22.7
Mean SE	0.5	0.3	0.3	0.2
Predicted	70.5	58.4	27.9	24.3
ECV	70.5	58.0	27.2	23.9
	1 soil : 1 peat : 1 sand			
Observed	54.6	52.0	21.2	15.4
Mean SE	0.6	0.6	0.5	0.4
Predicted	54.6	52.6	21.0	16.5
ECV	54.6	51.1	20.3	16.2
	Phenolic foam			
Observed	98.3	94.4	3.2	3.0
Mean SE	0.5	0.5	0.3	0.2
Predicted	98.3	94.5	3.2	3.0
ECV	98.3	90.2	3.1	3.0

[z] 1 kPa = 10.2 cm of H_2O = 0.01 bars.

[y] $\Theta = \Theta_r + (\Theta_s - \Theta_r)/[1+(\alpha h)^{nm}$, where $h = \log[(\text{kPa MT} * 9.8) + 1]$.

Table 3. Means of bulk density, water retained at 1500-kPa soil moisture tension by volume with their (SE) and water retained at 1500-kPa soil moisture tension by weight for five substrates.

Medium		Bulk density	Volume		Weight
No.	Description	($g \cdot cm^{-3}$)	Water (%)	SE	Water (%)
1	Cecil clay loam	1.13	16.2	0.83	14.4
2	1 peat : 1 vermiculite[z]	0.15	24.1	0.34	157.2
3	3 bark : 1 sand : 1 peat[y]	0.43	21.5	0.39	50.3
4	1 soil : 1 sand : 1 peat[y]	1.10	8.5	0.34	7.7
5	Phenolic foam	0.01	2.8	0.21	216.2

[z] v/v.

[y] By volume.

uchten and Nielsen (25) was used to describe the moisture retention data.

The function is defined as

$$\Theta = \Theta_r + (\Theta_s - \Theta_r)/[1 + (\alpha h)^n]^m \qquad [1]$$

where Θ_s is the mean percent moisture at saturation, Θ_r is the mean percent moisture at asymptotic residual, h is the log of MT, and α, n, and m are unknown. Estimation of parameters α, n, and m may be aided using their partial derivatives found in Milks et al. (16).

Table 4. Predicted equilibrium capacity variables[z] for mediums 1 (clay loam), 2 (peat mix), 3 (bark mix), 4 (soil mix), and 5 (foam) packed in a 7.6 × 7.6 cm (height × diameter) cylinder.[y]

Capacity variable	Clay loam	Peat mix	Bark mix	Soil mix	Foam
TP	60.5	87.1	70.7	54.7	98.6
CC	50.7	75.7	58.7	51.6	91.4
AW	34.5	51.6	37.2	43.1	88.6
UW	16.2	24.1	21.5	8.5	2.8
AS	9.8	11.2	11.8	3.0	6.9

[z] TP = total porosity, CC = container capacity, AW = available water, UW = unavailable water, AS = air space.

[x] Complete media descriptions listed in Table 1.

Data for UW were collected on a measured volume basis at MT of 1500 kPa, according to Klute (13). Determining UW on a pressure plate has some limitations (18, 21). To avoid variability in bulk density due to handling, the four replications of each medium were packed in rigid aluminum cylinders 2.2 cm tall by 7.6 cm in diameter. Packing and handling techniques were as similar as possible to those used with the larger cylinders, and were adjusted to give similar bulk densities.

Container state variables were calculated from the data using the ECV model. TP and UW were equal to the volume wetness (Θ) at saturation and 1500 kPa, respectively. CC was predicted using procedures similar to those used by Karlovich and Fonteno (12), but using Van Genuchten and Nielsen's (25) function to predict Θ at specific MT in container zones 0.5 cm high. AS was calculated as the difference between TP and CC. AW was calculated as the difference between CC and UW.

To validate the model, means of moisture retention data were compared both to points of corresponding MT on the nonlinear curve, and to model predictions using the 7.6-cm aluminum cylinder as the container. The cylinder was chosen because the moisture retention curve could be tested on the same media samples from which data were collected. Also, because the container was a cylinder rather than a frustrum of a cone or pyramid, both the nonlinear function and the container model could be tested against the means. When more complicated geometry is encountered, only the container model can be used.

Four tensions were evaluated: 0 kPa (saturation) as a determinant of TP, 0.4 kPa (the average MT of the aluminum core at drainage under atmospheric pressure), 5 kPa, and 30 kPa (endpoint of MT tested in large cylinders).

Results and Discussion

Precision of data about their means was determined by their SEs (Table 2). All SEs for collected data were small (0.2 to 0.8), indicating that laboratory precision for media preparation and handling was high. The largest absolute residuals (observed minus predicted) for the means vs. regression predictions occurred for MT at 30 kPa for three media, but the differences barely exceeded 1%. This difference reflected the fact that the means at 30 kPa were not the true asymptotic residual water content, so the equation predicted values slightly higher than observed. Where accuracy at higher MT levels (>100 kPa) is desired, data at high MT should be collected so as to give a better estimate of the true asymptotic residual.

Accuracy of the ECV model predictions was also very high (Table 2). For clay loam and all mixtures, the largest residual was 2.0%. The foam had a container model residual of 4.2% at 0.4 kPa, although the regression function predicted means very well. Because the ECV model works very well for media

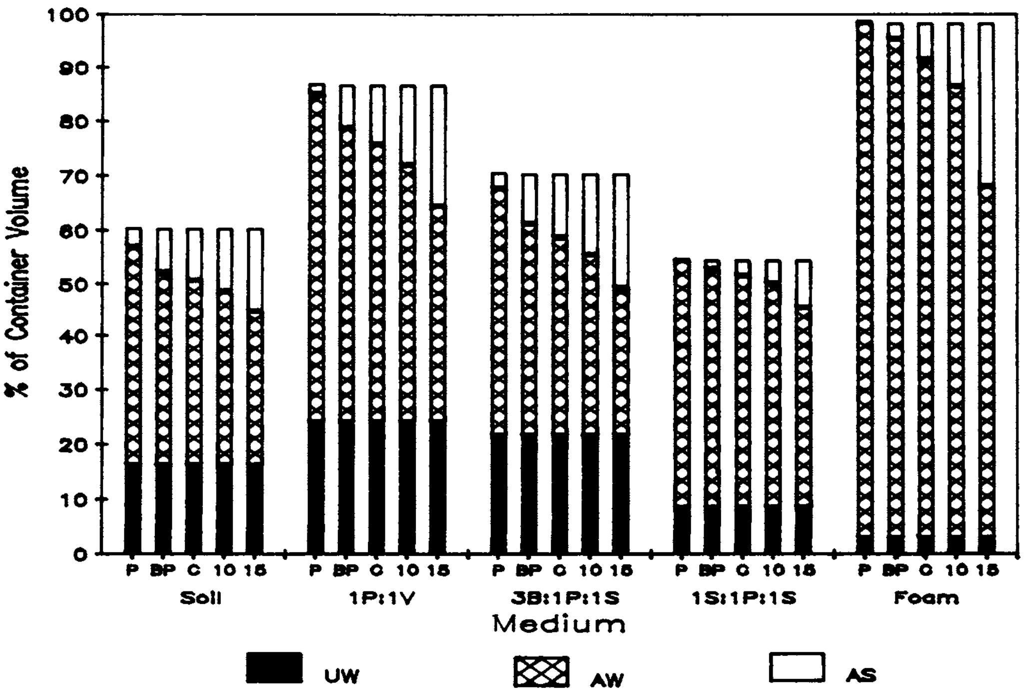

Fig. 1. Equilibrium capacity variables for five media (see Table 1) and five container combinations. Total porosity = air space + available water + unavailable water, container capacity = available water + unavailable water. Containers are: (P) plug cell (273 cells per flat), (BP) bedding plant cell (48 cells per flat), (C) 7.6 × 7.6 cm core, (10) 10-cm standard (medium volume = 415 cm^3) and (15) 15-cm standard (medium volume = 1370 cm^3) containers, respectively.

with heterogeneous pore size distributions (shallow slope of Θ vs. MT curve), the discrepancy in the model for foam may not indicate a problem with the theory, but could rather be an artifact of the MT values at which the data were collected. Too few data points collected near both true asymptotes could still result in an accurate regression curve but not an accurate description of the true physical response of the medium (25). If the ECV model is accepted as valid from its performance on clay loam and the three mixtures, then it could be used to evaluate the choice of data collection pressures, especially for media with more homogeneous pore size distributions.

The data clearly indicate the model's ability to predict container capacity. This procedure reduces the measurement errors associated with the "fill and drain" methods commonly used in determining CC (11). If CC predictions are accurate, then calculating the difference between measured TP and predicted CC would give an equally accurate prediction of air space.

Results from the 1500-kPa moisture determination are given in Table 3. Bulk density means are similar to those in Table 2, indicating consistent packing across the two aluminum ring sizes. Percent moisture SEs were small for all media, again evidence of laboratory precision. Unavailable water (UW), the volume percent moisture remaining at 1500 kPa, was high for the peat- and bark-based media (24.1 and 21.5, respectively). These data are consistent, however, with more than 100 other soilless media tested (not shown), where UW ranged from 20% to 40% by volume. These high values indicate the necessity of including 1500-kPa measurements in any model that attempts to describe plant-available water. Mean percent gravimetric moisture retained is also listed in Table 3; the extreme range in these values suggests that volumetric data are more convenient and consistent in describing wettness of horticultural substrates.

Capacity variables for the five media modeled in 7.6 × 7.6 cm cylinders are shown in Table 4. Total porosity and UW were measured values, while container capacity, available water, and air space were predicted from the ECV model. Change in TP from one medium to another did not necessarily reflect similar changes in CC or AS. For example, a 16% (absolute) increase in TP from the bark mix to the peat mix was accompanied by no change in AS. Comparing more similar materials, a 6% (absolute) increase in TP from the soil mix to the clay loam resulted in a slight loss in CC. These comparisons are valid only within this container size, as CC and AS (but not TP) are determined by the container shape as well as the moisture retention curve of the medium.

CC and UW were both used to calculate AW. Since UW varies considerably among media and is independent of CC, available water cannot be satisfactorily determined from CC alone.

The utility of the model is demonstrated in Fig. 1, which shows volumes of AS, AW, and UW for the five media. TP is the sum of AS, AW, and UW (the top of each bar). CC is the sum of AW and UW and can be read as the value at the top of the AW portion of each bar. Each medium was mathematically placed into five containers ranging from a plug cell (273 cells per flat) to a 15 cm standard plastic container. Notice that TP and UW do not vary among containers and are independent of container size. However, CC and AS are greatly affected by container parameters. These data demonstrate the need to consider both medium and container size when described air and water values.

The same trends across container size appeared in all media, the degree of change in AS and CC being affected by the nature of moisture retention patterns. For example, the foam medium had both the greatest value for AS (>30% in the 15-cm container) and the lowest (0.2% for the plug cell). This phenomenon was caused by the shape of the moisture retention curve and must be taken into consideration in all media–container combinations.

In summary, the concept of predicting CC and AS by methods described by Tilt (23) is still valid when Van Genuchten and Nielsen's (25) nonlinear function was incorporated. In addition, measuring UW with controlled bulk density makes possible the determination of AW on a volume basis. Using the ECV model, any medium can be evaluated for performance in any container. This gives horticulturists the tools to better define the root environment when working with plant and soil scientists, growers, and media formulators.

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