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Hydrology of Horticultural Substrates: III. Predicting Air and Water Content of Limited-volume Plug Cells

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Abstract. **Plants grown in small containers often show limited growth due to low levels of aeration and water holding capacity in the medium. These levels can be changed by management practices such as medium compaction, medium wetness at time of container filling, container height and volume, peat : vermiculite ratio, particle size, and the use of a wetting agent. A modified equilibrium capacity variable model was applied to an investigation of media-container interactions for short containers (<5 cm tall). Predicted volume percentages for total porosity (TP), container capacity (CC), air space (AS), unavailable water (UW), and available water (AW) were developed from measured moisture retention data and container geometry. AS increased with: 1) increased particle size, 2) increased media moisture at time of container filling, 3) decreased medium compaction, 4) increased wetting agent concentration, 5) decreased ratio of peat : vermiculite, and 6) increased container height. Increased percent AW resulted from smaller particle size, increased media moisture at time of container filling, decreased container compaction, decreased wetting agent concentration, increased ratio of peat : vermiculite and decreased container height.**

Limitations of growing plants in containers are well-documented, primarily reflecting the dilemma between two little and too much water (15). Shallowness of containers results in too much water, and therefore too little air, while the small volume of containers limits the amount of water available for plant growth.

These problems as delineated by Spomer (14) were the impetus behind development of special media for container sizes popular in the floriculture industry. A popular group of soilless mixes are the Cornell peat-lite mixes consisting of blends of sphagnum peat and vermiculite or perlite (2). Peat-lite mixes hold large quantities of water, so skill is required in using them as growing media. Wetting agents are often used to effect thorough wetting of the medium (11).

Over the past 10 years, a growing practice known as the "plug" system has evolved. This system uses extruded, formed or heat-expanded plastic flats that have a large number of individual cells (plugs). Young plants are seeded in these flats and grown for several weeks at densities as high as 4800 plants/m^2. However, media that are acceptable in containers 15 cm tall do not necessarily perform well in containers shorter than 5 cm.

Bunt (4) reviewed physical properties of peat : sand formulations as they relate to handling and preparation practices such as moisture level during mixing, various particle sizes, and the use of wetting agents. Other workers (8, 17, 18) have also studied physical properties of various mixes. However, management practices can change media hydraulic properties substantially, primarily by altering the pore size distribution (7). It is apparent that handling and container geometry may have more effect on media physical properties than the mixes themselves.

Most of the in situ soil moisture measurement equipment was not designed for and will not adapt to small containers. Neutron moderation is designed for large masses of soil. Gamma-ray attenuation measures water in a column (container), but it is expensive and requires elaborate safety measures (7). Buoyoucous blocks, Phene cells, tensiometers, and in situ thermocouple psychrometers are too large and can have contact problems with coarse media (7, 13). Measurement of soil moisture tension in the root ball using a thermocouple psychrometer fails as light weight peat fibers coat all statically charged metallic surfaces (personal observation). Direct measurement of air and water volumes in plug cells is predisposed to technique variability.

The method outlined by Milks (12) removes the problems of small sample size, control of initial moisture level, coarseness of medium, and bulk density. It also allows determination of media physical properties in any container via modeling. Using this method, research was initiated to examine the effects of certain cultural factors on total porosity (TP), container capacity (CC), available water (AW), unavailable water (UW), and air space (AS), as modeled in plug cells <5 cm in height.

Materials and Methods

Determination of sample size and effects of peat : vermiculite ratio in plug cells 2.2 cm tall (Expt. 1). Eight replications of three media were packed (1) in aluminum cylinders 7.6 cm in diameter in each of two heights: 7.6 cm and 2.2 cm. The three media were composed of the following proportions of peat to vermiculite—3:1, 1:1, and 1:3 (v/v).

Data were collected for moisture retained at 10 moisture tensions from 0 to 30 kPa, according to Karlovich and Fonteno's (9) adaptation of Fonteno et al.(5). All cylinders were seated onto the porous plate of a Kimax 600 ml 90 F Buchner filter funnel and saturated with water by slowly adding water over a period of 24 to 48 hr between the funnel wall and the outside of the aluminum ring (8). An airtight lid was placed on top of the funnel and positive air pressures were applied in increments that resulted in pressures at the medium center of 3.8, 10, 20, 40, 50, 75, 100, 200, and 300 cm (H_2O). Volume outflow was recorded for each increment. Normally, 48 hr was required to

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establish equilibrium at pressures <50 cm and 24 hr for higher pressures. After measurement at 300 cm, each sample was removed and oven dry bulk density determined by calculating the volume of each sample and weighing each sample after drying 24 hr at 105°C (11).

A nonlinear function developed by Van Genuchten and Nielsen (16) was used to describe the data. Moisture tension values were converted to kPa, then the integer 1 was added to each value. This allowed a log transformation at a MT value of zero. A nonlinear, five-parameter function developed by Van Genuchten and Nielsen (16) 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 (taken to be 30 kPa), h is the log of MT, and α, n, and m are unknown.

Using similar packing techniques, four replications of the same three media were packed in cylinders 2.2 cm tall. Data for moisture retained on a measured volume basis were collected at a moisture tension of 1500 kPa, according to Klute (10).

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 Milks et al. (12). The modeled plug container (2.2 cm tall, 0.9-cm top radius, 0.6-cm bottom radius) was mathematically sectioned into 0.5-cm-tall increments. The nonlinear equation was used to predict the percentage of water values at the midpoint of each 0.5-cm section. Multiplying the percentage of water value by the volume of each pot section gave the water volume held in that section at container capacity. The water volumes of all zones were summed to give the total water volume in the pot at container capacity. AS was calculated as the difference between TP and CC. AW was calculated as the difference between CC and UW.

Effects of wetting agent concentration and peat : vermiculite ratio (Expt. 2). Data were collected in a manner similar to Expt. 1. Only the taller (7.6-cm-high) cylinders were used and media were saturated with 0%, 0.1%, 0.5%, and 1.0% (v/v) solutions of a wetter agent, Triton X-100 (Rohm and Haas).

Effects of particle size (Expt. 3). Data were collected in a manner similar to Expt. 1, using only the 1 peat : 1 vermiculite (v/v) medium. Components were screened to maximum diameters of 0.635, 0.318, and 0.159 mm before mixing.

Effects of compaction, media moisture at packing, and container geometry (Expt. 4). Data were collected in a manner similar to Expt. 1, using the 1 peat : 1 vermiculite (v/v) medium. The medium was wetted to two moisture levels, 160% and 250% (w/w) before filling the cylinders. The media were compacted to three dry bulk density (BD) levels, all within "normal" range for horticultural media. The BD levels were similar for the two wetness levels: 0.170, 0.202, and 0.236 $g\cdot cm^{-3}$ for the lower wetness level, and 0.168, 0.206, and 0.261 $g\cdot cm^{-3}$ for the higher. Container state variables were modeled for a 4.4-cm-tall as well as for a 2.2-cm-tall plug, both with a 0.9-cm top radius and a 0.6-cm bottom radius.

Results

Determination of sample size and effects of peat : vermiculite ratio in plug cells 2.2 cm tall (Expt. 1). Unavailable water and AS decreased, while AW increased, with increased proportions of peat (Table 1). AW increased more than the sum decrease of AS and UW; therefore, both CC and TP also increased with increasing peat. It is apparent that, in very short containers, increasing the proportion of peat increases the amount of available water, but at the expense of air space.

Table 1. Predicted[z] equilibrium capacity variables for three peat : vermiculite media (v/v) in plug cells 2.2 cm tall with data collected in two cylinder heights (Expt. 1). TP = total porosity, CC = container capacity, AW = available water, UW = unavailable water, AS = air space, all on a percent-volume basis.

Equilibrium capacity variable	Cylinder ht (cm)	Peat : vermiculite (v/v)		
		3:1	1:1	1:3
TP	2.2	85.9	84.6	81.5
	7.6	89.5	85.6	78.4
CC	2.2	82.9	80.3	76.2
	7.6	87.4	82.7	75.2
AW	2.2	64.1	59.5	52.5
	7.6	68.5	61.9	51.5
UW	2.2	18.9	20.8	23.7
AS	2.2	3.0	4.2	5.3
	7.6	2.2	2.9	3.2

[z]All nonlinear regressions used for predicting ECV model had r^2 of 0.998 or greater.

Total porosity increased with cylinder size in the 3 peat : 1 vermiculite medium, but decreased in the 1 peat : 3 vermiculite medium. Porosity is generally considered a medium effect not altered by container size (6). The difference between the two cylinder sizes may therefore be a result of experimental technique, the very reason large cylinders are preferred. Because the potential for absolute error is a function of area of the ends of the cylinder and both cylinders have the same diameter, potential absolute error is the same for both sizes. Since relative error is a function of volume, the larger cylinders have a lower percentage of error.

Because all data collected at 1500 kPa must be from short cylinders to ensure plate contact, values for UW are listed only at 2.2 cm. TP did not differ by cylinder size for the 1 peat : 1 vermiculite (v/v) mixture, so this medium is probably the best of this experiment to determine accuracy of the container state variables CC, AS, and AW. Because of the inherent problems using shorter containers and the closeness of predicted values for the two methods, the taller cylinders can be used for accurate predictions of container state variables.

Although packed so bulk density would be the same in the two cylinder sizes, the trend for all media was higher bulk densities in the larger cylinders. Bulk densities measured at the end of the experiment were slightly different ($LSD_{0.05}$) for the 1 peat : 1 vermiculite and 1 peat : 3 vermiculite (v/v) media.

Effects of a wetting agent concentration and peat : vermiculite ratio (Expt. 2). Increasing the proportions of wetting agent from 0% to 1.0% increased UW slightly and decreased AW (Table 2). AS increased as percent wetting agent increased from 0.1% to 1.0%, but the zero wetting agent treatment showed AS values between those of the 0.1% and 0.5% treatments. Increased wetting agent concentration, like increased vermiculite content, increased airspace, but at the expense of available water.

Effects of increasing peat concentration were very similar to those in Expt. 1, with the difference the UW was lowest with the 1 peat : 1 vermiculite medium. Media components for this study may not have been of uniform consistency, so confirmation of peat : vermiculite ratio effects must come from Expt. 3.

Table 2. Predicted[z] equilibrium capacity variables of three peat : vermiculite media (v/v) with a wetting agent in 2.2-cm-tall plug cells (Expt. 2). TP = total porosity, CC = container capacity, AW = available water, UW = unavailable water, AS = air space, all on a percent-volume basis.

Equilibrium capacity variable	Percent Triton X-100 (v/v)			
	0	0.1	0.5	1.0
		3 Peat : 1 vermiculite		
TP	89.6	87.3	86.1	86.3
CC	88.1	86.2	82.9	82.8
AW	68.8	63.6	59.6	59.4
UW	19.3	22.5	23.3	23.4
AS	1.5	1.2	3.1	3.4
		1 Peat : 1 vermiculite		
TP	82.4	80.4	82.0	82.8
CC	79.7	79.3	78.4	77.8
AW	64.7	59.3	58.3	57.5
UW	15.1	20.1	20.1	20.4
AS	2.7	1.1	3.6	5.0
		1 Peat : 3 vermiculite		
TP	81.3	79.5	79.0	77.5
CC	79.8	78.3	75.7	73.9
AW	58.1	52.0	47.0	46.1
UW	21.8	26.3	28.7	27.8
AS	1.5	1.2	3.3	3.6

[z]All nonlinear regressions used for predicting ECV model had r^2 of 0.998 or greater.

Table 3. Predicted[z] equilibrium capacity variables of three peat : vermiculite media (v/v) of three particle sizes in 2.2-cm-tall plug trays (Expt. 3). TP = total porosity, CC = container capacity, AW = available water, UW = unavailable water, AS = air space, all on a percent-volume basis.

Equilibrium capacity variable	Maximum particle diam (mm)		
	0.635	0.318	0.159
		3 Peat: 1 vermiculite	
TP	88.8	91.0	90.4
CC	87.1	89.5	89.4
AW	66.0	70.7	73.8
UW	21.1	18.9	15.6
AS	1.7	1.4	1.0
		1 Peat: 1 vermiculite	
TP	86.9	86.5	88.5
CC	85.1	86.0	88.1
AW	61.0	60.7	68.3
UW	24.0	25.3	19.9
AS	1.8	0.5	0.3
		1 Peat: 3 vermiculite	
TP	81.4	86.5	88.5
CC	77.4	82.1	85.4
AW	50.0	55.3	62.6
UW	27.4	26.9	22.8
AS	4.0	0.9	0.0

[z]All nonlinear regressions used for predicting ECV model had r^2 of 0.996 or greater.

Effects of particle size (Expt. 3). As maximum particle size increased, TP decreased, as often seen in mineral soils (Table 3). Although the largest particle size gave less total pore space, more of that pore space drained at a height of 2.2 cm above the water table. CC thus also decreased and to a greater degree than TP. AS increased, illustrating the problem of equating air space to porosity (3).

At the smaller particle sizes, AS decreased as the proportion of peat decreased. The opposite effect was seen at the largest particle size. When screened to the smaller particle sizes, the multi-layered structure of vermiculite seemed lost (personal observation), apparently reducing its usefulness. Decreasing vermiculite particle size seemed to reduce the benefit of adding it.

UW increased with increased particle size. This presumably was due to the presence of more small pores associated with internal spaces of intact vermiculite particles and/or peat fibers. These are apparently reduced or destroyed during the screening process. Because UW increased, AW decreased with increased particle size and to a greater degree than CC.

Although decreasing particle size increased the amount of water available for plant growth, the drop in AS to negligible levels would seem to outweigh the benefit of more water. Maintenance of minimum levels of aeration is of primary importance in small containers. Limited AW is less important, as it is easier to add than to remove water.

As in Expt. 1, increasing the peat component increased TP, CC, AW, and decreased UW for all media. Increased peat also decreased AS for the largest particle size, which were used for Expts. 1 and 2. Therefore, we believe that this was confirmation of the effects of peat : vermiculite proportions given in Expt. 1.

Table 4. Predicted[z] equilibrium capacity variables of 1 peat : 1 vermiculite media (v/v) in 2.2-cm-tall plug trays (Expt. 4). Medium treatments were three levels of compaction and two levels of moisture at time of packing. TP = total porosity, CC = container capacity, AW = available water, UW = unavailable water, AS = air space, all on a percent-volume basis. BD = bulk density ($g \cdot cm^{-3}$).

Variable[z]	Compaction		
	Light	Moderate	Heavy
		160% moisture[y]	
BD[x]	0.170	0.202	0.236
TP	87.3	85.7	83.5
CC	85.3	85.0	83.2
AW	64.0	59.2	53.3
UW	21.3	25.8	29.9
AS	2.0	0.7	0.2
		250% moisture[y]	
BD[x]	0.168	0.206	0.261
TP	88.0	87.0	83.5
CC	81.3	83.5	82.8
AW	65.3	64.8	60.1
UW	16.0	18.7	22.7
AS	6.8	3.5	0.8

[z]All nonlinear regressions used for predicting ECV model had r^2 of 0.998 or greater.
[y]By weight.
[x]Observed means.

Effects of compaction, media moisture at packing, and container geometry (Expt. 4). For both moisture levels, increased compaction increased bulk density and so decreased porosity. Increased moisture at time of container filling had little effect on TP, because of the lack of increase in bulk density. Increased compaction increased UW, as more solids were present to hold water in internal pores.

For both moisture levels, increased bulk density decreased

TP and AS, as might be expected. Because AS drops at the same rate as TP, CC remains about the same for all compaction levels. Therefore, AW decreased with increased compaction.

The higher moisture level at packing increased drainage, presumably because media integrity was maintained and drainage pore did not collapse. Therefore, the higher moisture level produced slightly lower CC and higher AS. By the same reasoning, increasing moisture level at packing decreased UW.

Maximum AS and AW occurred with the same treatment (light compaction of moist medium), and minimum AS and AW also occurred with the same treatment (highly compacted drier medium). AS and AW did not increase at the expense of one another, in agreement with Bunt's (4) observation for taller containers with peat and sand mixtures.

Effects of container geometry on equilibrium capacity variables were modeled using the medium packed at 250% moisture at three compaction levels. To allow comparison over a wider range, effects were also modeled in a 15-cm-tall pot as well as in 2.2-cm-tall and 4.4-cm-tall plug cells (Fig. 1). The shorter plug had a calculated volume of 3.94 ml and the taller plug had 7.87 ml.

TP and UW were unaffected by container geometry, so their values were identical in all three containers. AS doubled as height increased from 2.2 to 4.4 cm (and much more so in 15-cm containers), regardless of the level of compaction. Because percent AS increased so much, percent CC decreased; therefore, percent AW also decreased. On a volume basis, of course, the amount of available water increased. The effects of compaction on percent available water had a different basis in the different containers. In plugs, compaction decreased AW primarily by increasing UW, while, in large pots, compaction increased AW mostly by decreasing drainage.

Discussion

For containers as short as 2.2 cm plugs, peat : vermiculite mixes do not offer optimum physical characteristics. AS of even 4% is difficult to obtain using "normal" handling practices, unless one uses a very high proportion of vermiculite. This, in turn, risks plant desiccation, as AW is decreased. Changing media handling and packing practices has the potential to bypass some of the limitations inherent in these media.

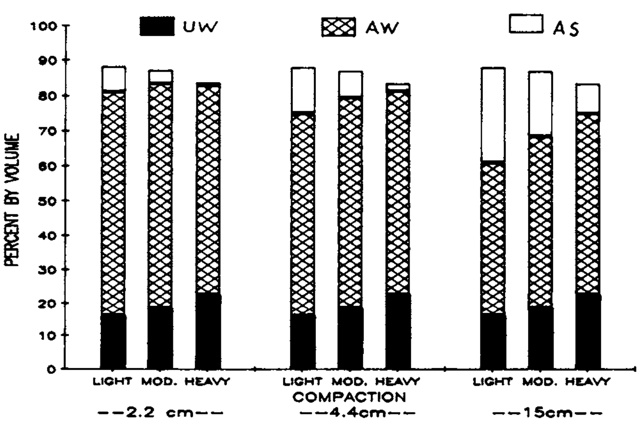

Fig. 1. Predicted equilibrium capacity variables of a 1 peat : 1 vermiculite (v/v) medium at three compaction levels for three containers (Expt. 4). UW = unavailable water, AW = available water, AS = air space, total porosity = UW + AW + AS, container capacity = UW + AW, all on a percent-volume basis.

Increasing container height to 4.4 cm has at least as much effect on container state variables as peat : vermiculite ratio, moisture at packing, or compaction. The single most effective way to increase percent aeration while simultaneously increasing the volume of available water is to increase the container height. Water volume and aeration are gained, with no reduction in plant density.

Where container height cannot be increased, AS may be increased by incorporating large particles with enough moisture to stabilize the components, using light compaction and a wetting agent. Alternatively, AW may be increased by using smaller particles without a wetting agent, again at a high level of medium moisture. Changing the peat : vermiculite ratio was less effective than changing any of the other particles.

A change in AS does not necessarily reflect a change in TP; an increase in AS does not necessarily occur at the expense of AW and a change in AW does not necessarily reflect a change in CC. It is apparent that making inferences regarding one container state variable based on only one other can be misleading due to the complex interaction of the moisture release curve and container geometry. Quantifying all of these variables provides a more accurate and comprehensive description of the root physical environment.

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Economic Analyses of Space Management Practices In High-density Pecan Groves

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Additional index words. canopy closing, temporary trees, pruning, tree removal, *Carya illinoensis*

Abstract. **A growth equation and a yield relationship were calculated to estimate space requirements and yields of two pecan cultivars (*Carya illinoensis* (Wangenh.) C. Koch]. The resulting estimates were used with pruning cost estimates in a simulation model to determine the orchard space management practice that maximizes income over time. The income maximizing spacings were 10.7 × 10.7 m and 13.7 × 13.7 m for the precocious 'Desirable' and the non-precocious 'Stuart', respectively. Annual pruning after the canopy closed produced the highest income for both cultivars.**

Horticulturists have demonstrated that increased density of pecan trees increases yield and return per land unit during the initial years following establishment (3, 7, 11). However, as a high-density orchard matures, the trees become crowded, with a subsequent reduction in yield.

Production and nut quality decline as the orchard becomes crowded because the area of the tree crown that is exposed to sunlight is reduced. The upper branches, with free access to sunlight, grow vigorously and shade the lower branches. The orchard's canopy eventually closes, and nut production occurs only on a small part of the crown near the top of the trees.

Before the orchard's canopy closes, the producer must open the orchard to sunlight to maintain production. The extreme option would be to remove all trees and replant. However, reestablishing an orchard is costly and entails several low or nonproductive years, so it is not economically feasible. Removing some of the trees is postulated to be more economical, but this practice would also reduce production by leaving empty, nonproductive spaces in the orchard until it recloses. A third option, which has gained the attention of growers and researchers, involves designating temporary trees, ones that will be eventually removed, and pruning them to allow the permanent trees to grow uninhibited. In this way, non-productive space would be minimized.

This paper analyzes alternative methods of keeping pecan orchards open. Thinning practices, various patterns of pruning, and tree removal are compared with respect to yield and revenue over the life of the orchard, with the goal to maximize discounted net revenue.

Net present value of returns is used in the comparison since there is a time preference of money. That is, a dollar received today has a higher value than a dollar that will be received a year from today. The concept is the reverse of increases in value to accrued interest. For example, with a rate of 6%, $1.00 is worth $1.06 after 1 year, but $1.06 a year in the future is worth $1.00 today.

Two orchards, one containing a precocious cultivar and the other a non-precocious cultivar, are also compared. Precocious cultivars bear nuts early in their life, while non-precocious cultivars take somewhat longer to bear nuts.

Producers can maximize discounted net returns with an orchard that provides the highest yield in the shortest time and maintains high production levels over an extended period. A high-density planting of precocious cultivars can accomplish this goal.

A high-density orchard is an orchard with a tree spacing under 18.3 × 18.3 m (30 trees per hectare). One of the most common spacings is 9.1 × 9.1 m (120 trees per hectare). Precocious pecan trees are usually used in high-density orchards, as the trees have the greatest number of productive years before the orchard becomes crowded. Another advantage of precocious cultivars is their increased ability, over non-precocious, to produce nuts following pruning. We selected the precocious cultivar Desirable, the second-most popular cultivar grown in Georgia (5, 8), and the non-precocious cultivar Stuart, the most popular cultivar in Georgia (5, 8).

A disadvantage of high-density orchards is the additional costs associated with planting. Cost of establishing a high-density orchard is greater than a low-density orchard because more trees are planted per land unit. However, establishing a high-density orchard is economically feasible if it generates greater discounted net returns than a low-density orchard.

A comparison of net returns to management from a high-density orchard and those from a low-density orchard for several improved cultivars of pecans showed the break-even period—the time period required to recover all costs excluding management—of a high-density orchard to be 8 years after planting with machine harvesting vs. 24 years for a low-density orchard (7). The respective average annual net returns were $2228/ha and $198/ha.

The pruning and spacing practices in a high-density orchard also affect yield and nut quality. Hedging 'Desirable' (removing the sides or tops of trees) causes an overall reduction in yield

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