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Developing Moisture Characteristic Curves and Their Descriptive Functions at Low Tensions for Soilless Substrates

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Abstract. Moisture characteristic curves (MCC) relate the water content in a substrate to the matric potential at a given tension or height. These curves are useful for comparing the water-holding characteristics of two or more soils or soilless substrates. Most techniques for developing MCC are not well suited for measuring low tensions (0 to 100 cm H_2O) in coarse substrates used in container nursery production such as those composed of bark. The objectives of this research were to compare an inexpensive modified long column method with an established method for creating low-tension MCCs and then to determine the best model for describing MCCs of bark-based soilless substrates. Three substrates composed of douglas fir (*Pseudotsuga menziesii*) bark alone or mixed with either peatmoss or pumice were used to compare models. Both methods described differences among the three substrates, although MCC for each method differed within a substrate type. A four-parameter log-logistic function was determined to be the simplest and most explanatory model for describing MCC of bark-based substrates.

Moisture characteristic curves (MCCs) the water content (θ) in a substrate to the matric potential (Ψ_m) (Raviv and Lieth, 2008) at a given tension or height (h). There are many methods for deriving MCCs, many of which are described by Klute (1986). Generally, each method attempts to measure θ at multiple intervals of applied pressure or tension. The corresponding scatterplot (h, θ) is then fit with a function relating the two parameters. Functions can then be used to compare MCCs and thus water-holding characteristics of two or more soils or substrates.

Buckingham (1907) first described MCCs (Nimmo and Landa, 2005). Buckingham packed six different soils into 1.2-m-long × 6.3-cm-diameter metal tubes, saturated the bottom 3.2 cm of the tubes thus establishing a water table (Z_0), and used the height above Z_0 as a measurement of tension or matric potential. The long column (LC) method described by Dane and Hopmans (2002) is similar in that it uses a 1-m column packed with coarse soils or substrates. Water content is determined by use of gamma radiation and matric pressure as the height above the known water level (Z_0). Dane and Hopmans (2002) comment that the LC method is ideally suited for coarse soils because values of h can be no more than 100 cm. This range of tension is ideally suited for soilless substrates. Personal observation (Buamscha et al., 2007) as well as those published by others (Gizas and Savvas, 2007; Karlovich and Fonteno, 1986; Milks et al., 1989) confirm that the sigmoid nature of MCCs for soilless substrates lie within the 0- to 100-cm tension range. de Boodt and Verdonck (1972) partitioned the water occurring in the 0- to 100-cm tension range into two categories: easily available water (EAW) being water occurring between 10 and 50 cm tension (H_2O) (EAW = θ_{10} to θ_{50}), and water buffering capacity (WBC) being water occurring between 50 and 100 cm tension (WBC = θ_{50} to θ_{100}).

Little work has been done to correlate EAW or WBC to plant growth. Bilderback et al. (1982) compared MCC of five substrates composed of varying combinations of pine bark, peatmoss, and peanut hulls. They (Bilderback et al., 1982) found that pine bark + peanut hulls had the lowest EAW (10.7%) but the highest azalea (*Rhododendron indicum* 'George L. Taber') growth increase, whereas pine bark + peat had the highest EAW (20.1%) and least azalea growth increase. Ownley et al. (1990) reported a positive correlation ($R = 0.66$, $P < 0.01$) between shoot fresh weight of rhododendron (*Rhododendron* 'Nova Zembla') and water held between 10 and 50 cm tension. The use of MCCs is not to predict which substrate is most ideally suited for production of containerized plants, but to compare the relative water-holding characteristics of several substrates so that they can be best matched or engineered to accommodate plants with varying water requirements.

Once data for MCCs are acquired (h, θ), a function can be developed that accurately describes the relationship. Numerous models have been proposed to describe MCCs (Brooks and Corey, 1966; King, 1965). van Genuchten (1980) proposed the

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following model for describing soil water content (θ) as a function of pressure (h):

$$\theta = \theta_r + (\theta_s - \theta_r)/[1 + (h/x_0)^n]^m \quad (1)$$

where θ_s is water content at saturation, θ_r is residual water content, x_0 is an estimated parameter that represents the value of h where the sigmoid function transitions from convex to concave in shape, and *n* and *m* are estimated parameters whose values affect the steepness of the curve's slope. van Genuchten and Nielsen (1985) prefer Eq. 1 over others because of the model's relative simplicity when used for derivation of hydraulic conductivity. In addition, Eq. 1 allows θ to be expressed as [θ(h)] as well as its inverse [h(θ)]. This model has gained acceptance by scientists studying soils and soilless substrates. Wallach et al. (1992) used the van Genuchten equation to describe the hydraulic properties of scoria used in container media. Milks et al. (1989) compared the van Genuchten model with a cubic polynomial model and concluded the van Genuchten model was superior in describing MCCs for peat, pine bark, and soil-based substrates. The log-logistic function:

$$\theta = \theta_r + (\theta_s - \theta_r)/[1 + (h/x_0)^n] \quad (2)$$

has also been used successfully by van Genuchten (1980) to describe MCCs. van Genuchten's preference for Eq. 1 seems to be because it provides a systematic method for determining the parameters using either direct measurement or estimation (van Genuchten, 1980).

A common problem in developing MCCs for soilless substrates is that most procedures require expensive equipment such as ceramic plate extractors or Tempe pressure cells. Many also require long periods of time for allowing soil water to equilibrate at each point of applied pressure, and it is difficult to generate ample and reliable data occurring at tensions less than 100 cm. Thus, the first objective of this research was to compare an inexpensive modified long column (MLC) method for creating low-tension MCCs with a common and established method that uses a volumetric pressure plate extractor (Milks et al., 1989). The second objective of this research was to compare the van Genuchten model (Eq. 1) with the log-logistic function (Eq. 2) for describing MCCs of bark-based soilless substrates.

Materials and Methods

General procedures. Douglas fir bark [DFB (screened to 0.9 cm)] was collected from stockpiles intended for nursery container production (Marr Brothers Monmouth, OR). Pumice (less than 9.5 mm; Pro-Gro, Sherwood, OR) and Canadian sphagnum peatmoss (Sun Gro Horticulture Canada, Laval, Quebec, Canada) were used as additional components to make the substrates. The following three substrates were mixed and used for method development: 100% DFB, 70 DFB:30 peatmoss, and 70 DFB:30 pumice (v/v). All three substrates were mixed, adjusted to 1.5 $g \cdot g^{-1}$ mass wetness, and stored in plastic tubs until needed. Substrates were subsequently used to compare a new MLC approach with the method currently used by the North Carolina State University Substrates Laboratory (NCSL).

Modified long column method. Columns (112 cm tall × 7.6 cm i.d.) were cut from schedule 40 polyvinyl chloride (PVC) rigid pipe. Columns were extended for packing by adding 30-cm-long sections of schedule 40 PVC rigid pipe to both ends of the 112-cm pipe using clear packing tape. Columns were hand-packed. Substrate was constantly settled while packing by tapping on the column wall at 100 taps/min with a schedule 40 PVC rigid pipe (61 cm long × 1.3 cm i.d.). Columns were tapped for the duration of time needed to fill the column with substrate, ≈2 min. After filling the extended column, the 30-cm PVC pipe extension at the top of the column was removed. A PVC base was placed on a column using a rubber coupling (8.6 cm i.d.) and fastened with hose clamps (Fernco, Davison, MI). The base contained rigid mesh screen to ensure the substrate remained stable in the column. To ensure uniform bulk density (D_b), columns were inverted and the length of the column was tapped. The second 30-cm-long extension was removed. A 9.5-cm-wide petri dish was used to cover the top of the column to prevent evaporation. Columns were bottom-saturated with water for 4 h, then remained saturated for 8 h, and allowed to drain to ≈6 cm above the base of the column (Z_0) for 4 h (Fig. 1). Columns were placed in a freezer at −21 °C for 2 d. Frozen cores were cut into 10 sections (≈10 cm tall) starting ≈6 cm above the base of the column at Z_0. A section was also cut ≈5 cm below Z_0 to approximate θ_s at 0-cm tension. Columns were cut using a horizontal bandsaw (Jet, Rockford, IL) with a 0.9-mm-thick saw blade. Actual height of cut sections was determined by measuring height at four points along the circumference of each cut section. Volume (cm^3) was calculated for each section separately using its averaged height. Tension or height (h) was measured as the height of the midpoint of each section above Z_0. Each cut section was weighed, oven-dried at 60 °C for 3 d, and weighed again to determine water content ($cm^3 \cdot cm^{-3}$). The D_b was measured for each cut section as the weight of dried substrate per volume. cv for D_b was calculated for the cut sections within each column to ensure uniform D_b throughout the column. Only columns with cv less than 5% were used for analysis. Columns with cv for D_b greater than 5% are uncommon with this packing method. There were four replicate columns for each substrate type.

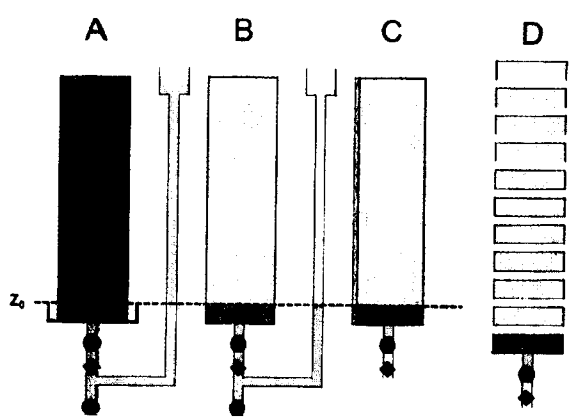

Fig. 1. Diagram of the modified long column method: (A) substrate packed into a polyvinyl chloride column, attached to a piezometer, and saturated; (B) column drained, the water level within the column marked as the same level in the piezometer and defined as Z_0; (C) valve closed at the base of the column to maintain Z_0, the piezometer removed, and the column frozen; (D) frozen, column cut into sections, and measured for water content (θ) and tension as height (cm) above Z_0.

North Carolina State University Substrate Laboratory method. Moisture characteristic curves were also determined by the NCSL according to the method described by Milks et al. (1989). Briefly, substrates were packed into aluminum rings (7.6 cm i.d. × 7.6 cm tall) and seated onto the porous plate inside a volumetric pressure plate extractor (Soil Moisture Equipment Corp., Santa Barbara, CA). Substrates were then saturated by adding water over a period of 34 to 48 h. An airtight lid was placed on top of the extractor and positive air pressures were applied at 3.8, 10, 20, 40, 50, 75, 100, 200, and 300 cm H_2O. Volume outflow was recorded for each increment of pressure and converted to percent moisture of the substrate volume. There were four replications for each substrate type.

Model comparison. To compare the van Genuchten model (Eq. 1) with the log-logistic model (Eq. 2), ≈0.11 m^3 of nine substrates was prepared by mixing components with a shovel on a non-porous concrete floor. The nine substrates were composed of the nine possible combinations of DFB amended with 0%, 15%, or 30% (by vol.) of peatmoss and pumice. Physical properties of these nine substrates were previously described by Gabriel et al. (2009), and the same data were used here solely for purposes of model comparison. There were three replicate columns per substrate type.

Statistical methods. Data were fit to selected models in SAS (Version 9.1; SAS Institute, Cary, NC) using the PROC NLIN procedure. Models were rejected if convergence of the iterative fitting process used by SAS had failed. Fitted models of the substrate types, methods (MLC and NCSL), and functions (Eq. 1 and Eq. 2) were compared using the lack-of-fit test (Schabenberger and Pierce, 2002). Fitted models were considered similar if probability values from the lack-of-fit test were non-significant. Fitted models with higher R^2 values and fewer estimable parameters were considered more desirable.

Results and Discussion

Methodology comparison. Scatterplots of MLC and NCSL methods appeared sigmoid in shape (Fig. 2), similar to those previously reported for soilless substrates (Gabriel et al., 2009; Milks et al., 1989). We explored the possibility of using sigmoid and exponential curves for describing MLC and NCSL methods. Sigmoid curves were chosen because they fit the data with higher R^2 values and with fewer terms than exponential curves (data not shown). Among sigmoid curves, a four-parameter log-logistic function was used as a result of the amount of variability explained with relatively few parameters as well as the interpretation of fitted parameters.

Four-parameter functions were fit to MLC and NCSL data from each of the three substrates (Fig. 2; Table 1). Probability values testing the null hypothesis that the two methods result in similar curves were 0.0002, 0.0001, and 0.0001 for the DFB substrate alone, DFB amended with peatmoss, and DFB amended with pumice, respectively. Although the curves for the two methods within each of the three substrates appear relatively similar, the two methods yield different functions.

Fitted curves of the three substrates measured by the NCSL differed ($F = 11.4$, $P = 0.0001$). Model differences can be explained by several of the estimated parameters. With the NCSL, addition of peatmoss or pumice reduced the value of θ_r ≈6% (Table 1). This was unexpected because it suggests that DFB alone would hold more water at higher tensions than DFB amended with peatmoss. Gabriel et al. (2009) reported a slight

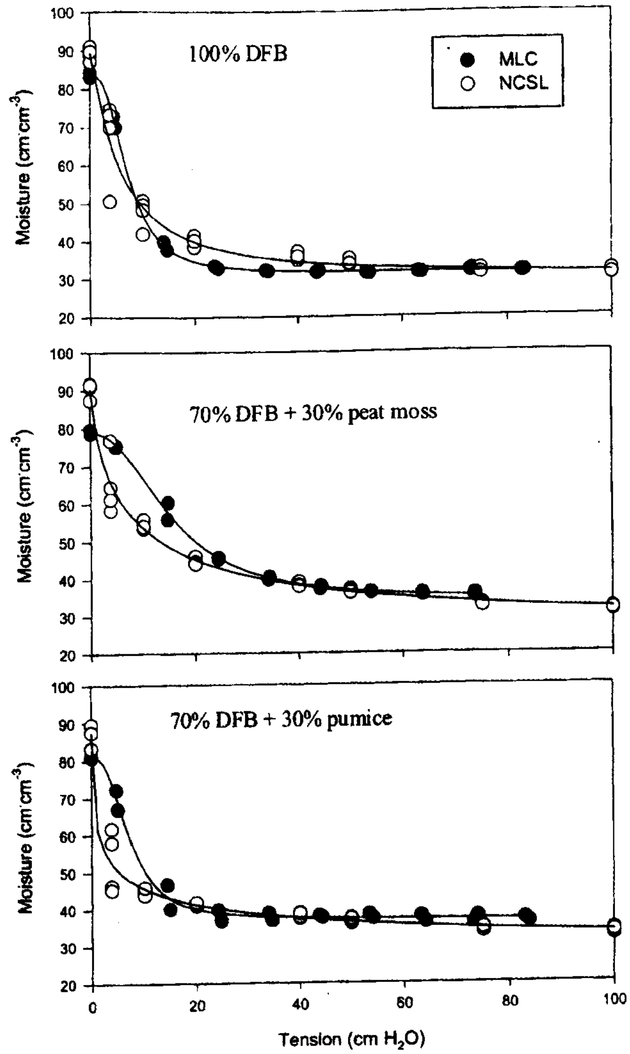

Fig. 2. Moisture characteristic curves of three douglas fir bark (DFB) substrates generated by either a modified long column (MLC) or modified hanging column (NCSL) method. See Table 1 for predicted equations.

increase in θ_r with increasing levels of peatmoss in a DFB substrate. The parameter θ_s was similar for all substrates (0.89 to 0.90 $cm^3 \cdot cm^{-3}$). The parameter x_0 was highest for DFB amended with peatmoss and lowest for DFB amended with pumice. These differences in x_0 are reflected in estimates of EAW and WBC. Easily available water was similar for DFB and DFB amended with peatmoss, both of which were greater than DFB amended with pumice (Table 1). Water buffering capacity was 2.4% higher for DFB amended with peat compared with DFB alone. Therefore, DFB amended with peatmoss would have slightly higher available water over the range of 10- to 100-cm tensions according to curves generated with the NCSL, whereas DFB amended with pumice would have the least available water.

Fitted curves for each of the three substrates determined by the MLC also differed ($F = 82.5$, $P = 0.0001$). The primary difference among estimated parameters for curves generated by the MLC was in the parameter x_0. The parameter x_0 for DFB amended with peatmoss was approximately twice as high as the other two substrates, resulting in greater EAW and WBC. DFB

Table 1. Estimated parameters for moisture characteristic curves of three substrates containing douglas fir bark (DFB) using either the modified long column method (MLC) or the North Carolina State University Substrates Laboratory (NCSL) method (n = 4).

Method	Substrate	θ_r[z]	θ_s	x_0	n	r^2	EAW[y]	WBC[x]
		($cm^3 \cdot cm^{-3}$)					($cm^3 \cdot cm^{-3}$)	
NCSL	100% DFB	0.30	0.89	5.55	1.23	0.9677	0.16	0.021
	70% DFB + 30% peat	0.24	0.90	7.56	0.78	0.9839	0.17	0.045
	70% DFB + 30% pumice	0.25	0.89	2.14	0.48	0.9917	0.09	0.029
MLC	100% DFB	0.32	0.84	7.27	2.69	0.9995	0.15	0.002
	70% DFB + 30% peat	0.34	0.79	15.49	2.29	0.9972	0.30	0.023
	70% DFB + 30% pumice	0.37	0.81	7.28	2.61	0.9915	0.13	0.002

[z]Parameters were estimated for the log-logistic function $\theta_r + (\theta_s - \theta_r)/[1 + (h/x_0)^n]$, where θ_r represents residual water content, θ_s represents water content at saturation, n (when $n < x_0$) is the air entry value, and x_0 is the tension at which the curve changes from convex to concave. The parameter r^2 is the coefficient of determination for the model.

[y]EAW represents easily available water or that which is available between –0 and –50 cm H_2O.

[x]WBC represents water buffering capacity or that which is available between –0 and –100 cm H_2O.

alone and DFB amended with pumice had curves that resulted in similar EAW and WBC. Gabriel et al. (2009) also showed pumice to have little effect on the water-holding capacity of DFB substrates.

The MLC and NCSL methods were able to distinguish differences among the three substrates, although interpretation of those differences was not the same for the two methods. Packing density is sometimes implicated as the cause for differences in two different methods of measuring physical properties (Gabriel et al., 2009). Packing bulk densities for the bark, bark + peatmoss, and bark + pumice were 0.18, 0.17, and 0.28 $g \cdot cm^{-3}$, respectively, for the MLC method; and 0.19, 0.16, and 0.29 $g \cdot cm^{-3}$, respectively, for the NCSL method. In this specific case, differences in bulk density between the methods for each substrate were so minor that they were unlikely to be the cause of differences in the curves. Higher values of θ_s in the NCSL method could have been caused by longer saturation times for that method. The MLC method used 12 h for saturation and equilibration, whereas the NCSL method used 48 h. The freezing step in the MLC method could have affected measured water content, because water expands when frozen. Differences caused by freezing would probably only affect lower tensions with higher water contents, because DFB substrates are very porous and would have sufficient air space to allow for expanding ice. Differences in curves generated by the two methods were pronounced at the 0-cm tension and may have been amplified by freezing in the MLC method. Finally, lower θ_r in the NCSL method may have been caused by different drying regimes used by the two laboratories. The NCSL samples were eventually dried at 105 °C for 24 h to determine final moisture content, whereas MLC samples were dried at 60 °C for 72 h. The authors believe it is unlikely different drying regimes could have accounted for all the discrepancy in θ_r.

A primary advantage of the NCSL method is that the upper range of measurable tensions is far greater than what is available with the MLC method. Some applied-pressure equipment such as the 1.5-MPa pressure plate (Soil Moisture Equipment Corp.) can measure soil moisture at tensions as high as 1.5 MPa (15,296 cm tension), whereas the MLC method is limited to ≈100 cm tension. However, the MLC method can provide greater detail at lower tensions. The most critical information for accurately describing the MCC lies in the sloped region of the sigmoid curve, which occurs at tensions between 10 and 40 cm for most bark-based soilless substrates. Columns described in this article were cut in 10-cm intervals above Z_0; however, those sections could be cut at smaller intervals to more precisely describe the sloped region of the sigmoid curve.

Model selection. The van Genuchten model (Eq. 1) was compared with a log-logistic model (Eq. 2) for nine substrates (Table 2). For two of the substrates, the PROC NLIN procedure failed to converge; thus, model parameters could not be estimated. Models were estimable for all substrates using the log-logistic model. Among substrates in which both models were estimable, the lack-of-fit test shows no significant difference between the two models. Because there is no significant difference, it is concluded that the extra term in the van Genuchten model does not provide additional information and thus can be dropped.

As a rule, the simplest model that describes the most variation is preferable. Coefficient of determination (R^2) for each of the log-logistic models was greater than 0.99; thus, the log-logistic model is not only simpler (fewer estimable parameters), but it also describes nearly all the variation in the data. van Genuchten (1980) also describes use of the log-logistic function (Eq. 2) for MCCs. van Genuchten (1980) seems to prefer Eq. 1 because it provides a systematic method for determining the parameters using either direct measurement or estimation. However, using modern computers and software, parameters of these non-linear functions can be easily and simultaneously estimated. Past difficulties in parameter estimation should no longer be a factor determining the most appropriate function or number of parameters. van Genuchten further suggests restricting m and n to ($m = 1 - 1/n$) to simplify derivation of closed-form analytical expressions for unsaturated hydraulic conductivity (van Genuchten and Nielsen, 1985). This might be relevant to some studies of soilless substrates; however, most of the literature on bark-based nursery substrates has thus far been primarily concerned with comparing the water retention characteristics of two or more substrates.

In summary, this article describes a MLC method that is inexpensive, rapid, and reliable for determining low-tension MCC for bark-based soilless substrates. It is limited in range only by the height of the freezer used to process the samples. In our case, that was ≈80 cm, but taller laboratory-style freezers are readily available. Typically these curves will have a characteristic sigmoid shape and are easily fit with a four-parameter log-logistic function using various software programs. Parameters

Table 2. F statistic and probability values for comparing the van Ganuchten model with a four-parameter log-logistic model for relating water content (θ) to pressure (h) on nine substrates composed of douglas fir bark amended with 0%, 15%, or 30% peatmoss or pumice.[z]

		van Genuchten model[y]					Four-parameter log-logistic model[x]				Lack-of-fit test	
		θ_r	θ_s				θ_r	θ_s				
Peat (%)	Pumice (%)	($cm^3 \cdot cm^{-3}$)		x_0	n	m	($cm^3 \cdot cm^{-3}$)		x_0	n	F	$P > F$
0	0	0.31	0.83	10.16	2.22	1.65	0.31	0.83	7.38	2.62	0.00148	0.970
0	15	0.34	0.83	11.04	2.25	1.76	0.33	0.82	7.73	2.66	0.00170	0.967
0	30	—[w]					0.31	0.81	6.42	1.86	—	—
15	0	0.32	0.86	6.23	2.54	0.70	0.32	0.85	7.83	2.20	0.00082	0.977
15	15	0.34	0.83	18.83	1.79	3.45	0.33	0.82	7.76	2.36	0.00826	0.928
15	30	—[w]					0.32	0.82	7.66	1.83	—	—
30	0	0.33	0.86	29.67	1.52	4.63	0.31	0.85	8.63	2.04	0.00764	0.931
30	15	0.34	0.85	10.70	1.62	1.27	0.33	0.84	8.76	1.73	0.00091	0.976
30	30	0.35	0.83	7.27	2.20	0.69	0.36	0.82	9.41	1.93	0.00067	0.980

[z]Data were generated using a modified long column method ($n = 3$).

[y]Model is defined as: $\theta = \theta_r + (\theta_s - \theta_r)/[1 + (h/x_0)^n]^m$ where θ_r represents residual water content, θ_s represents water content at saturation, n (when $n < x_0$) is the air entry value, x_0 is the tension at which the curve changes from convex to concave, and m is an estimable parameter.

[x]Model is defined as: $\theta = \theta_r + (\theta_s - \theta_r)/[1 + (h/x_0)^n]$ where θ_r represents residual water content, θ_s represents water content at saturation, n (when $n < x_0$) is the air entry value, and x_0 is the tension at which the curve changes from convex to concave.

[w]The van Genuchten model failed to converge for this data set; thus, parameter estimates are not available.

of these log-logistic functions also reveal intuitive values or properties. The parameter θ_r represents the point on the y-axis at which the curve flattens to a minimum, which is the amount of water ($cm^3 \cdot cm^{-3}$) that is retained in substrates at higher tension. The parameter θ_s estimates water content when tension is zero (complete saturation) and should be equivalent to total porosity as determined by the porometer method (Fonteno and Bilderback, 1993). The parameter n (when $n < x_0$) is the tension at which water content declines from the maximum and is often called the air entry value (Scott, 2000). The parameter x_0 is the tension at which the sigmoid curve changes from convex to concave (inflection point). The parameter x_0 is the most critical parameter in how it shapes the MCC. As x_0 increases, the inflection point moves to the right, which results in the higher value of water content at 10-cm tension. This in turn results in higher calculated values for EAW. Thus, simple examination of the four-parameter log-logistic function allows a reader to draw conclusions on the soil or substrate that it represents.

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