AN ABSTRACT OF THE THESIS OF

Magdalena Zazirska Gabriel for the degree of Master of Science in Soil Science presented on March 11, 2009.

Title: The Effect of Physical and Hydraulic Properties of Peat Moss and Pumice on Douglas-fir Bark Based Soil-less Substrates.

Abstract approved:

Dan M. Sullivan

Douglas-fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB), sphagnum peat moss, and pumice are the most common substrate components used in the Oregon nursery industry. Despite the widespread use of these three components, little information is available on the effect of physical and hydraulic properties of peat moss and pumice on DFB based soil-less substrates used in container production. Therefore, two studies were conducted in 2007 and 2008. The objectives of the first study were to (1) document the effect of peat and pumice addition on the physical and hydrological properties of Douglas-fir bark soil-less substrates; (2) determine if measured properties of mixed soil-less substrates can be accurately predicted from the known properties of the individual components. The second study was a continuation of the research. The objectives of this second study was to (3) compare volumetric and gravimetric method to determine particle size distribution of soil-less substrates composed of varying components; and (4) determine if existing model of Haverkamp and Parlange can be used to predict the

moisture characteristic curve (MCC) of mixed substrates with known particle size distribution.

In the first study, treatment design was a 3 x 3 factorial with three rates each of sphagnum peat moss and pumice (0%, 15%, and 30% by vol.) added to DFB. The resulting nine substrates were measured for total porosity, air space, container capacity and bulk density using porometers. Moisture characteristic curves were generated by measuring water content along a continuous column. Adding pumice to DFB decreased total porosity, container capacity, available water and water buffering capacity, but increased bulk density. Adding peat moss to DFB increased total porosity, container capacity and available water but decreased air space and bulk density. Comparison of predicted values against measured values indicated that bulk density could be predicted reliably; however, all other physical properties could not be accurately predicted.

The second study focused on comparing methods to measure particle size distribution for soil-less substrates and using those methods to predict moisture characteristic curve using soil based models. Treatment design was a 3 x 3 factorial with three rates each of sphagnum peat moss and pumice (0%, 15%, and 30% by vol.) added to DFB. Particle size distribution of the nine substrates was determined using volumetric and gravimetric methods. The particle size distributions of each substrate were used to determine if the Haverkamp and Parlange (1986) model could be used to accurately estimate a moisture characteristic curve for each substrate. There were statistical differences in particle size distribution between volume and weight based method. This resulted in shifts in the particle size summation curve (weight- or volume-based), however both methods remained strongly correlated providing relatively equivalent information. Regardless of substrates composition there was no similarity in measured particle size summation curve (weight- or volume-based) and measured moisture characteristic curve. Therefore, the Haverkamp and Parlange model was unable to be used to predict the moisture characteristic curve any of the soil-less substrates included in the study.

The Effect of Physical and Hydraulic Properties of Peat Moss and Pumice on Douglas-fir Bark Based Soil-less Substrates

by

Magdalena Zazirska Gabriel

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Magdalena Zazirska Gabriel, Author

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DEDICATION

To Michael B Gabriel – my friend and partner in life.

To my parents (Dla moich rodziców).

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CHAPTER 1

General Introduction

Pacific Northwest nursery producers create substrates for container corps by mixing two or more components. The primary components of soil-less substrate used in the Pacific Northwest are Douglas-fir [*Pseudotsuga menziesii* (Mirbel) Franco] bark (DFB) often amended with sphagnum peat moss and /or with pumice. Each substrate is unique and varies in physical properties (Bilderback et al., 2005). Nurseries have numerous combinations of components to create unique substrates used in crop production. Blythe and Merhaut (2007) documented the relationship of 127 different substrates commonly used by nursery growers in California which consisted of 11 organic and inorganic components. In Hillsborough County, FL, nurseries brought 40 soil-less substrates for analysis to a hands-on workshop. Yeager and Newton (2001) reported from that meeting that 26 of these substrates were unique and comprised of 16 different components.

Douglas-fir is the primary component of soil-less substrates used in the Oregon nursery industry. Commonly, sphagnum peat moss, or pumice is mixed with DFB to create desired physical properties. Many of the individual components used in soil-less substrate have been studied. Buamscha et al. (2007) evaluated physical and chemical properties of fresh and aged DFB and reported that aged DFB had lower airspace (AS) and higher container capacity (CC) compared to fresh DFB. These results were similar to findings reported by Bilderback et al. (2005) that aged pine bark increase CC and decrease AS compared to fresh pine bark. Puustjarvi and Robertson (1975) reviewed the properties of peat moss. They state that one of the most important properties of peat is its capacity to absorb and internally retain large quantities of water. Peat, depending on type, can hold 15 to 20 times its own weight in water. Pumice is a porous igneous rock found primarily in volcanic regions of the world, such as the Cascade Mountain Range in Oregon. The impact of pumice on crop growth and container physical properties has been studied throughout the world with each source having unique properties (Gizas and Savvas, 2007; Gunnlaugsson and Adalsteinsson, 1995; Lenzi et al., 2001). Buamscha and Altland (2005) documented the physical properties of pumice used for containerized nursery production in the Pacific Northwest. Pumice is usually added to bark or peat substrates to increase aeration, porosity, and drainage; however, there is little or no data to support this hypothesis.

Physical properties of substrates have been shown to affect crop growth (Tilt and Bilderback, 1987), water usage (Beardsell et al., 1979), and disease incidence (Ownley et al., 1990). Commonly used terms of physical properties of soil-lees substrates are included total porosity (TP), CC, AS. Total porosity is calculated from the total volume minus the volume occupied by the solids at zero pressure. Air space is the differences between TP and container capacity at 1 kPa of moisture tension (MT). Container capacity is the percent volume of first saturated and drained substrate and is divided into unavailable water (UAW), and available water (AW; de Boodt and Verdonck, 1972; Fonteno, 1996). Unavailable water is held in the substrate at ≥ 1.5 MPa, and AW (Fonteno, 1996). Bulk density (D_b) and particle size distribution (PSD) play very important roles in the physical properties of soil-less substrates. Bulk density is the ratio of the mass of dry solids to the bulk volume of substrate (Fonteno, 1996). Bulk densities of three different components are not uniform. When three different components are combined together that may reduce pore space and influence plant growth (Blok et al., 2008)

Particle size distribution can be divided in to three size groups or textures, coarse (19.00 mm to 2.00 mm), medium (1.40 mm to 0.50 mm), and fine (0.35 mm to <0.10mm). Moisture characteristic curve (MCC) shows the substrate ability to retain water under different tensions. From MCC we can calculate easily available water (EAW) as a percent of available water between 10 and 50 cm suction (H_2O) ($EAW = \Theta 50 - \Theta 10$), while water buffering capacity ($WBC = \Theta 100 - \Theta 50$) was calculated as percent water available between 50 and 100 cm suction (de Boodt and Verdonck, 1972).

It is not well known how each potential substrate component affects the resultant substrate physical properties. Considering the cost of component amendments and the energy required to mix them, it would be useful to know or predict the influence of component amendments on substrate physical properties.

In many instances these properties can be predicted in soil system with known composition or texture. Beardsell et al. (1979) attempted to predict the physical properties of substrate component combinations from the known properties of each component. They found excellent agreement between measured and predicted physical properties using an additive model (Eq. 1) for combinations of bark, peat, sawdust, and poppy straw amended with either sand or scoria. However, this study was limited to equal ratios of just two materials for any given substrate. Comparable component ratios are rare in containerized nursery crop production.

$$\{\text{Eq. [1]: Mixture property} = \sum_{i=1}^{n}(\text{component volume ratio}_i)(\text{component property}_i)\}$$

Jenkins and Jarrell (1989) attempted to validate Eq. [1] for prediction physical properties. They found that linear relationships between measured and predicted properties of bark:sand and bark:perlite substrates were strongly correlated for bulk density (D_b), but correlation was poor for other parameters such as total porosity, air space, and container capacity. When attempting to predict air space, total porosity, and container capacity Milks et al. (1989) have shown that only bulk density can accurately be predicted for soil-less substrate composed of bark and peat.

Soil scientists have used particle size to predict MCC with varying success. In the wide range of soil textures, Zhuang et al. (2001), Haverkamp and Parlange (1986) and Rajkai et al. (1996) were able to accurately predict soil moisture characteristic curve based on particle size summation curves when organic matter was less than 5%. Smettem and Gregory (1996) reported that soil moisture characteristic curves (MCC) can be predicted for two sandy textured Western Australian soils, Entisols and Alfisols, using their soil particle size distribution. Arya and Paris (1981) successfully developed a physico-empirical model to predict the moisture characteristic curve for silty clay and sandy loam using the particle size distribution. Both of the above models are based on the similarity between the shape of moisture characteristic and particle size summation curves. Zhuang et al. (2001) presented a model for non-similar media. They estimated the moisture characteristic curve from basic soil properties like bulk density. They reported that this model applies very well to soils of all textures except sandy soils. Haverkamp and Parlange (1986) had similar difficulty predicting moisture characteristic curves of sandy soils. They hypothesized that the wide extent of grain sizes created a pore distribution that could not be accurately predicted because fine sand with small particles nested in large pores created by large sand grains.

Soil-less substrates are like sandy soils in that they are extremely porous (>80% TP) and contain particles with a wide range of size. Unlike sandy soils, particles have unique shapes that range from plate-like to round. In addition, the particles themselves have unique physical properties that allow them to absorb water. Particle density and water retention varies widely for each component (DFB, peat, and pumice) used to create soil-less substrate mixtures for containerized nursery production in the Pacific Northwest. Pumice used in the Northwest has wide range of particle size, with each particle able to retain 45 to 55 % water by volume within internal vesicles (Boertje, 1995). Peat and bark are both sponge-like and able to retain 50 to 90% water by volume, respectively (Maher et al., 2008). Peat particle size is relatively uniform, however unscreened bark has particles ranging in size anywhere ≤6.3 mm. This wide particle size distribution creates a large array of micro- and macro- pores that influence water distribution in relation to matric potential. When these components are mixed, a complex system is created with varying pore space, component water-holding capacity and component particle density. Individual, time-consuming analyses must be performed to determine the physical properties and hydrology of each substrate mixture.

Containerized nursery production requires soil-less substrate that is easy to adapt to the special needs of specific plant species. Making a soil-less substrate from more than two components may bring unexpected results in physical properties and that reduce plant growth and vigor. Two studies were conducted to evaluate substrate physical properties and the resulting container mix hydrology. The objectives of the first study were to: (1) document the effect of peat and pumice addition on the physical and hydrological properties of Douglas-fir bark soil-less substrates and (2) determine if measured properties of mixed soil-less substrates can be accurately predicted from the known properties of the individual components. The objectives of this second study was to: (1) compare volumetric and gravimetric methods to determine particle size distribution of soil-less substrates composed of varying components; and (2) determine if existing model of Haverkamp and Parlange can be used to predict the moisture characteristic curve (MCC) of mixed substrates with known particle size distribution.

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CHAPTER 2

The Effect of Physical and Hydraulic Properties of Peat Moss and Pumice on Douglas-fir Bark Based Soil-less substrates

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Abstract

Douglas-fir [*Pseudotsuga menziesii* Mirb.(Franco)] bark (DFB), sphagnum peat moss, and pumice are the most common substrate components used in the Oregon nursery industry. The objective of this study was to document the effect of peat and pumice addition on the physical and hydrological properties of Douglas-fir bark soil-less substrates. A secondary objective was to determine if measured properties of mixed soil-less substrates can be accurately predicted from the known properties of the individual components. Treatment design was a 3 x 3 factorial with three rates each of sphagnum peat moss and pumice (0%, 15%, and 30% by vol.) added to DFB. The resulting nine substrates were measured for total porosity, air space, container capacity and bulk density using porometers. Moisture characteristic curves were generated by measuring water content along a continuous column. Adding pumice to DFB decreased total porosity, container capacity, available water and water buffering capacity, but increased bulk density. Adding peat moss to DFB increased total porosity, container capacity and available water but decreased air space and bulk density. Comparison of predicted values against measured values indicated that bulk density could be predicted reliably, however all other physical properties could not be accurately predicted.

Introduction

Nursery producers create their own substrates by mixing two or more components. Components are often regional and based on local resources available to the nursery operation. Outdoor container nurseries use bark as the primary component mixed with one or more other materials to create an infinite number of possible substrates. Yeager and Newton (2001) reported that at a hands-on workshop in Hillsborough County, FL, nurseries brought 40 soil-less substrates used for containerized nursery production for analysis during the workshop. Twenty-six of these substrates were unique and comprised of 16 different components. The relationships of 127 different substrates which consisted of 11 organic and inorganic components commonly used by nursery growers in California (Blythe and Merhaut, 2007). The aforementioned papers illustrate the broad number of substrate components and virtually unlimited numbers of combinations that nursery growers utilize.

Physical properties of substrates affect crop growth (Tilt and Bilderback, 1987), water usage (Beardsell et al., 1979), and disease incidence (Ownley et al., 1990). However, it is not well known how each potential component affects the resultant substrate physical properties. Considering the cost of component amendments and the energy required to mix them, it would be useful to know or predict the influence of component amendments on substrate physical properties. Beardsell et al. (1979) attempted to predict the physical properties of substrate component combinations from the known properties of each component. They found excellent agreement between measured and predicted physical properties using an additive model

$$\{\text{Eq. [1]: Mixture property} = \sum_{i=1}^{n} (\text{component volume ratio}_i)(\text{component property}_i)\}$$

for combinations of bark, peat, sawdust, and poppy straw amended with either sand or scoria. However, this study was limited to equal ratios of just two materials for any given substrate. Comparable component ratios are rare in containerized nursery crop production.

Jenkins and Jarrell (1989) attempted to validate Eq. [1]. They found that linear relationships between measured and predicted properties of bark:sand and bark:perlite substrates were good for bulk density(D_b), but mixed or poor for other parameters such as total porosity (TP), air space (AS), and container capacity (CC).

The most common substrate components use in the Oregon nursery industry is Douglas-fir [*Pseudotsuga menziesii* Mirb. (Franco)] bark (DFB), sphagnum peat moss, and pumice. Each of these individual components has been studied. Buamscha et al. (2007) evaluated physical and chemical properties of fresh and aged DFB and reported that aged DFB had lower AS and higher CC compared to fresh DFB. These results were similar to findings reported by Bilderback et al. (2005) that aged pine bark increase CC and decrease AS compared to fresh pine bark.

Puustjarvi and Robertson (1975) provide a thorough review of the properties of peat moss. They state that one of the most important properties of peat is its capacity to absorb and internally retain large quantities of water. The amount of water held by a given weight of peat can be 15 to 20 times its own weight, depending on peat type. Pumice is a porous igneous rock found primarily in volcanic regions of the world, such as the Cascade Mountain Range in Oregon. The impact of pumice on crop growth and container physical properties have been studied throughout the world, as pumice from each volcanic region has unique properties (Gizas and Savvas, 2007; Gunnlaugsson and Adalsteinsson, 1995; Lenzi et al., 2001). Buamscha and Altland (2005) documented the physical properties of pumice used for containerized nursery production. Pumice is usually added to bark or peat substrates to hypothetically increase aeration, porosity, and drainage, however there is no or little data to support this hypothesis.

Due to widespread use of peat and pumice as an amendment for DFB in the Oregon nursery industry, the objective of our research was to document the effect of these components on the physical and hydrological properties of DFB substrates.

A secondary goal was to determine if prediction algorithms such as those proposed by Jenkins and Jarrell (1989) can accurately predict physical properties of DFB, peat, and pumice mixes.

Materials and Methods

General procedures

Aged Douglas-fir bark [screened to 0.9 cm (0.4 in)] was collected from stockpiles intended for nursery container production (Marr Bros. Monmouth, OR). Pumice (< 9.5 mm), (Pro-Gro, Sherwood, OR) and Canadian sphagnum peat (Sun Gro Horticulture Canada Ltd., Laval, Quebec) were used as the components to make nine substrates. Physical properties of the components prior to mixing are provided (Table 2.1). Approximately 0.11 m^3 of each substrate was prepared by mixing components with a shovel on a non-porous concrete floor. Substrates were stored individually in plastic containers in a dark, cool shed until needed for analysis.

Substrate Physical Properties

Douglas-fir bark samples were adjusted to 1.5 $g \cdot g^{-1}$ mass wetness and packed in 347cm^3 aluminum cores (7.6 cm tall by 7.6 cm i.d.) according to methods described by Fonteno and Bilderback (1993). There were three replications for each substrate. Aluminum cores were attached to North Carolina State University Porometers™ (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, N.C.) for determination of AS. Cores were weighed, oven-dried for four days at 60°C, and weighed again to determine CC. Total porosity was calculated as the sum of AS and CC. All physical properties (TP, AS, CC) were calculated as the algebraic mean of the core. Bulk density was determined using oven dried (60°C) substrate in 347 cm^3 cores. Unavailable water (UAW), held in the substrate at ≥ 1.5 MPa, was determined with 174 cm^3 cores (3.3 cm tall by 7.6 cm i.d.) using a porous ceramic pressure plate extractor via a procedure developed by Milks et al. (1989). Available water (AW) is the water determined by subtracting UAW from CC. Particle size distribution of DFB, pumice and peat using approximately 100 cm^3 oven dried substrate (60°C) was determined using 19.0, 12.5, 6.30, 4.0, 2.8, 2.0,1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm soil sieves (Table 2.1). Particles ≤ 0.11 mm were collected in a pan. Sieves and pan were shaken for 3 min with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}) (W.S. Tyler, Mentor, OH).

Moisture Characteristic Curves

Columns (112 cm tall by 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^{-1} with a schedule 40 PVC rigid pipe (61 cm long by 1.3 cm i.d.). 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 column using a rubber coupling (8.6 cm i.d.) and fastened with hose clamps (Fernco, Inc. Davison, MI). The base contained rigid mesh screen to ensure the substrate remained stable in the column. To ensure uniform 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 hr. Columns were placed in a freezer at -21°C for ≥ 2 d. Frozen cores were cut into ten sections [≈10 cm tall] starting ≈ 6 cm above the base of the column at Z_0. Columns were cut using a Jet 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; volume was calculated for each section separately using its averaged height. Each cut section was weighed, oven dried at 60°C for 3 d and weighed again to determine water content ($cm^3 \cdot cm^{-3}$). From moisture characteristic curve (MCC), easily available water (EAW) was calculated as the percent of available water between 10 and 50 cm suction (H_2O) ($EAW = \Theta_{50} - \Theta_{10}$), while water buffering capacity ($WBC = \Theta_{100} - \Theta_{50}$) was calculated as percent water available between 50 and 100 cm suction (de Boodt and Verdonck, 1972).

Physical properties were subjected to univariate and multivariate analysis of variance. Moisture characteristic curves were fit with a four-parameter sigmoid curve (Table 2.2). Curves for each substrate were compared to each other using the lack of fit test. All statistical analyses were conducted with SAS 9.1 (SAS Institute, Cary, N.C.). Figures were constructed with SigmaPlot 10.0 (Systat Software, Inc., San Jose, Calif.).

Results and Discussion

Physical properties

Multivariate analysis shows that peat and pumice interacted to affect physical properties (TP, AS, and CC) of DFB substrates (Table 2.3). Total porosity was affected by peat moss and pumice, however there was no interaction (P=0.25). Averaging across levels of pumice, TP increased from 85% to 89% as the level of peat moss increased from 0% to 30%. Conversely, TP decreased from 89% to 85% with increasing level of pumice. Both CC and AS were affected by the interaction of peat moss and pumice. Within a given level of peat moss, adding pumice caused a decrease in CC (with the exception of the substrate containing 15% pumice and 30% peat) while measured values of AS were erratic. Within each level of pumice, adding peat moss caused an increase in CC and decrease in AS. Unavailable water was affected by peat and pumice, but not their interaction (Table 2.4). Averaging across levels of pumice, adding peat moss caused a decrease in UAW and thus an increase in AW. Conversely, adding pumice caused an increase in UAW at the highest amendment rate. Lowder et al. (2006) reported the changes in physical properties of pine bark by amending with 10% or 20% sand which, in general, contradicts our findings. They reported that increasing levels of sand increased CC and AW. Sand and pumice are often thought to be analogous potting materials in that they are both inorganic and dense components. However, the two materials have drastically different properties. While sand and pumice can vary by source, Pokorny et al. (1986) reported sand to have D_b of 1.6 g·cm^3 with 27% by weight have a particle size less than 0.42 mm. In contrast, pumice has D_b of 0.41 g·cm^3 with only 17% by weight having a particle size less than 0.35 mm (Table 2.1). Differences in D_b and fine particles may explain the different response of bark to sand and pumice.

The effect peat moss and pumice have on substrates TP, AS, CC, UAW and AW is probably related to particle size of the amendments. While the distribution of pumice is skewed heavily towards coarse particles, over 11% were less than 0.11 mm compared to DFB that contained just 2% of those sized particles (Table 2.1). Fine pumice particles will settle between the larger pores of DFB substrate thus causing a decrease in TP. Container capacity also decreased, likely because pumice is inorganic and retains little water. Particle size distribution of peat moss is more uniformly distributed across the range of measured sizes than pumice, but also with a greater amount of fine particles than DFB. While fine peat moss particles would have settled between DFB particles, similar to pumice, peat moss can hold up to 20 times its weight in water (Puustjarvi and Robertson, 1975). Thus, adding peat moss increased CC and decreased AS, with the net effect of increasing TP.

Bulk density was affected by an interaction between peat moss and pumice. Within a given level of peat moss, adding pumice increased D_b of the substrate; within a level of pumice, peat moss caused a decrease in D_b. Bulk density of DFB alone is 0.16 g·cm^{-3}, while that for peat moss and pumice is 0.07 and 0.41 g·cm^{-3}, respectively (Table 2.3). Substituting a part of a DFB substrate with less dense peat moss lowered D_b, while amending with the denser pumice increased D_b.

Predicted values for physical properties

An attempt was made to predict the physical properties of the nine substrate mixes, using only the known physical properties of the components (Table 2.1) and the equation provided by Jenkins and Jarrell (1989). A linear relationship was fit to measured and predicted physical properties of the nine substrates (Table 2.4). If two different procedures for estimating substrate physical properties (measured and predicted) were to provide the same results, their relationship could be described by a straight line with slope (m) = 1, *y*-intercept (b) = 0, and r^2 approaching 1.0. The equation by Jenkins and Jarrell (1989) was effective in predicting D_b (m = 0.75, b = 0.03, and r^2 = 0.99). The slope of the line relating measured and predicted D_b is less than 1, meaning the prediction equation would tend to underestimate D_b slightly. Pokorny et al. (1986) also reported that an additive model underestimates D_b of pine bark and sand substrates. They attributed underestimation to shrinkage that occurs when two components of disparate particle sizes are mixed. The equations for TP, AS, and CC each had slopes far from 1, b far from 0, and low r^2 values (Table 2.4). Linear relationships for TP, AS, and CC were poor, and scatter plots of the data (not presented) clearly demonstrated that no other linear or non-linear relationship would provide a better explanatory equation.

Moisture characteristic curves

Moisture characteristic curves relate the availability of water in a given substrate over a range of tensions. The influence of peat within a given level of pumice on moisture characteristic curves are provided in Fig. 2.1A through 2.1C, and likewise the influence of pumice on MCC within a given level of peat are provided in Fig.s 2.2A through 2.2B. The parameters of estimates for each curve are in Table 2.2. The lack-of-fit test was use to compare all curves resulting in 36 unique comparisons in which all curves were found to be different from each other (P <0.01, data not presented).

The parameter y_0 represents the point on the y-axis at which the curve flattens to a minimum, which is the level of water ($cm \cdot cm^{-1}$) that is retained in substrates at high tension. The sum of parameters $y_0 + a$ estimate water content when tension is zero (complete saturation) and should be equivalent to TP (Table 2.3). Comparing $y_0 + a$ offers slightly different values than TP measured by porometers (Table 2.3), although the trends with respect to peat and pumice are similar. Differences between porometer TP and column estimation with $y_0 + a$ are likely due to differences in D_b from variation in packing procedures. The parameter b is the tension at which water content declines from the maximum, while x_0 is the tension at which the sigmoid curve changes from convex to concave (inflection point). The parameter b decreases slightly with increasing peat and pumice, although differences are minor. The parameter x_0 is the most important parameter in how it shapes the moisture characteristic curve. 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. Parameter x_0 increases with increasing peat moss but changes relatively little with increasing pumice. As a result of differing MCC (Table 2.2), EAW remained constant or decreased slightly with increasing pumice level. Averaging across levels of peat, EAW was 0.19, 0.18, and 0.17 $cm \cdot cm^{-1}$ with pumice at 0%, 15%, and 30%, respectively. Conversely, adding peat caused an increase in EAW and RAW both within and across levels of pumice. Water buffering capacity is much less than EAW but followed the same trend as EAW with respect to its response to peat and pumice.

Conclusion

This research demonstrates three important characteristics of DFB based substrates: 1) peat moss and pumice affect physical properties of DFB substrates; 2) there is often an interaction between peat moss and pumice regarding their effects on substrate physical properties; and 3) substrate physical properties discussed herein, with the exception of D_b, cannot be accurately predicted from the known properties of the components using Eq. [1]. Fonteno (1996) stated that when components are blended, the chemical and physical properties of the components are married to form new properties that are different from the individual components. This is a more realistic perspective on substrate mixes than the notion that physical properties of substrate mixes could be predicted with a mathematical model. Despite our inability to accurately predict most substrate physical properties, this research demonstrates that peat moss generally increases TP, CC, AS, and EAW, while decreasing D_b and UAW. Furthermore, pumice generally decreases TP, CC, and EAW, while causing an increase in D_b.

This research does not suggest one amendment is superior to the other, or that the resulting properties of any of the nine substrates are more conducive to plant growth. Lowder et al. (2006) grew hellebores (*Helleborus* ×*hybridus* and *H. foetidus*) in pine bark amended with different rates of sand or peat moss, and demonstrated that hellebores are best grown in substrates with high AW and low AS. Conversely, Breedlove et al. (1999) grew ‘Hershey Red’ azalea (*Rhododendron* sp.) in pine bark alone or pine bark amended with peat moss or perlite, and showed that greatest growth and quality occurred in 100% pine bark, which among all substrates had the highest AS and lowest AW. No single substrate is universally suitable to all plant species (Lea-Cox and Smith, 1997). Plants will respond more favorably to substrates that best mimic conditions of their natural habitats. The utility of this research is to demonstrate how Douglas-fir bark substrates respond to the most common amendments used along the west coast of the U.S. Nursery growers can utilize this to make better decisions about peat moss and pumice amendment rates, and how they might interact with production or irrigation regimes.

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Table 2.1. Particle size distribution and physical properties of Douglas-fir bark (DFB), peat, and pumice (n=3).

Particle size distribution	Sieve size (mm)	DFB	Peat	Pumice
Coarse		-----------------------------%-----------------------------------		
	19.00	0.00	0.00	0.00
	12.50	0.00	2.13	0.00
	6.30	0.26	8.85	8.13
	4.00	8.45	7.94	17.63
	2.80	13.19	5.80	14.49
	2.00	13.33	5.00	12.22
Medium	1.40	12.34	4.72	10.03
	1.00	10.47	6.13	7.57
	0.71	8.91	7.64	5.24
	0.50	9.48	8.68	4.60
Fine	0.35	7.63	10.64	3.12
	0.25	6.57	9.18	2.11
	0.18	4.59	6.85	1.54
	0.11	2.99	7.94	2.13
	Pan	2.01	6.59	11.25
Total porosity (%)		87	91	77
Air space (%)		28	22	39
Container capacity (%)		60	69	38
Bulk density ($g \cdot cm^{-3}$)		0.16	0.07	0.41

Table 2.2. Parameters estimates (with standard errors in parentheses) for moisture characteristic curves of nine Douglas-fir bark substrates amended with peat moss or pumice (see Fig. 2.1A – 2.1C and 2.2A – 2.2C).

		Parameter estimated										WHC estimates					
												10 cm	50 cm	100 cm			
Peat[z]	Pumice	y_0		a		x_0		b		n	r^2				EAW[y]	WBC[x]	RAW[w]
0	0	0.31	(0.002)	0.52	(0.003)	7.38	(0.102)	2.62	(0.066)	30	0.999	0.47	0.31	0.31	0.16	0.00	0.16
0	15	0.33	(0.002)	0.49	(0.004)	7.73	(0.135)	2.66	(0.079)	30	0.998	0.49	0.33	0.33	0.16	0.00	0.16
0	30	0.31	(0.005)	0.50	(0.008)	6.42	(0.235)	1.86	(0.110)	30	0.993	0.46	0.32	0.31	0.14	0.01	0.15
15	0	0.32	(0.003)	0.53	(0.006)	7.83	(0.177)	2.20	(0.074)	30	0.997	0.52	0.33	0.32	0.19	0.01	0.20
15	15	0.33	(0.002)	0.49	(0.004)	7.76	(0.136)	2.36	(0.067)	30	0.998	0.50	0.34	0.33	0.16	0.01	0.17
15	30	0.32	(0.006)	0.50	(0.010)	7.66	(0.308)	1.83	(0.119)	30	0.992	0.51	0.34	0.32	0.17	0.02	0.19
30	0	0.31	(0.004)	0.54	(0.008)	8.63	(0.239)	2.04	(0.092)	30	0.996	0.54	0.33	0.31	0.21	0.02	0.23
30	15	0.33	(0.003)	0.51	(0.005)	8.76	(0.164)	1.73	(0.050)	30	0.998	0.56	0.35	0.34	0.21	0.01	0.22
30	30	0.36	(0.004)	0.46	(0.008)	9.41	(0.289)	1.93	(0.096)	30	0.995	0.58	0.38	0.37	0.20	0.01	0.21

[z] Parameters were estimated for the sigmoid function $y = y_0 + (a/(1+(x/x_0)^b))$.

[y]EAW represents easily available water, or that which is available between 10 and 50 cm.

[x]WBC represents water buffering capacity, or that which is available between 50 and 100 cm.

[w]RAW represent readily available water, or that which is available between 10 and 100 cm.

Table 2.3. Physical properties of Douglas-fir bark affected by incremental additions of peat moss and pumice.

Peat[z]	Pumice	TP[y]	AS	CC	UAW	AW	Db
		(% by vol.)					($g \cdot cm^{-3}$)
0	0	87	28	60	23	37	0.16
0	15	86	29	57	23	34	0.22
0	30	82	28	54	25	29	0.27
15	0	88	24	64	22	42	0.15
15	15	87	26	61	21	40	0.20
15	30	86	27	59	24	35	0.25
30	0	92	29	64	21	43	0.14
30	15	88	19	69	22	47	0.18
30	30	87	25	62	22	40	0.24
Tukey's LSD (0.05)		5	8	6	2		0.01
Univariate main effects		Pr>F					
Peat		0.0003	0.0930	<.0001	0.0002		<.0001
Pumice		0.0010	0.0055	0.0001	0.0001		<.0001
Interaction		0.2466	0.0082	0.0030	0.2205		0.0067
Multivariate main effects			Pr>F				
Peat			0.0001				
Pumice			0.0001				
Interaction			0.0104				

[z] Peat and pumice were added at 0, 15, or 30%, by volume, to Douglas-fir bark.
[y] TP, CC, AS, UAW, AW, and D_b stand for total porosity, container capacity, air space, unavailable water, available water and bulk density, respectively.

Table 2.4. Linear relationship between predicted (y) and measured physical properties (x) of nine substrates comprised of Douglas-fir bark, peat moss, and pumice using additive model of Jenkins and Jarrell.

Properties	Equation	r^2
Bulk density	y = 0.75x + 0.03	0.99
Total porosity	y = 0.23x + 65.75	0.30
Air space	y = 0.08x + 26.58	0.06
Container capacity	y = 0.38x + 34.64	0.37

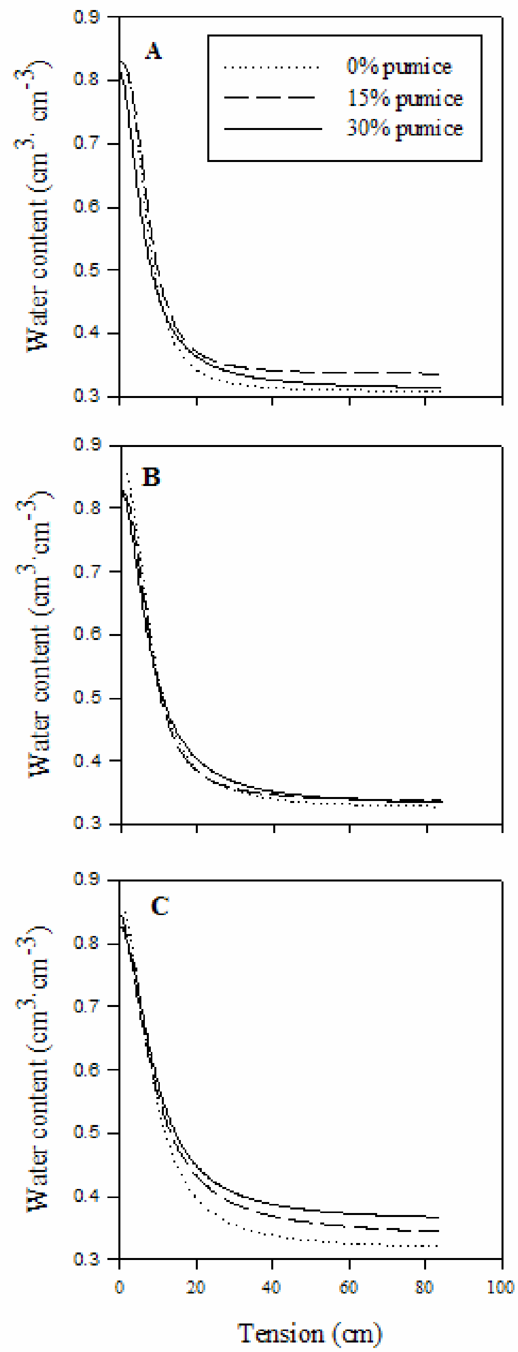

Figure 2.1. Moisture characteristic curves of substrates containing 0% (A), 15% (B), and 30% (C) peat moss, respectively, amended with varying levels of pumice (see Table 2.2 for fitted regression equations).

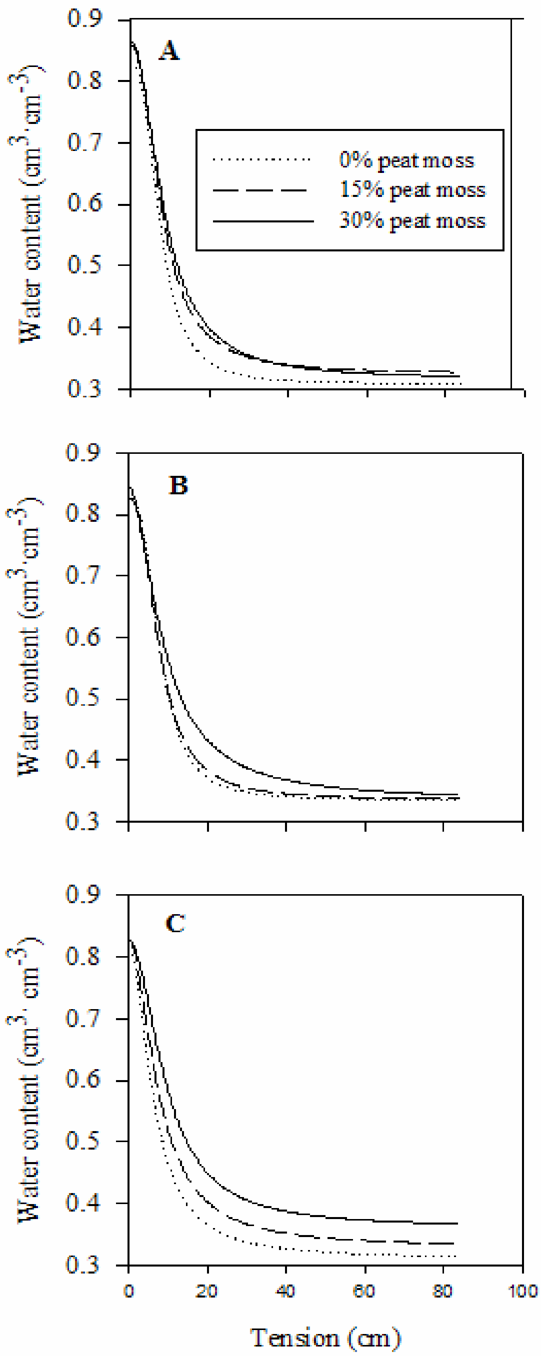

Figure 2.2. Moisture characteristic curves of substrates containing 0% (A), 15% (B), and 30% (C) pumice, respectively, amended with varying levels of peat moss (see Table 2.2 for fitted regression equations).

CHAPTER 3

Relationship Between Particle Size Summation Curves and The Moisture Characteristic Curve for Soil-less Substrates

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Abstract

Particle-size distribution influences the physical properties and hydrology of soils and soil-less substrates. Soil-less substrates are commonly have more than one component with each component varying in particle density which can affect the meaning or accuracy of a gravimetric particle-size distribution. The objective of this study was to compare volumetric or gravimetric methods to determine particle size distribution of single [Douglas-fir bark (DFB) only], dual (DFB plus peat or pumice), or multiple component (DFB plus peat and pumice) soil-less substrates. A secondary objective was to determine if the existing model of Haverkamp and Parlange (1986) can be used to predict moisture characteristic curve of single, dual or multiple component substrates with known particle size distribution. Treatment design was a 3 x 3 factorial with three rates each of sphagnum peat moss and pumice (0%, 15%, and 30% by volume) added to DFB. Particle-size distribution of the nine substrates was determined using volumetric and gravimetric methods. The particle-size distribution of each substrate was used to determine if the Haverkamp and Parlange (1986) model could be used to accurately estimate a moisture characteristic curve for each substrate. There were statistical differences in particle-size distribution between the volumetric and gravimetric methods. This resulted in a shift in the particle-size summation curve (weight- or volume-based), however both methods remained strongly correlated providing similar information. Regardless of substrate composition, there was not a strong predictive relationship between measured particle-size summations curves (weight- or volume-based) and measured moisture characteristic curve. Therefore, the Haverkamp and Parlange (1986) model did not predict the moisture characteristic curve of single-, dual-, or multiple-component soil-less substrates.

Introduction

Douglas-fir bark (DFB) is the primary component of soil-less substrates used for containerized crop production in the Pacific Northwest. Commonly, peat or pumice is mixed with DFB to create desired physical properties to ensure maximum crop growth. Zazirska Gabriel et al. (2009) studied physical properties (air space, container capacity, total porosity) and hydrology of Pacific Northwest substrates with differing composition (DFB, peat, and/or pumice). In many instances these properties can be predicted in a soil system with known composition or texture. In the wide range of soil textures, Zhuang et al. (2001), Haverkamp and Parlange (1986) and Rajkai et al. (1996) were able to accurately predict a soil moisture characteristic curve based on the particle-size summation curve when organic matter was less than 5%. Milks et al. (1989) have shown that only bulk density can be predicted accurately for soil-less substrate composed of bark and peat, respectively, when attempting to predict air space, total porosity, and container capacity.

Soil scientists have used particle size to predict moisture characteristic curves with varying success. Smettem and Gregory (1996) reported that soil-moisture characteristic curves (MCC) can be predicted for two sandy textured Western Australian soils, Entisols and Alfisols, using their soil particle-size distribution. Arya and Paris (1981) successfully developed a physico-empirical model to predict the moisture characteristic curve for silty clay and sandy loam using the particle size distribution. Both of the above models are based on the similarity between shape of moisture characteristic and particle-size summation curves. Zhuang et al. (2001) presented a model for non-similar media concept to estimate the moisture characteristic curve from basic soil properties like bulk density. They reported that this model applies very well to soils of all textures except sandy soils. Haverkamp and Parlange (1986) had similar difficulty when using sandy soils to predict moisture characteristic curves. They hypothesized that the wide extent of sizes in grain sizes created a dissimilar pore distribution that could not be accurately predicted because sand with small particles nested in large pores created by large sand grains.

Soil-less substrates are like sandy soils in that they are extremely porous (>80% TP) and contain particles with a wide range of size. Unlike sandy soils, particles have unique shapes that range from plate-like to round. In addition, the particles themselves have unique physical properties that allow them to absorb water. Particle density and water retention varies widely for each component (DFB, peat, and pumice) used to create soil-less substrate mixtures for containerized nursery production in the Pacific Northwest. Pumice used in the northwest has a wide range of particle size, with each particle able to retain 45 to 55% water by volume because of internal vesicles (Boertje, 1995). Both peat and bark are sponge-like and able to retain 50 to 90% and 87% water by volume, respectively (Maher et al., 2008). Peat particle size is relatively uniform, however unscreened bark has particles ranging in size anywhere ≤6.3 mm. This wide particle-size distribution creates a large array of micro- and macro- pores that influence water distribution relative to matric potential. When these components are mixed, a complex system is created with varying pore space, component water-holding capacity and component particle density. Individual time-consuming analyses must be performed to determine the physical properties and hydrology of each substrate mixture.

The objectives of our research was to: (1) compare volumetric or gravimetric methods to determine particle-size distribution of soil-less substrate composed of single, dual, or multiple components and (2) determine if particle-size distribution could be used to predict soil moisture characteristics curve of soil-less substrates using soil-based methods.

Materials and Methods

General procedures

Aged Douglas-fir bark [screened to 0.9 cm (0.4 in)] was collected from stockpiles intended for nursery container production (Marr Bros. Monmouth, OR). Pumice (< 9.5 mm) (Pro-Gro, Sherwood, OR) and Canadian sphagnum peat (Sun Gro Horticulture Canada Ltd., Laval, Quebec) were used as the components to make nine substrates. These consisted of single component (DFB only), dual component (DFB with peat or pumice), or multiple component (DFB with peat and pumice) soil-less substrates. Approximately 0.11 m^3 of each substrate was prepared by mixing components with a shovel on a non-porous concrete floor. Substrates were stored individually in plastic containers in a dark, cool shed until needed for analysis.

Substrate Physical Properties

Douglas-fir bark samples were adjusted to 1.5 $g \cdot g^{-1}$ mass wetness and packed in 347cm^3 aluminum cores (7.6 cm tall by 7.6 cm i.d.) according to methods described by Fonteno and Bilderback (1993). There were three replications for each substrate. Aluminum cores were attached to North Carolina State University Porometers™ (Horticultural Substrates Laboratory, North Carolina State University, Raleigh, N.C.) for determination of D_b. Bulk density was determined using oven-dried (60°C) substrate in 347 cm^3 cores. Total porosity, container capacity, air space and bulk density was reported by Zazirska Gabriel et al. (2009) for all nine substrates.

Particle Size

The particle size distributions of each nine mixes based on DFB, pumice and peat was determined by drying three 1000 cm^3 oven dried substrate (60°C) using 6.3, 4.0, 2.8, 2.0,1.4, 1.0, 0.71, 0.50, 0.35, 0.25, 0.18, and 0.11 mm soil sieves. Particles ≤ 0.11 mm were collected in a pan. Sieves and pan were shaken for 5 min with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}) (W.S. Tyler, Mentor, OH). The particles from each sieve were collected in an aluminum plate, weighted, and expressed as a percentage of the total weight. To determine the volume of the particles, materials were packed into 250 or 500 mL graduated cylinders and tappeded three times on the table surface; the actual volume was recorded and expressed as a percentage of a total volume. Weight of the substrate from each graduated cylinder was recorded and used to calculate the bulk density of each particle size for each of the nine substrates.

Statistics

Particle summation curves and MCC were fit using a four-parameter sigmoid model [$y= a +(c/(1+(x/x_0)^b))$] where a = the minima plateau, $a + c$= the maxima plateau, x= the independent variable, x_0 = the inflection point where the sigmoid curve transitions from convex to concave, and b = the air entry value. Moisture characteristic curves were determined by solving for a, c, x_0, and b, and are reported by Zazirska Gabriel et al. (2009) for all nine substrates. Models were fit using Proc NLIN in SAS (SAS Institute, Cary, N.C.). Models for particle summation curves were fit by setting a = 0 and $(a + c)$ = 100 and solving for b and x_0. Particle size density was subject to multivariate analysis of variance and comparison the gravimetric versus volumetric method each of the nine substrates within a particle size/sieve using an F-test.

Results and Discussion

Volumetric and gravimetric means to determine particle size distribution differ with soil-less substrates containing single (bark only), dual (bark plus peat or pumice), or multiple components (bark plus peat and pumice). The single component system containing bark only had differences in measured particle size <1 mm when using a volumetric versus gravimetric method (Table 3.1). The weight-based method increased the amount of particles occurring below 0.71 mm

(P-value = 0.02, F-value = 14.61), where as the volumetric method resulted in a decrease of particles occurring between 0 to 0.70 mm (Table 3.2). These differences results in a shift of the particle size summation curve to the right (Fig. 3.1) changing the interpretation of the bark texture. This shift would suggest decreased relative porosity. The shift or increased amount of particles less than 0.35 mm observed using gravimetric analysis also occurred when adding peat or pumice to make a dual component substrate.

In a bark soil-less substrate with peat addition (15 or 30%), the amount of fine particles <0.10 to 0.34 mm was greater using the gravimetric method versus volumetric (P-value = 0.0068, F-value = 26.40). In addition, significant differences in the two methods began to occur at a courser particle size; <2mm (P-value = 0.0114, F-value = 19.63) and <2.8 (P-value = 0.0192, F-value = 14.39) for substrates containing 15% and 30% (by vol.) peat, respectively (Table 3.1). Increased addition of peat measured gravimetrically did not show noticeable shifts in the particle size summation curve (Fig. 3.2B), however the shift is more gradual and discernable when employing the volumetric method (Fig. 3.2A).

With 15 or 30% (by vol.) addition of pumice to DFB, both ends of the particle size spectrum differed when measured using the gravimetric or volumetric method (Table 3.1), This resulted in the particle size distribution curve being shifted to the left with increasing additions of pumice indicating a coarser texture substrate. The volumetric method (Fig. 3.3A) showed a more gradual shift in the particle summation curve relative to the addition of pumice, whereas the gravimetric method (Fig. 3.3B) illustrated one large shift with an addition of either 15 or 30% pumice.

In multi-component substrates containing 15:15%, 15:30%, 30:15% and 30:30% (by vol.) additions of peat and pumice to DFB resulted in measured particles that differed depending on whether the volumetric or the gravimetric method was used; however, neither component, peat nor pumice, seemed to dominate the system. Volumetric- versus gravimetric-based measures of particle size, with increasing pumice, showed more significant difference when peat increased from 15 to 30% by vol. (Table 3.1). The volumetric and gravimetric methods to measure particles size were similar when peat was varied inside of a DFB substrate amended with 15 or 30% (by vol.) pumice. Increasing either peat or pumice from 0, 15, to 30% in the presence of a constant addition of either other component resulted in the summation curve shifting to the left indicating a courser substrate. This shift was much more discernable for increasing peat when pumice also present at the highest rate (30% by vol.). All shifts in the summation curve were more notable if the volumetric method was employed. The gravimetric method resulted in particle summation curves shifting to the right compared to those measured volumetrically.

The particle size distributions remain strongly related regardless of the variation occurring between the gravimetric and volumetric methods. Across substrates (single, dual, and multi-component), both x_0 and b were strongly correlated with r^2= 0.94 and r^2= 0.80, respectively (data not presented). This is surprising since particle density varies so greatly between components, however the gravimetric method provided like curves to volumetric measurement. The volumetric method appears to create more discernable, thus informative, summation curves; however this method may have an inherent error because bulk density is variable across particle size ranges. The overall trend is that bulk density decreases with increasing particle size (data not presented). Overall bulk densities of these three components are not uniform, with peat (D_b= 0.07 $g \cdot cm^{-3}$), DFB (D_b = 0.16 $g \cdot cm^{-3}$), pumice (D_b= 0.41 $g \cdot cm^{-3}$).

An attempt was made to predict MCC from either volumetric- or gravimetric-particle summation curves (Table 3.3) using a modified Haverkamp and Parlange (1986) method. Because a and ($a + c$) are set to 0 and 100, respectively, for particle summation curves, only x_0 and b need to be predicted to complete the sigmoid model (Table 3.3). Correlations between x_0 of particle summation curves (volumetric or gravimetric) and MCC were poor. There was similarly poor correlation among the analytical methods for b (Fig. 3.4 A, B, C, and D). Therefore, we were unable to predict moisture characteristic curve from particle summation curves in the nine substrates evaluated herein. Similar modeling between particle summation curves and MCC in mineral soils used samples ranging from gravels to clays, which vary widely in physical and hydraulic properties.

It is likely that soil-less substrates evaluated herein do not have enough variation in particle size distribution or matric potential to reveal the relationship between the two analytical methods. The nine substrates evaluated in this paper represent the range of substrates used in nursery production, and their differences can be measured with particle summation curves and MCC; however, these differences are not large enough to develop a model that predicts one from the other. Substrate with greater variation of these parameters may have an increased chance of predictability.

Conclusions

In conclusion, either a volumetric or gravimetric method of measuring particle-size distribution is informative. The volumetric method creates more discernable shift in the summation curve when amended with components that dramatically alter physical properties such as air space. The gravimetric method cannot be easily corrected for the large variation in particle density of components used in soil-less substrates. Bulk density varied across particle size when using the volumetric method which overestimated the distribution of large pores that will be filled with small particles. Neither method created particle summation curves that were similar to the moisture characteristic curve generated for the like substrate, making it impossible to predict the hydrology of the substrate. In addition, this approach was unable to take into account the physical properties and hydrology of the actual component particles which also effect matric potential. More basic research is needed with single component system to understand the relationship of particle-size distribution to pore distribution in soil-less substrate systems.

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Table 3.1. Particle size distribution by weight (g) and by volume (cm^{-3}) basis of nine soil-less substrates with varying ratios of peat, pumice and Douglas-fir bark.

			Particle size (mm)												
Component	Rate	Analysis	<0.10	0.11-0.77	0.18-0.24	0.25-0.34	0.35-0.49	0.50-0.70	0.71-0.99	1.00-1.39	1.40-1.99	2.00-2.79	2.80-3.99	4.00-6.29	>6.30
			Single component (DFB only)												
DFB		weight	2.19	3.73	5.16	7.21	8.53	9.39	8.47	9.55	11.78	12.74	12.60	8.34	0.32
		volume	1.37	2.94	4.31	6.49	9.08	10.48	8.87	10.36	12.54	13.06	12.41	7.58	0.51
			Dual component (DFB plus peat or pumice)												
DFB plus	15	weight	3.47	2.89	3.52	5.16	6.85	8.80	8.53	9.93	11.87	12.67	13.29	10.66	2.37
Pumice		volume	2.04	2.24	2.88	5.23	8.08	9.90	9.48	10.71	13.06	12.57	12.88	9.27	1.65
	30	weight	5.34	2.84	3.00	4.41	5.85	7.63	7.73	9.59	11.96	12.96	13.62	11.30	3.76
		volume	3.03	2.23	2.63	4.39	5.87	8.29	8.65	10.29	13.07	13.48	13.57	11.33	3.15
DFB plus	15	weight	1.84	3.40	4.66	6.63	8.30	9.98	9.35	10.00	11.73	12.74	12.20	8.34	0.82
Peat		volume	1.00	2.19	3.69	5.86	8.65	11.36	10.92	10.61	12.76	12.73	11.60	7.62	1.03
	30	weight	2.11	3.11	4.59	6.83	8.46	10.19	9.37	9.86	11.16	12.03	11.94	8.34	1.99
		volume	0.98	2.08	3.65	6.24	8.52	11.50	10.86	10.90	11.64	11.25	11.12	7.81	3.45
			Multiple component (DFB plus peat and pumice)												
DFB plus	15:15	weight	2.69	2.88	3.41	5.73	7.03	9.15	9.06	10.41	12.27	9.67	13.42	11.36	2.92
Peat:Pumice		volume	1.33	2.03	2.78	4.89	7.09	10.29	10.09	11.21	12.74	12.62	12.54	9.59	2.80
	15:30	weight	3.36	2.00	2.17	3.25	5.20	8.26	8.72	9.96	12.44	13.97	14.22	12.35	4.11
		volume	1.90	1.58	1.95	3.18	4.79	7.86	8.82	10.63	13.37	14.42	13.71	12.50	5.30
	30:15	weight	2.45	2.00	2.23	3.20	4.68	7.36	8.59	10.64	12.88	13.84	14.20	13.07	4.86
		volume	1.10	1.40	1.82	2.96	4.31	7.66	9.82	12.02	14.09	14.13	13.65	11.86	5.18
	30:30	weight	3.77	2.17	2.37	3.76	6.05	7.64	7.90	9.64	11.70	12.54	13.16	13.68	5.62
		volume	1.77	1.58	2.00	3.51	8.86	8.59	8.83	10.14	12.10	12.10	12.05	12.11	6.37
P-value			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.07	0.03	0.35	0.00	<0.0001	<0.0001
P-value			<0.0001	<0.0001	<0.0001	<0.0001	0.05	<0.0001	<0.0001	0.01	0.01	<0.0001	<0.0001	<0.0001	<0.0001
Multivariative main effects			Pr>F												
Treatment			<0.0001												
Method			<0.0001												
Interaction			<0.0001												

Table 3.2. Particle size distribution (mm) of three components by percentage.

	Particle size (mm)												
Component	<0.10	0.11-0.77	0.18-0.24	0.25-0.34	0.35-0.49	0.50-0.70	0.71-0.99	1.00-1.39	1.40-1.99	2.00-2.79	2.80-3.99	4.00-6.29	>6.30
	Volumetric analysis (cm^{-3})												
Bark	1.37	2.94	4.31	6.49	9.08	10.48	8.87	10.36	12.54	13.06	12.41	7.58	0.51
Peat	5.30	0.54	0.23	0.25	0.35	0.54	0.72	1.30	3.37	10.41	18.35	36.21	22.44
Pumice	1.33	3.90	5.24	8.20	10.58	11.74	10.59	6.56	6.25	5.75	7.91	10.86	11.09
	Gravimetric analysis (g)												
Bark	2.19	3.73	5.16	7.21	8.53	9.39	8.47	9.55	11.78	12.74	12.60	8.34	0.32
Peat	8.59	0.84	0.40	0.45	0.74	1.22	1.30	1.65	3.64	10.65	18.00	31.71	20.82
Pumice	3.68	7.99	6.23	8.80	9.98	11.20	7.87	5.62	5.27	5.47	6.79	10.70	10.39

Table 3.3. Parameter estimates (with standard errors in parentheses) for moisture characteristic curves of nine Douglas-fir bark substrates amended with peat moss or pumice.

Substrate Components	Amendment Rate	Analysis	Paremeter estimates					
			x0		b		n	r^2
			Single component					
DFB only		weight	1.1109	(0.0253)	1.4447	(0.0454)	39	0.998
		volume	1.1515	(0.0227)	1.5501	(0.0445)	39	0.998
			Dual component					
DFB amedned with Pumice	15	weight	1.3124	(0.0271)	1.4357	(0.0409)	39	0.9983
		volume	1.2858	(0.0219)	1.5738	(0.0397)	39	0.9988
	30	weight	1.3951	(0.0345)	1.3680	(0.0453)	39	0.9977
		volume	1.4608	(0.0272)	1.5252	(0.0414)	39	0.9986
DFB amedned with Peat	15	weight	1.1434	(0.0224)	1.4909	(0.0412)	39	0.9983
		volume	1.1802	(0.0185)	1.6335	(0.0390)	39	0.9989
	30	weight	1.1440	(0.0204)	1.4579	(0.0360)	39	0.9987
		volume	1.1981	(0.0152)	1.5638	(0.0291)	39	0.9993
			Multiple component					
DFB amedned with Peat:Pumice	15:15	weight	1.3066	(0.0280)	1.4335	(0.0425)	39	0.9982
		volume	1.3483	(0.0191)	1.6045	(0.0343)	39	0.9991
	15:30	weight	1.5776	(0.0296)	1.5346	(0.0424)	39	0.9987
		volume	1.6857	(0.0249)	1.6326	(0.0376)	39	0.9992
	30:15	weight	1.6691	(0.0277)	1.5784	(0.0397)	39	0.9990
		volume	1.6911	(0.0197)	1.7340	(0.0331)	39	0.9994
	30:30	weight	1.5818	(0.0299)	1.4147	(0.0371)	39	0.9987
		volume	1.5359	(0.0300)	1.4962	(0.0422)	39	0.9986

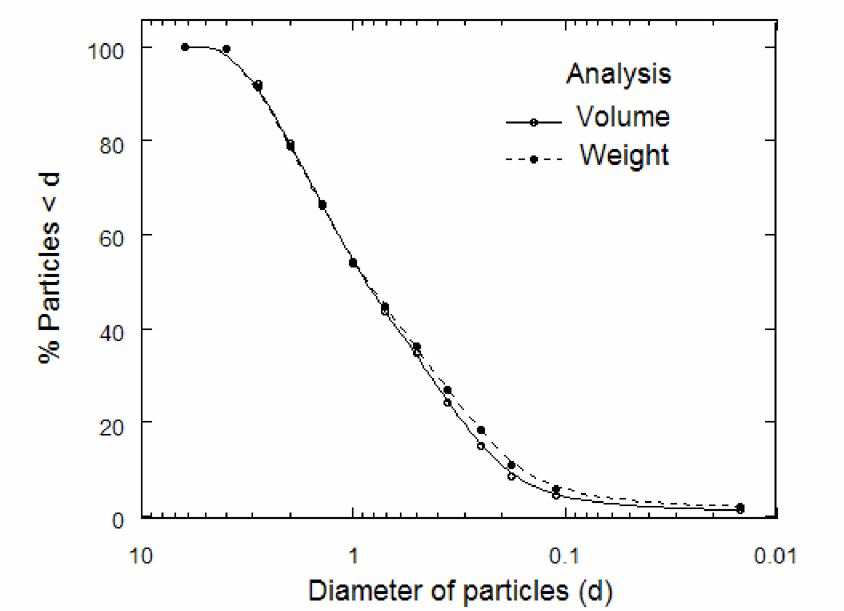


Figure 3.1. Moisture characteristic curve for single component DFB only for volumetric and gravimetric method.

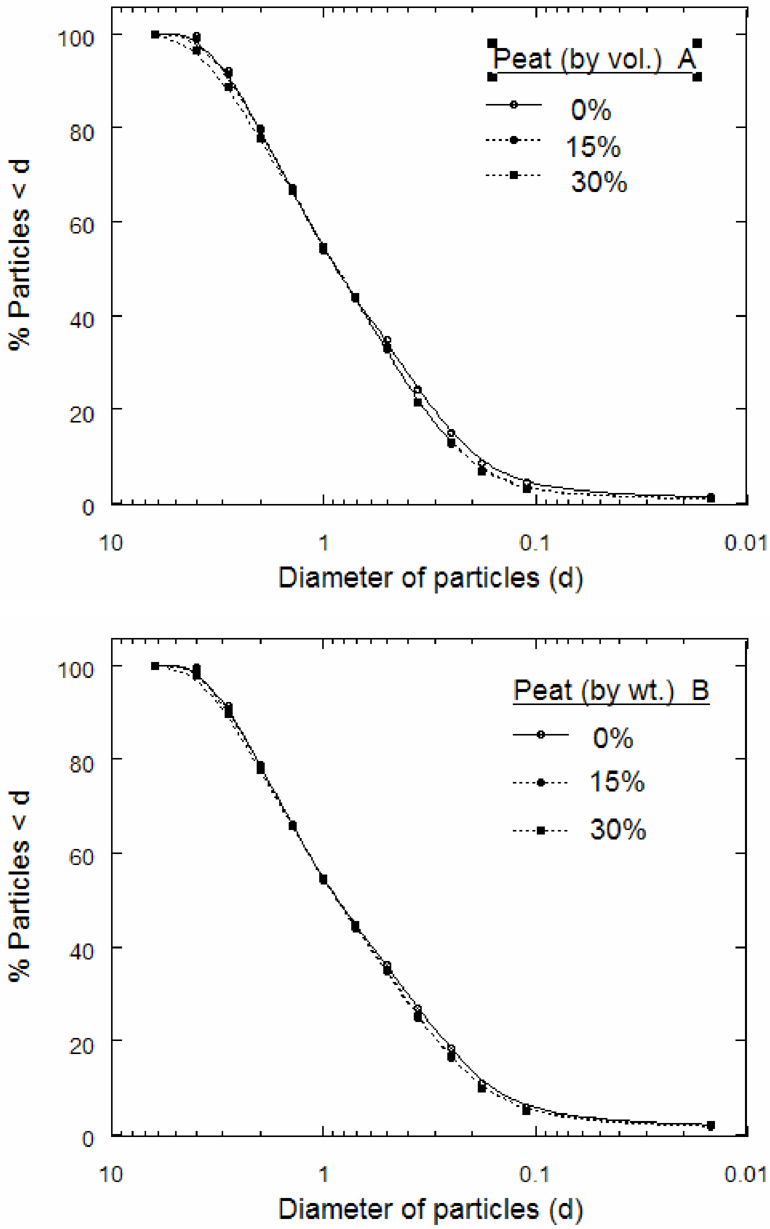
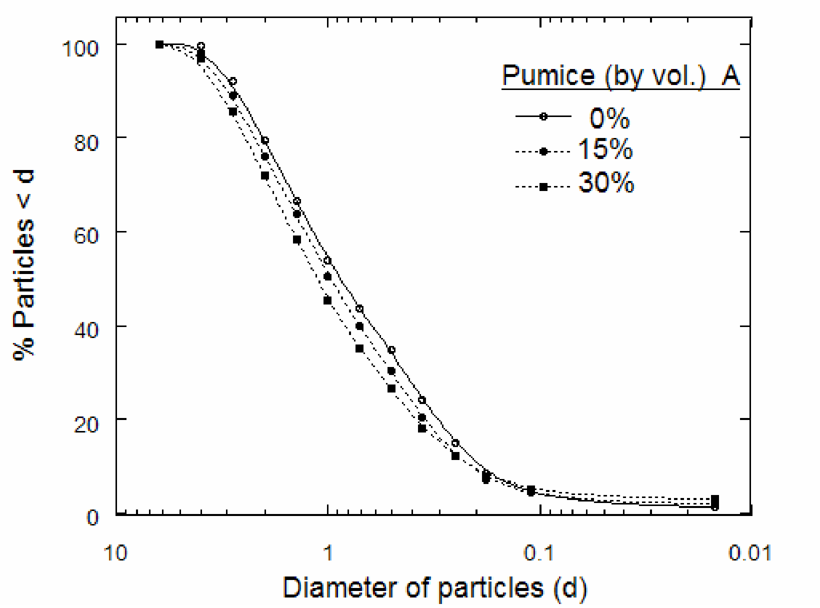


Figure 3.2. Moisture characteristic curve for volumetric (Fig. 3.2A) and gravimetric (Fig. 3.2B) methods for peat moss.



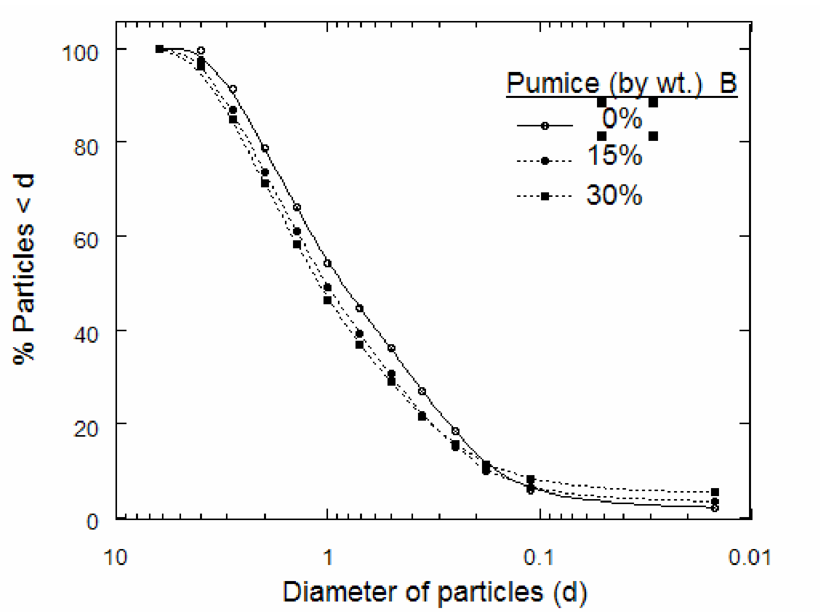


Figure 3.3. Moisture characteristic curve for volumetric (Fig. 3.3A) and gravimetric (Fig. 3.3B) methods for pumice.

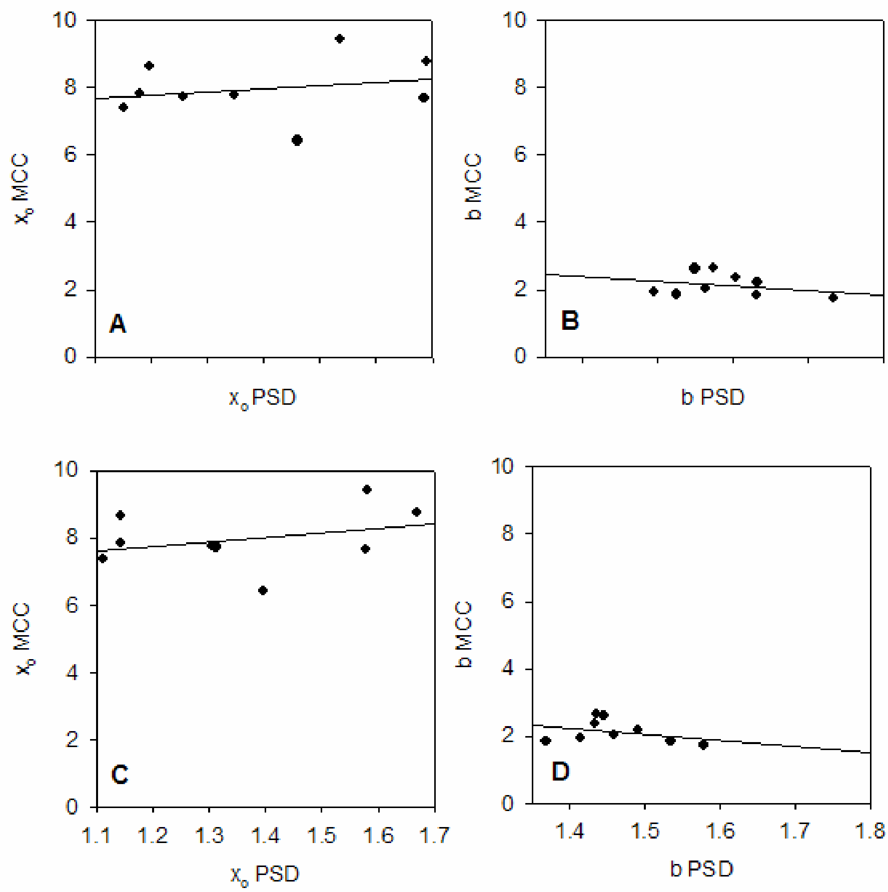


Figure 3.4. Correlation between x_0(A, C) and *b* (B, D) for moisture characteristic curve and particle size summation curve of nine soil-less substrates (DFB plus peat and/or pumice) determined using volumetric (A, B) and gravimetric (C, D) methods. Fig. 3.4A, y= 0.914x+6.682, R^2 = 0.0495; Fig. 3.4B, y= -1.3324x +4.2557, R^2= 0.0751; Fig. 3.4C, y= 1.4093x+6.0367, R^2= 0.1153; Fig. 3.4D, y= -1.8459x+4.8355, R^2= 0.1168.

CHAPTER 4

General Conclusion

The first study focused on the soil-less substrate physical and hydraulic properties affected by addition of peat moss and pumice to Douglas-fir bark. These two studies involved four main objectives. The first objective was to document the effect of peat and pumice addition on the physical and hydrological properties of Douglas-fir bark soil-less substrates. It was demonstrated that increasing the addition of sphagnum peat moss and pumice at equal ratios has little effect on the physical properties of Douglas-fir bark-based soil-less substrate. There was an interaction between peat moss and pumice regarding their effects on substrate physical properties, e.g., total porosity, air space, container capacity, easily available water, and buffering capacity. The second objective was to determine if measured properties of mixed soil-less substrate can be accurately predicted from the known properties of the individual components. Only bulk density could be accurately predicted using given properties of the individual components. Single-, dual-, and multi-component substrates need to be better understood in their physical properties.

The second study was a continuation of the first study and the goal was to detect whether there is any relationship between particle size summation curves and the moisture characteristic curve for soil-less substrates. The first objective was to compare volumetric and gravimetric methods to determine particle-size distribution of soil-less substrate composed of varying components. Both methods were informative. The volumetric method creates shifts in summation curve when amended with components that change physical properties such as air space. The gravimetric method cannot be easily corrected for the large variation in particle density of components used in soil-less substrate. The final, second objective was to determine if existing model of Haverkamp and Parlange (1986) can be used to predict the moisture characteristic curve (MCC) of mixed substrates with known particle-size distribution. Neither the volumetric- nor gravimetric-based particle size summation curves were mathematically similar to the MCC. Therefore the criteria to employ the Haverkamp and Parlange (1986) model was not met and the model could not be used. This made it impossible to predict hydrology of the substrate.

In completing this research, it is clear that dual- and multi-components are very complex. Each component has a different particle density and can vary in the particle size. This variation created unexpected results. These two studies show how dual- or multi-component substrates may affect physical properties. To better understand how these mechanisms work, more basic research is needed with single-component systems to understand the relationship of particle–size distribution to pore distribution in soil-less substrates.

The results of these two studies can be used by growers when they try to make a decision about which component should be used in their substrate. For specific taxa there are different expectations of created substrate that should provide air space and water-holding capacity for good plant growth. Many growers have the beliefs that pumice increasing air space and peat moss increasing water-holding capacity. Additionally, we do not know how plants will respond if we change the percentage of peat or pumice to bark-based substrate or any other different component. Further research is needed to determine whether these practices give the expected results. If so, then they should be continued.

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