ABSTRACT

FIELDS, JEB STUART. Hydrophysical Properties and Hydration Efficiency of Traditional and Alternative Greenhouse Substrate Components. (Under the direction of Dr. William C. Fonteno and Dr. Brian E. Jackson.)

Pine tree substrate (PTS) components are becoming more prevalent in greenhouse substrate mixes. Two different PTS components were engineered to serve different roles in substrate dynamics. Pine wood chips (PWC) were made from chipped logs and shredded pine wood (SPW) was made from shredded logs. Although these two materials were manufactured from the same logs, they are inherently different in their geometry. The PWC were of a “blockular” nature, and were relatively uniform in size and shape, while the SPW was more fibrous and shows more variation in size and shape. In this work, these two PTS components were tested for hydration efficiency, hydrophysical properties, drainage profiles, and unavailable water, while simultaneously being compared to more traditionally used greenhouse substrate components (peat, coir, aged pine bark, and perlite). Pine wood chips were quite similar to perlite and aged pine bark in ability to increase aeration and drainage while having high hydration efficiency levels. Conversley, the SPW resulted in a more “peat-like” component with higher water holding capacities yet surpassing peat in hydration efficiency. Unlike peat and aged pine bark, neither of the PTS components exhibited signs of hydrophobicity under dry conditions, which allowed them to achieve a higher hydration efficiency rating. The two PTS components were proven to have more influence on mix dynamics when incorporated in a substrate in comparison to perlite. This resulted in smaller quantities of PTS required to achieve similar results of perlite in a mix.

Another objective of this research was to determine a more accurate method of determining unavailable water in a greenhouse substrate. The most commonly used method

involved pressurizing the substrate to -1.5 MPa, and measuring the moisture content of the material. It has been hypothesized that samples lose hydraulic connectivity during this process, causing them to not release moisture past a specific pressure. As a result of this unavailable water has previously been overestimated in substrates, and therefore available water was underestimated. Using dewpoint technology, direct water potentials of a substrate are able to be determined. The pressure plate values for unavailable water of common organic greenhouse substrate components were between 25 and 35% moisture by volume. All materials tested using dewpointt technology were shown to actually have little variation in moisture content at -1.5 MPa, with all having between 4 and 8% by volume moisture. This leads to the hypothesis that substrates, comprised of these and other similar organic materials, will have unavailable water levels of under 10% by volume, a lower amount than previously reported.

Hydrophysical Properties and Hydration Efficiency of Traditional and Alternative Greenhouse Substrate Components

by
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DEDICATION

I would like to dedicate this work to my parents, Beth and Jeb, for inspiring me to pursue my dreams as well as instilling a respect and admiration for nature and agriculture as well as the importance of an education. Without you I would never have made it this far.

BIOGRAPHY

Jeb Stuart Fields was born in Winter Haven, FL in May of 1985 to Jeb and Beth Fields. He graduated with high honors from Winter Haven High School in 2003 and attended the University of Florida. He graduated with a Bachelors of Science in Horticultural Science from University of Florida in December 2008. In January 2011, Jeb moved to Raleigh, NC to begin work on a Master of Science degree at North Carolina State University. Jeb graduated NC State with degree in Horticultural Sciences and a minor in Soil Sciences in May 2013. Jeb will begin work on a doctorate at Virginia Polytechnic University in the Fall of 2013.

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TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1. Exploring Unavailable Water of Traditional and Alternative Organic Greenhouse Substrate Components

CHAPTER 2. Moisture Retention and Drainage Profiles of Traditional and Alternative Greenhouse Substrate Components and Mixtures

CHAPTER 3. Hydration Efficiency of Traditional and Alternative Greenhouse Substrate Components

LIST OF FIGURES

CHAPTER 1. Redefining Available Water of Traditional and Alternative Organic Greenhouse Substrate Components

CHAPTER 2. Moisture Retention and Drainage Profiles of Traditional and Alternative Greenhouse Substrate Components and Mixtures

CHAPTER 3. Hydration Efficiency of Traditional and Alternative Greenhouse Substrate Components

Introduction

Plants have been containerized for thousands of years, going back, at least as far as the ancient Egyptians (Raviv & Lieth, 2008). The primary reason for the containerization of plants was to allow for transplanting throughout the year, as well as allowing for easy transportation of plants. Throughout history, containers were filled with field soil, and various amendments which were meant to increase fertility, drainage, water holding, etc. However, aeration and drainage was lacking compared to plants grown in the same mineral soils in situ, plus the containers were still quite heavy. In the 1960's growers started filling their containers for plant production with soilless substrates in order to lower the weight while increasing the drainage in their containers (Nelson, 2012). Substrate is the most accepted term for soilless materials, however they can also be identified as potting soil, media, container soil, potting medium, rooting media, among others. Using soilless substrates, a grower is able to build the physical and chemical properties of the substrate, and thus more accurately regulate plant growth and development. The soil column in containers is much shorter than in the field and thus there is a more constricted volume in containers. This reduces the drainage of a soil in containers. Using mineral soils in these containers will result in a more saturated condition, and thus restrict plant growth. This occurs because soils in the field lose water through evaporation and deep drainage (Hillel, 2004). Containers both limit the surface area of the soil exposed to the environment, as well as the column length (hydraulic head) of the water. Increases in column length generate a larger difference in gravitational potential (force of gravity pulling water down through the container/soil profile) between the two column boundaries. This increase causes water to drain until the soil water reaches equilibrium with the matric potential (force exerted by soil particles that holds water in place; Spomer, 1974).

PHYSICAL PROPERTIES

Substrates and field soils are quite similar when it comes to their physics. There has been much research dedicated to soil physics, with relatively little research efforts focusing on substrate physics, up until about 30 years ago (Raviv & Lieth, 2008). Today, some of the most important and widely researched properties for substrates are physical properties. Understanding a substrate's physical properties allows an understanding of the substrates' ability to be used as a successful growth medium for plants.

Bulk Density

One of the most commonly reported and observed physical properties for substrates is bulk density (Db). Proper bulk densities have been shown to have positive effects on plant growth, by allowing adequate room for root growth and water holding (Stirzaker et al., 1996; Cornish et al., 1984; Goodman and Ennos, 1999), whereas an inadequate Db can restrict root growth and thus lead to improper plant growth and development (Iijima et al., 2003). Bulk density is the mass of solids (M_s) divided by the total volume (V_t) of the sample, $Db=M_s/V_t$ (Blake and Hartge, 1986). Soilless substrates tend to have much lower bulk densities than that of mineral soils (Kipp et al., 2001), which can be attributed to lower particle densities, higher porosities, and presence of internal porosity in several components of soilless media. Higher Db equate to an increase in cost of transportation, as you are required to move more weight to get the same volume of a material with a lower bulk density.

Porosity, Container Capacity, and Air Space

Total porosity (TP) is a measure of void space in a substrate, which can be both air filled porosity and water filled porosity. TP can be calculated from Db and particle density (Ds) using the following equation, $TP=1-(Db/Ds)$. However, in substrates, Ds is not easily calculated. As a result of this, we use laboratory methods to find TP. Using the porometer method (Fonteno et al., 2010), container capacity (CC) and air space (AS) of a substrate can be determined by saturating samples and allowing them to drain. Total porosity can then be estimated as: $TP = AS + CC$. Using this calculation, the addition of all the moisture that can be held by a substrate to the total amount of void spaced filled with air equals TP. Container capacity is described by White and Mastalerz (1966) as the amount of water held by a substrate in a container after allowing for sufficient drainage. Because CC values represent a moisture content at a particular water potential, values will vary with varying container geometry (Bilderback and Fonteno, 1987) due to water potential being a thermodynamic equilibrium between suction and gravity (Caron and Riviere, 2003). Air space is a term used to describe the portion of a substrate's porosity not occupied by water at CC. Along with TP, both AS and CC make up three important substrate classification criteria.

Moisture Retention Curves

An important technique for determining how a substrate will release water is the determination of a moisture release curve (MRC). This curve is a plot that depicts relationships between the suction (or moisture tension) exerted by a substrate (on a substrate) on the moisture within, and the percent by volume of water left in the substrate. These curves also go by other names including water release curves, moisture characteristic curves, water characteristics curves, soil moisture tension curves, and soil water tension curves. These curves have been used in soil science for determination of water holding characteristics of field soils for decades, and Bunt (1961) first described these curves on substrates. In general, MRCs on horticultural substrates are described over a tension span from 0cm to 300cm tension at the most, due to little change in water content as tensions are increased beyond this range. Pustjarvi and Robertson (1975) claimed that most greenhouse crops use water that is being held between pressures of -10 and -10 kPa, negating a need for MRCs to be described in in larger tensions. Field soils, however, can have significant changes in volumetric water content as tensions are increased well beyond -30 kPa presenting the need for many MRCs in field soils to be described to -1500 kPa and beyond.

A MRC enables an understanding of a substrate's hydrophysical properties by revealing some intuitive characteristics, including easily available water (EAW), water buffering capacity (WBC), and volume percentage of air (de Boodt and Verdonck, 1972). These three values, determined by differences in water content at specific tensions on the curve, can accurately predict how a substrate will hold and release water at over broad tension ranges. White and Mastalerz (1966) were able to use MRCs to describe CC, which is similar to field capacity for a field soil. Bilderback and Fonteno (1987) were able to more accurately describe CC as being a function of container geometry. Fonteno (1989) also described how MRCs can be used to determine available and unavailable water for a substrate in a pot. Substrate water is not held evenly throughout the entire range of its availability, instead different amounts are released under different pressures (Karlovich and Fonteno, 1986). Moreover, different substrates release water very differently from each other. Fonteno et al. (1981) showed that both a linear and a quadratic relationship between volumetric water content and matric tension exist at different pressure ranges. Many cubic models then followed suit, including one discussed by Karlovich and Fonteno in 1986. Milks et al., (1989a) compared this cubic model to the widely used closed parameter Van Genuchten model (Van Genuchten, 1980). The Van Genuchten model was based off the Brooks and Corey model (Brooks and Corey, 1964). The Brooks and Corey model is a four parameter model, as is the Van Genuchten model. Van Genuchten then modified his model in 1985, and released a new model, which is a five parameter model due to the removal of restrictions on one parameter (Van Genuchten and Nielsen, 1985). This new model provides a better fit, and is now the preferred model to use.

Wettability

Wettability of a material has been defined by Letey et al. (1962) as the ability of a liquid to spread over a surface. A method for measuring wettability in soils by measuring contact angles has also been described by Letey (1969). The contact angles that are measured are located at the point where the three phases meet, solid, liquid, and gas (Hillel, 2008). Horticultural substrates tend to have a problem with wettability, or lack of wettability, due to their high percentages of organic matter (OM). The OM in these substrates, which is primarily composted sphagnum peat moss, can become hydrophobic, thus creating a lack of wettability during containerized crop production (Dekker et al., 2000a). When allowed to air dry these hydrophobic properties of the OM, such as peat, can be magnified and the wetting process can be complicated (Valat et al., 1991). The measurement of contact angles, described by Letey (1969), although being the most commonly used and most accurate methods are very complex and extreme precision is required (Michel, 2009). As a result of this, machines have been created to undertake this task, however these machines are quite expensive and have to alter the material's physical state before it is tested. Another method also described by Letey (1969) and reevaluated by Dekker and Ritesma (2000b) is known as the water drop penetration time (WDPT) test. To test WDPT a drop of water is placed on the surface of a substrate and the time it takes for the drop of water to penetrate the substrate is measured. This method is more inexpensive to preform, however results can be varied as the test has more subjective elements. A more recent method of testing for wettability has been described by Fonteno et al., (2012) in which water is poured through a sample of material, and effluent is collected and used to determine water retained. Michel et al., (2001) described another method for measuring wettability of organic materials which is known as the capillary rise method. This method does provide accurate data, but requires intricate equipment with high costs and challenging precision required to perform.

Plant Available Water

The term available water capacity (AWC) was first described by Veihmeyer and Hendrickson (1927) as the difference in water content between field capacity (FC) and permanent wilting point (PWP). Richards (1928) deemed this term to be oversimplified, and interpreted AWC as being comprised of two parts. First the ability of the plant to absorb water from the soil, and secondly, the velocity at which water moves through the soil to replace the water used by the plant. Later, Richards (1952) deemed AWC as the range of water that can be stored in soil and is available for plant use. The term plant available water (PAW), is referred to as water being held on to a substrate at a suction low enough so that plants are able to uptake it for use in biological functions. In field soils, a commonly accepted value for PAW is suctions less than -1.5 MPa, which is the accepted value for PWP (Hillel, 2004). However, this can vary dependent on the plant species being evaluated. The PWP of most common agricultural plants is between -1.0 and -2.0 MPa. In the field, tensiometers are applied to a soil or substrate and water potentials are given, however these are unable to measure pressures exceeding -0.1 MPa (Klute 1986). To achieve the potentials beyond -0.1 MPa, Bouyoucos (1929) first described an apparatus which produces suction, which draws upon the soil sample. This idea was refined by Richards and Fireman (1943) using the same principals, but applying pressure instead of suction. Presently, the most commonly used method is described by Klute (1986) which is a modified version of Richards and Firemans's pressure plates. However, inaccuracies have been shown as a result of lack of connectivity when using these plates (Stevenson, 1982).

Soil and soilless mixes exhibit a range of suctions, depending on pore size and particle makeup, on water in a system. In order to access this water and the nutrients held within, a plant must be able to overcome this suction and remove the water from the substrate. Some water is readily available to plants, while some water is held with such high suction, due to the high matric tensions being exerted by the substrate particles, that a plant is unable to absorb it. Water that is adsorbed to the particles of the substrate, and being held at this suction or higher will not be available for plant use, and will be referred to as plant unavailable water or (PUW).

Wetting Agents

Wetting agents are a type of surfactant, which in turn is a type of adjuvant. The word surfactant is a combination of the words "surface active agents." All surfactants are composed of a hydrocarbon chain tail and a hydrophobic head. The four types of surfactants are anionic, cationic, nonionic and amphoteric, depending on the charge of the head. Wetting agents are nonionic surfactants, due to their lack of charge while in solution (Guillen and Urrestarazu, 2012). Surfactants are used to improve spread, wetting, and penetration of water in soils. They do this by lowering surface tension of the water (Miller and Westra, 1998). Wetting agents are used in the horticultural industry to increase wettability and penetration of water through a substrate, without altering substrate physical properties (Powell, 1987). Wetting agents allow for uniform movement of water through a substrate (Moore et al., 1983). Due to the limited volume of substrate, and in turn limited amount of water that can be held in a plant, maximization of water retention, and minimization of leaching is a critical aspect to the horticultural industry (Yeager et al., 2007). Wetting agents have been reported to increase water holding capacity in some substrates (Elliott, 1992; Blodgett et al., 1993). Wetting agents are also used to aid in rewetting (Boodley and Sheldrake, 1977), which takes place during plant growth between irrigation events. Another use for wetting agents in horticultural substrates is to overcome hydrophobicity or water repellency of a substrate. Studies have shown that plants not only grow well in substrates amended with wetting agents, but often grow better than plants grown in substrates not amended with wetting agents (Bilderback et al., 1997; Bhat et al., 1992).

SUBSTRATE COMPONENTS

Understanding the components that make up a substrate allows a better understanding of substrate properties and their management. Components are the individual materials which when mixed together make up a substrate. These can traditionally consist of many different substances, including but not limited to, peat, perlite, vermiculite, coconut coir, and pine bark. However, in more recent years wood components have been increasing in use and interest.

Peat

Peat moss is the major component in horticultural substrates (Bunt, 1988). Peat production, for horticultural use, has been estimated in 1998 to be about 25,000,000 m^3/yr, in 1998, with the United States consuming more than any other country worldwide at 5,800,000 m^3/ year (Caron and Riviere, 2003). Peat is the most used material due to its high water holding capacity, low Db, high AS, and availability. Peat can be harvested from peat bogs from a variety of different locations, consisting of different types of peat species. However, in the US, the primary source of peat is from sphagnum peat moss bogs in Canada. Physical properties of peat moss, as well as chemical properties, are dependent on the source of the peat as well as the manufacturing process by which it is turned into horticultural grade peat, thus causing peat to often lack uniformity (Puustjarvi & Robertson, 1975). Peat moss substrates demonstrate the ability to hold large quantities of water, while possessing high volumes of AS, and still possess a relatively high cation exchange capacity (CEC), thus allowing nutrients to be readily available for plant growth (Robertson, 1993; Puustjarvi and Robertson, 1975).

There are, however, some current and potentially future issues with peat harvest and supply. According to The Canadian Sphagnum Peat Moss Association the peat harvest for 2011 was only about 15-30% of the targeted demand (Greenhouse Grower; 23 September, 2011). This is due to unfavorable weather patterns, primarily lengthy wet months during the peat harvest seasons. Bogs that are not allowed to dry properly are unable to be harvested. With recent unpredictable weather patterns becoming more normal this could become a more frequent problem. Another problem with peat has been the rising costs, which have been steadily rising for the past two decades for various reasons including peat shortages and increase fuel costs for transportation (Meerow, 1994; Griffith, 2007). Perhaps the major concern with the current use and growing demand for peat moss is an environmental concern. Peat bogs are natural habitat for a great deal of flora and fauna that depend on the bogs to sustain life. These peat bogs also play a large role in sequestering carbon dioxide from our atmosphere, thus reducing the effects of greenhouse gasses. When these bogs are disturbed by harvesting, vast quantities of greenhouse gasses are released into our atmosphere. The question has arisen in the past 20 years that the continual harvest of these bogs coupled with rising demand may cause these practices to be unsustainable. For these reasons, many European countries have already begun the process of slowly banning peat from horticultural use completely. The United Kingdom has already reduced its peat moss usage, for horticultural purposes by 40% (Nelson, 2012). The UK is proposing peat to be banned from domestic use by 2020 and commercial use by 2030.

Coir

Coconut coir, also known as coco dust, coco peat, and coco fiber, among many other trade names, consists of fibers from the mesocarp of the fruit from the coconut palm (*Cocos nucifera* L.). These fibers are a byproduct from coconut processing for oils and fruit. As a result, coir is generally produced in tropical countries, including Sri Lanka, India, the Philippines, Indonesia, Mexico, Costa Rica, and Guyana (Evans, et al., 1996). Coconut coir has reportedly been used in substrates for plant production for several decades however it is becoming a bigger aspect in horticultural substrates globally due to peat limitations, shortages, and costs. Coconut coir does have very suitable physical properties to be a major peat replacement. Coir has a high water holding capacity, although not as high as peat, but possesses more air filled porosity than peat, thus allowing for more aeration and drainage. One of the major advantages to using coir is its rewettability, or ability to be rewet after being allowed to dry out, whereas peat will often exhibit a hydrophobicity under the same conditions (Nelson, 2012; Fonteno, et al., 2012). Coir does possess a lower Db than peat, thus allowing it to be compressed up to 8-10 times into bricks, whereas peat is normally compressed only 2-3 times, thus making coir easier to ship. Coir, like peat, is a variable product that possesses differences in properties depending on location of origin and extraction practices (Abad, et al., 2002; Evans, et al., 1996). The main issue with coir, as a substrate component, is that it has been reported to occasionally have high salinity depending on the source, causing their electrical conductivity values to increase. Electrical conductivity of a substrate is a property that describes the concentration of soluble salts in the material. This is a result of the coconut palm being grown in coastal areas, and therefore the plant takes up salts in its water. The fruit, the coconut, of this tree acts as a sink for the salt, therefore much of the salt taken up by the plant ends up in the coconut and in turn the coconut coir. However, if washed properly, this problem can be avoided. Another problematic issue with the use of coir as a peat substitute is its generally high cost, which can be attributed to the long distance it has to be shipped.

Perlite

The most commonly used aggregate in greenhouse mixes is perlite (Evans, 2004). Perlite is an aluminosilicate rock that is formed by volcanic activity, and then mined, ground to desired particle size and heated to 982 Celsius (Nelson, 2012). Perlite, like most aggregates, is added to a substrate to enhance physical properties. Perlites biggest role in most substrates is to increase aeration, which in turn will help improve a substrate's wettability, drainage, capillary movement of water, and gas exchange (Bunt, 1988). Perlite has a closed structure, which means it has little to no internal porosity**,** therefore water is not absorbed inside the mineral, thus increasing a substrate's drainage. Perlite is sterile and has a neutral pH, so it will not affect a substrates pH or crop fertility. Perlite does not contribute to a substrates ability to hold nutrients, for this same reason (Bunt, 1988). Dogan and Alkan (2004) showed perlite's CEC to be 25-35 cmol kg^{-1}, which is very low compared to other substrate components, thus proving perlite's lack of nutrient holding capacity. Perlite is expanded at high temperatures, creating its rigid and structurally stable form. As a result, perlite helps reduce compaction of a substrate, however this also means that perlite does not break down readily (Bunt, 1988). Because perlite is produced from a mined rock and not renewable, and it does not break down it is not considered sustainable or ecofriendly (Drotleff, 2007). Another issue with perlite is its high cost which is representative of the intense procurement and production methods, with include mining, heating, and transportation (Evans & Gachukia, 2007). Also, due to perlite's lack of compressibility and relatively high bulk density (0.17 g/cm^3), shipping costs are generally high on perlite. Perlite has also been declared to be a nuisance dust, considered, when dried, to be an eye, skin, and lung irritant, however there are no confirmed long term effects.

Bark

The major component of nursery substrates for many years, which has also become important in greenhouse substrates in more recent years, is aged softwood bark. The most common types of bark used for horticultural substrates are pine, fir, and redwood, depending on the relative location (Hanan, 1998). Bark has been regarded as a waste product of the forestry industry for many years, until it was discovered to be advantageous for use as a substrate or substrate component (Bunt, 1988). Horticultural bark is procured when trees are harvested for wood planks or for pulpwood for paper products. However more recently bark has been discovered to be an important component in biofuels, thus causing a potential decline in supply of horticultural bark and an increase in price (Griffith, 2007). The term bark is used to refer to multiple parts of a tree, including inner and outer bark, or phloem and rhytidome, and tends to comprise an average of 10% of the volume of a tree (Bunt, 1988). After bark is removed from logs it is hammer-milled to reduce the initial particle size and then screened to a pre-determined size and either aged or used fresh. Aging is a process where the bark is piled up and allowed to sit. The piles are turned periodically, to prevent overheating, as well as keep a uniform particle size. The more bark is turned, the smaller the overall particle size will be, as handling promotes breakdown of particle size. Aging usually lasts for 6 months to 1 year, depending on its intended use. Aging not only allows for a more uniform product, but it also helps break down the white wood in the bark. This white wood tends to decompose faster and becomes involved in nitrogen tie-up problem (Nelson, 2012). Aging the bark also encourages better wettability, as fresh bark repels water more than aged bark (Hayden, 2005). The duration of aging that the bark is allowed, as well as pre-production conditions, and manufacturing methods can alter its physical properties (Bilderback, et al., 2005), which in turn yields a varied product. The harvest date of the trees also plays a role in the variability of bark. Bark harvested in the colder months will be more uniform, while bark harvested in the spring months tends to be more varied. The amount of wood in bark also has to do with the harvest date (Solbraa, 1974). Growers had exclusively used aged bark in the past, however a recent trend has seen more growers switch to using fresh bark. Self and Pounders (1974) showed that plants can be grown in fresh pine bark, however aged pine bark has a more uniform and appropriate particle size distribution for plant growth (Pokorny, 1975). Pine bark also possesses a high amount of available water, in fact pine bark, while having a lower water-holding capacity than peat moss, has a higher percentage of water that is available, which can be attributed to its internal pores (Pokorny 1979).

Wood Components

Sawdust

Sawdust is a byproduct of various wood manufacturing processes. Sawdust tends to be comprised of small particles of heart wood and not much bark. Sawdust also has the tendency to readily break down, more rapidly than other suitable horticultural substrates (Bunt, 1988). This is due to the wood content which decomposes more rapidly than bark. Wood wastes tend to have high levels of readily available organic carbon. When microorganisms metabolize this carbon, soluble nitrogen (N) in solution is immobilized and therefore unavailable for plant use (Handreck 1993).

Wood Fiber Substrates

A few commercial wood fiber substrate products from Europe have been produced, including Toresa, HortiFibre, CultiFibre, Torbella, Bio-Culta-Faser, Pietal, and Torbo. Of these, only Toreas and HortiFibre are still currently on the market. Toresa consists of spruce (*Picea sp.)* wood chips that are shredded and a N source is added due to N-immobilization that occurs in this substrate (Gruda & Schnitzler, 2004). The physical properties have been studied by Gumy (2001), and deemed to be satisfactory for plant growth, however these wood fiber products no longer have any significant market relevance (Schmilewski, 2008). A major problem with these is they are not made readily available, although Toresa and HortiFibre can be found in the US.

Pine Tree Substrates

A relatively newer substrate component that is gaining attention in the horticultural world is the use of fresh pine wood (Nelson, 2012). The use of fresh pine wood was first studied by Laiche and Nash (1986), who found that wood chips and wood chips mixed with pine bark to be suitable for plant growth, however inferior to pine bark itself. They attributed this inferiority to higher leaching, lower nutrient retention, and lower water holding capacity. Recently, however, research has been conducted to find a suitable way to turn wood into a suitable horticultural substrate. Loblolly pine trees (*Pinus taeda* L.) have been the focus of this revolution due to their rapid growth rate and local abundance in the south eastern United States. Loblolly pines were compared with two other local pine species, slash pine (*Pinus elliottii* L.) and longleaf pine (*Pinus palustris* L.), and found to have similar Db, particle size fractions, and porosity, however loblolly had a significantly higher CC than did the other species (Fain, et al., 2008), thus retaining more water than the others. Different methods have arisen for using pine tree substrates, including chipped pine logs (Wright & Browder, 2005; Jackson, et al., 2010), whole tree (Fain, et al., 2008), clean chip residue (Boyer, et al., 2006) and among others. Whole tree is the term used for grinding all the above ground portions of a tree, including wood, bark, limbs, pine needles, etc (Gaches, et al., 2011). Clean chip residual is the term used to describe a byproduct for the pulp tree industry, that is, the residue left over after the pulp trees are harvested (Boyer, et al., 2009). Substrates composed of fresh pine tree material also have N immobilization problems, however not nearly to the extent as finer grade byproducts like sawdust. Jackson et al., (2009) showed that N is immobilized in pine tree substrates at higher rates than in pine bark, however this is easily corrected with addition of a starter charge, which is normal for production settings.

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CHAPTER 1

Exploring Unavailable Water of Traditional and Alternative Organic Greenhouse Substrate Components

Exploring Unavailable Water of Traditional and Alternative Organic Greenhouse Substrate Components

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Abstract

A new commercially available method employing a dewpoint potentiameter for determining water potentials in organic substrate components was tested against the currently accepted method of desorbing samples on pressure plates. Highly porous organic substrate component samples received 1.5 MPa of pressure on pressure plates and then water potentials were determined in a dewpoint potentiameter. The water potentials were significantly higher than previously expected from pressure plate experimentation. Water potentials of -0.2 to -0.3 MPa were achieved in organic substrates, whereas mineral soils reached -1.4 MPa or lower. Because of this, five traditional and alternative organic greenhouse substrate components were tested to determine volumetric water content at permanent wilt potential (PWP) with this new method. According to the new method, the volumetric water contents for all components were less than 10% by volume at -1.5 MPa, whereas previous research attributes volumetric moisture contents between 25 and 35% for these materials. With the added accuracy of the dewpoint potentiameter, it is now understood that previous studies were overestimating volumetric water contents of substrate components at PWP

by about 20-30% by volume, and therefore underestimating plant available water by the 20-30% by volume.

Introduction

Water efficiency is becoming one of the most highly researched and regulated aspects of agricultural production and the horticultural industry is no different (Hatfield et al., 2001; Van Iersel et al., 2010; Knox et al., 2011; Howell 2001). Over the past few decades, more and more of the world's production systems have begun switching to containerized plants (Raviv and Leith, 2008; Ingram et al., 1993). For this reason, water efficiency of containerized crops produced in soilless substrates has become an important topic in horticultural research (Nemali and Van Iersel, 2008).

The term available water capacity (AWC) was first described by Veihmeyer and Hendrickson (1927) as the difference in water content between field capacity (FC) and permanent wilting point (PWP). Field capacity is the term used in soil science for the percentage of porespace filled with water after allowing sufficient drainage. Horticultural substrates use the term container capacity (CC) to describe the percent volume of water left in pores after drainage has occurred in a container (White and Mastalerz 1966). Permanent wilting point is described by Taiz and Zeiger (1996) as the water content at which plants wilt and do not recover overnight, and is generally classified as water contents at tensions of -1.5 MPa. The PWP of most common agricultural plants is at tensions between -1 MPa to -2 MPa depending on plant species (Richards and Wadleigh, 1952), yet the average value of -1.5 MPa is commonly used for PWP. Richards (1928) deemed the term AWC to be oversimplified, and interpreted it instead as being comprised of two parts. First the ability of the plant to absorb water from the soil, and secondly, the velocity at which water moves through the soil to replace the water used by the plant. Later, Richards and Wadleigh (1952) deemed AWC as the range of water that can be stored in soil and is available for plant use. In field soils, a commonly accepted value for available water (AW) is the water that is held between FC and PWP, or water held between about -0.03 MPa and -1.5 MPa (Hillel, 2008). In horticultural substrates, AW is the amount of water held between CC and PWP. Container capacity of a substrate varies with container geometries (Fonteno and Bilderback, 1987) and therefore so does AW (Milks et al., 1989). In container crop production, CC is generally considered to be less than -0.001 MPa (-1 kPa) in containerized substrates, which results in a larger range of AW potentials for container substrates. However, just because water is considered available, that does not mean plants expend equal amounts of energy acquiring the moisture across this entire range. De Boodt and Verdonck (1972) described water held in horticultural substrates as easily available if held at less than -10 kPa, thus alluding that the less tension required to absorb water the more available that water is. Water that is adsorbed to the particles of the substrate, and being held at a suction of -1.5 MPa or more will not be available for plant use, and is referred to as unavailable water (UW). Because PWP varies with plant species and substrate or soil type there is not a definite potential for where water in the soil ceases to be available and becomes unavailable instead there is a more gradual approach to the AW/UW divide (Hagan, 1956). Denmead and Shaw (1962) showed that many plants started to reduce transpiration rate at as low as -0.2 MPa. Similarly, Caron et al. (1998) showed that horticultural plants in peat based substrates start to show stress signals when the substrate water potential reaches as low as -0.02 MPa.

The most commonly used and described method of measuring water potential outside of a laboratory is through the use of tensiometers, which are inserted into a soil or substrate in order to measure the water potential of the given soil or substrate (Cassel and Klute, 1986). However, tensiometers are unable to measure pressures exceeding -85 kPa due to the vaporization of the water introducing a gas phase in the tensiometer (Klute 1986), although more recent work has shown tensiometers filled with a polymer in place of water are able to measure much lower pressures (Bakker et al., 2007). In order to accurately measure potentials beyond -0.1 MPa Bouyoucos (1929) first described an apparatus which produces a suction equal to -1.5MPa, which draws upon the soil sample. This idea was refined by Richards and Fireman (1943), who applied pressure and employed the use of porous plates that allowed water to be extracted. Presently, the most commonly used methods for measuring PWP are the sunflower method and the pressure outflow apparatus method (Cassel and Nielsen, 1986). The sunflower method, which was first proposed by Furr and Reeve (1945), involves growing dwarf sunflower seedlings and allowing them to wilt until PWP is reached, then measuring soil water content. This method can take long periods of time and involves subjective measurements. The pressure outflow apparatus is a modified version of Richards and Firemans' pressure plates. This method determines moisture content (MC) at a specific water potential and can be performed in a relatively short period of time. However, inaccuracies with this method have been shown as a result of lack of hydraulic connectivity when using these plates (Stevenson, 1982; Fonteno and Bilderback, 1993; Gee et al., 2002). Hydraulic connectivity is the term used to describe the connection of the water molecules with each other. Water generally moves by displacing water, therefore if the water column is broken the pressure being applied will be allowed to build up in the void where the water column is broken, effectively pressurizing the water from multiple directions making either negative pressure or positive pressure method unable to provide an adequate measure of PWP.

More recent research has shown the effectiveness of a dewpoint potentiameter to determine the water potential of inorganic amendments at a higher precision compared to estimation based on pressure plate data (Curtis and Claassen, 2008). Using the dewpoint temperature and relative humidity, the potentiameter is able to calculate water potential.

The first objective of this research was to determine the accuracy of 1.5 MPa pressure plate apparatuses, and its capability to observe -1.5 MPa water equilibrium potential in horticultural substrate components. Hydraulic connectivity was hypothesized by the authors of this paper to break at some point in the desorption process, thus resulting in water potential of samples not reaching -1.5 MPa. Locating the breaking point of the hydraulic connectivity for substrate components, will greatly aid in the understanding of PWP in horticultural substrates. A second objective of this research was to develop a procedure for using the dewpoint potentiameter (Decagon; Pullman, WA) to determine the water status of organic materials. A third objective of this experiment was to determine the PWP range of two differently manufactured pine tree substrates (PTS) and compare these values to more traditionally used greenhouse substrate components.

Materials and Methods

Testing of Pressure Plate Equilibrated Water Potentials

This experiment required the use of pressure plate extractors (PPE; Soilmoisture Equipment Corp.; Santa Barbara, CA), 1.5 MPa pressure plates (25.9 cm dia.; Soilmoisture

Equipment Corp.; Santa Barbara, CA), and soil sample retaining rings (Soilmoisture Equipment Corp.; Santa Barbara, CA). A WP4C Dewpoint potentiameter (Decagon; Pullman, WA), and 3.7 cm i.d. x 1.1 cm tall stainless steel sample cups with plastic caps (Decagon; Pullman, WA). Traditional horticultural substrate components including, sphagnum peat moss (Premier Tech, Canada), aged pine bark, perlite, were tested along with two mineral soils as control, including a 99% sand mix and a clayey soil.

Five rubber rings were placed on each moistened 1.5 MPa pressure plate, and each sring was filled to the top with one of the materials being tested. There were 25 total samples tested (5 materials x 5 replications), so 5 pressure plates were required. Plates were then placed in aluminum trays (five cm depth), and each was saturated from the bottom by adding deionized water to the tray, outside of the plate, until the top of the samples were glistening with water. The deionized water was used to prevent additional solutes and ions from getting into the samples, which could cause the dewpoint potentiameter to provide inaccurate readings due to altered osmotic potentials. The samples were left out to saturate for 24 h. After saturation, the samples were placed in PPEs and tube that was protruding from the pressure plates was connected to a port that was exposed to the outside of the PPE and thus atmospheric pressure. Circular lead weights (weight and diameter**)** were placed on top of each sample, in order apply a slight down force to ensure connectivity. The PPE lids were then closed and sealed by tightening the eight clamping bolts surrounding each PPE. Nitrogen gas (N_2) was then slowly passed into the PPEs from a N_2 tank, until the insides of the PPEs were pressurized to 1.5 MPa. The valves connecting the PPEs to the N_2 tank were then closed and the lines connecting them were depressurized by opening a release valve on the N_2 tank. The PPEs each had ports open to atmospheric pressure, which plates could be connected to through a hose. A 1 L beaker was placed under each of these ports collected all water that was desorbed out. The pressure in the PPEs was monitored and pressure was kept at 1.5 MPa by adding N_2 gas from the tank until water ceased to flow out of the PPE (about 48 h). Once equilibration was complete the PPEs were opened and the samples were covered with petri dish lids to prevent water loss from evaporation. A subsample of each sample was removed and placed in 1.1 cm tall stainless steel cups until the sample reached ½ the height of the cup. Samples in the stainless steel cups were immediately sealed with the plastic lids and wrapped with Parafilm M® (American Can Co.; Greenwich, CT) to prevent water loss from evaporation. The samples were then individually placed in the drawer of the WP4C dewpoint potentiameter and water potentials were determined using precise mode which results in a repeated measure until successive readings are equal. A dewpoint potentiameter uses the chilled-mirror dewpoint technique, in which a sample of material is sealed in a chamber with a mirror with a sealed void space between the sample and the mirror. Relative humidity is measured until equilibrium is attained between the air in the chamber and the sample. At equilibrium the water potential of the air in the void space is the same as that of the sample. As the mirror is heated and cooled, condensation is formed. The precise point when condensation is formed is known as the dewpoint. A beam of light that is being reflected off the mirror is altered at the precise moment when condensation is formed. Testing the samples from the pressure plate experiment allowed the materials to have actual water potential rendered to determine how close to -1.5 MPa these materials actually were.

Determination of PWP ranges for highly porous organic soilless substrate components

Substrate components tested were coconut coir pith (Densu Coir, Canada), sphagnum peat moss (Premier Tech, Canada), aged pine bark (PB), and two types of hammer-milled loblolly pine wood (*Pinus taeda* L.). Freshly harvested loblolly pine logs were hammer-milled through a 6.35 mm screen after initially being processed through either a wood chipper or a wood shredder. The pine logs destined for chipping were harvested on 9 Dec. 2011, and processed through a DR Chipper (18 HP DR Power Equipment, model 356447; Vergennes, VT) on 3 Jan. 2012, and hammer-milled (Meadows Mills, North Wilkersboro, NC) on 5 Jan. 2012. The pine logs destined for shredding were harvested on 12 Dec. 2011, and shredded in a Wood Hog shredder (Morbark; Winn, MI) on 9 Jan. 2012. The shredded pine wood was then hammer-milled as previously described above for the chipped wood on 10 Jan. 2012. The peat was removed from the bale, fluffed, and screened by hand through a 1.25 cm screen, to prevent any larger aggregates (foreign debris) from being included in the sampling. No additional screening was needed for the coir, pine bark, pine wood chips (PWC), or the shredded pine wood (SPW).

Samples of each component were made by pulling from various locations and depths of the bags or piles, depending on component, until a representative sample of 0.5 ft^3 was achieved. The samples were placed in 28.3 L plastic bags (Consolidated Plastics; Stow, OH) and allowed to equilibrate for 24 h. The moisture content (MC) of these samples was then identified by taking three samples from three different locations in each bag, weighing the samples, and oven drying the samples in a forced air drying oven at 105 degrees Celsius (C) for 48 h until dry. Once dry, the samples were weighed again and MC was identified using the following equation [MC = (wet weight - dry weight)/ wet weight x 100]. Using this MC, water was added to each sample until a MC of 50% by weight was achieved. This was done by using the MC of the sample and the total weight of the sample to determine the weight the sample should be when at 50% MC. Then subtracting the actual weight from the desired weight you get the total weight of water needed to be added. Water has a specific gravity of 1 g/cm^3, so each gram needed to achieve 50% MC equals 1 mL.

An initial test for each component was conducted to determine water potentials of components at different MCs as the component was dried down. Using the data from the initial dry down test (unpublished), a MC was chosen to best represent -1 MPa, -1.5 MPa, and -2 MPa for each individual component. Samples were made at the three chosen MCs of each component. After allowing 24 h for equilibration, three stainless steel sample cups were filled half way from the top (0.5 cm) from each of the different MC for a component and covered with a plastic cap to prevent evaporation. These nine total samples for each component (three reps x three MCs) were tested for water potential using the WP4C Dewpoint potentiameter in precise mode. Once water potential was determined, samples were removed and plastic lids were placed back on. Samples were then weighed (without the plastic lids) and placed in a drying oven at 105 C for 48 h to attain dry weights. The precise MC of each sample was then determined by the following equation:

[(wet weight - cup weight)-(dry weight - cup weight)/(wet weight - cup weight) x 100]

After testing all nine samples from all five components (45 samples total), the data were analyzed to determine if a proper range covering -1.0 to -2.0 MPa was attained. Two additional MC were chosen for each component in order to attain five different MC points so that a regression line could be made between -1.0 and -2.0 MPa. These MCs were determined by selecting the part of the potential range least represented from the initial MCs, and these were different for each component.

The 15 samples tested for each component had their MC transformed to volumetric water content, by multiplying the MC by the bulk density (Db) of the material, which was obtained by packing three samples of each component in 7.5 cm i.d. aluminum cores and conducting porometer analysis following procedures of Fonteno and Harden (2010). The volumetric water contents were then plotted against their water potential, and a regression analysis was conducted for the points of the desired range using SAS version 9.2 (SAS Institute; Cary, NC). The regression lines were then used to determine MC values for water potentials at -1.5 MPa, as well as a range of water potentials covering -1.0 to -2.0 MPa. The convention is to use -1.5 MPa as the water potential to represent PWP, however previous work has shown that many plants are described as having their PWP somewhere in the -1.0 to -2.0 MPa range (Richards and Wadleigh, 1952). The equation of the regression lines were used to calculate predicted values for -1.0, -1.5, and -2.0 MPa for each substrate (Table 1). The container capacity obtained from porometer analysis was then split into AW and UW using -1.5 MPa (obtained from using the equations from the regression lines) in order to compare AW/UW values given from WP4C dewpoint potentiameter analysis to previously reported AW/UW values obtained from pressure plate analysis.

Results

Figure 1 shows the inability of the horticultural substrates to attain -1.5 MPa using a pressure plate apparatus. The clayey soil was desorbed to a water potential of -1.4 MPa, almost to the desired -1.5 MPa, before ceasing to desorb any water from sample. The sand mixture went beyond -1.5 MPa, however this is likely a result of rapid evaporation of water off the surface of the coarse sand during removal of samples from the PPE, as well as a dramatic change in water potential can result from a small change in volumetric water content. The peat, pine bark, and perlite all reached potentials between -0.1 and -0.4 MPa which is less than 1/3 of the pressure applied, which is hypothesized to be a result of a loss in hydraulic connectivity (or the connectivity of the water column throughout the sample) within these samples at pressures below 0.4 MPa. Fonteno and Bilderback (1993) showed that particles in contact with the pressure plate may be dehydrated which would cause shrinkage, thus losing connectivity with particles located further away from the surface of the pressure plate. This is a likely explanation for why the horticultural substrate components do not reach -1.5 MPa. Because of these findings, another method of attaining PWP data for horticultural substrates is needed.

Another test was performed to determine at what pressures the hydraulic connectivity breaks within organic substrate components. In this test, samples of peat and pine bark were desorbed on pressure plates in PPEs in the same fashion as previously stated, except 1, 3, and 1.5 MPa of pressure were applied to five different samples of both the peat and pine bark yielding 30 samples (2 substrates x 3 pressures x 5 relplicates). From these results the authors were able to determine that the materials lose connectivity very early in the experiment, as the data showed no difference in MC in either component between 1, 3, and 1.5 MPa of pressure applied. Heiskanen (1999) considered no difference in θ between -10k kPa and -1.5 MPa for peat and peat perlite/sand mixtures, which could allude to a loss in hydraulic connectivity causing a lack in θ differences.

The θs obtained for the components across the range of -1.0 MPa to -2.0 MPa provided a small difference θ across the range of PWP. There was not a difference in θt greater than 5% by volume for any of the components across this range (Figure 2). The θ range for PB was the highest ranging from 6.8 to 8.7% by volume, which is attributed to the nearly twice as high Db (0.21 g/cm^3) as the rest of the materials tested. The coir had the lowest Db, at 0.09 g/cm^3, resulting in the lowest values for θ (3.5 to 4.6% by vol). The peat, SPW, and PWC all had similar ranges which were between 4 and 5% by volume. The R^2 for the regression analysis was almost identical between linear and quadratic on all materials, which resulted in little difference between predicted values for -1.0, -1.5, and -2.0 MPa (Table 1). Table 1 also shows the little variation in range between -1.0 and -2.0 MPa as well as little variation amongst substrate components alluding to all components having similar PWPs.

As a result of the lack of variation between -1.0 and -2.0 MPa, an estimation of UW for the components was conducted using -1.5 MPa as PWP, and CC values from porometer testing were used (Table 1). Peat and coir have very high amounts of AW both in the 70-75% by volume range. The PWC and PB have significantly lower AW (about 35% by volume each) and SPW has about 48% by volume AW. The differences are due to differences in CC, as there is little difference amongst components in PWP.

Discussion

The new technology, with which the dewpoint potentiameter provides to the horticultural community, enables researchers to more accurately predict UW, which in turn allows for more precise AW predictions. For instance, several previous studies have reported the AWs of peat mixes to be higher than 30% by volume, Milks et al. (1989) showed UW of a peat:vermiculite mixture to be 20% by volume, which was attained by using the pressure plate method. It is now understood that due to loss in hydraulic connectivity early in this pressure range, these values have been dramatically underestimated. Wright and Browder (2005) reported AW of PB as 27.9% and a PTS as 25.1%, with UW of 26.6 and 23.6% by volume respectively. Again, like most previous work, this has been determined to be a significant overestimation of UW (26.6 and 23.6% by volume as compared to 7.5 and 4.8% by volume), and therefore an underestimation of AW by about 20% by volume of these materials.

Pine bark is generally used in greenhouse substrates to increase drainage (Pokorny, 1979), and due to its similarities with PWC, it can be assumed that PWC would provide a good alternative to more traditionally used greenhouse substrate aggregates, such as PB and perlite. Shredded pine wood possesses a similar PWP, yet a significantly greater CC, yielding increased AW, which allows it to be incorporated into a substrate to increase drainage, while still holding on to moisture needed for plant growth.

Another interesting point observed throughout this experiment was the conversions from θ to MC. As a result of the low Db of the organic substrate components the MCs convert to low θs. The importance of converting MCs to θs for organic substrates when relating to water potential has been discussed by Boelter and Blake (1964) in order to make comparisons to mineral soils. According to Boelter and Blake (1964), on a percent weight basis while peat would have a high MC between -1.0 and -2.0 MPa, mineral soils would have a low unchanging MC due to their high Db. When converted to θ, the shapes of the curves are not altered significantly, but the relationship to each other is. For instance, if left in terms of MC, peat would have a CC of over 650% (80.1 / 0.12). Table 1 shows coir with 4.5%

moisture in a sample by volume at -1.5 MPa. When divided by coir's Db (0.09 g/cm^3) you get a MC of 50% by weight. During initial potting of most greenhouse crops, it is important to have adequate moisture in the substrate (Yeager et al., 2007), and generally speaking, most growers tend to use 50% MC for initial planting. From this research, it is now understood that at this MC, coir is already at -1 MPa of tension which is within the accepted range of PWP. Kiehl, et al. (1992) showed water stress in plants at -16 kPa, much lower than the -1 MPa of coir at 50% MC. According to Puustjarvi and Robertson (1975) the majority of the water used by greenhouse crops is held at tensions higher than -10 kPa which is significantly lower than where a substrate would be at planting. Moisture contents of 50% are also considered to be heavy for transportation, in fact coir is normally dried, compressed, and formed into blocks for shipping (Raviv and Lieth, 2008). Peat is normally compressed 2 to 3 times and bailed at a MC of about 20-25% (personal observation) for shipping purposes, which is significantly lower than PWP (37% MC). This establishes that not only is proper hydration of substrates important for planting, but previously accepted MC levels may be inducing water stress in the plants. This also implies that plants should not be allowed to sit for prolonged periods of time once planted before initial watering.

Conclusions

In conclusion, the use of the dewpoint potentiameter has allowed more insight into new estimates of plant UW, which is lower than previously reported values on substrates. The loss of hydraulic connectivity in these organic components creates ineffectiveness of testing using pressure plates. Due to the relative similarity of the PWPs for the components tested (PWP ranged from 4 to 7.5% by volume across all components), the authors of this paper feel it is safe to assume that mixtures of multiple components tested would yield similar UW as the components, as the mixing process should not add any additional surface area or micorpore volume. Similar mixture predictions based on component water potentials have been made by Nash and Pokorny (1992), however these predictions were at lower tensions. As a result of these findings, more research is now needed to determine actual PWPs and AW percentages for substrates and substrate components that were previously thought to be known.

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Table 1. Estimated values of -1.0, -1.5, and -2.0 MPa, as well as available water for coir, peat, bark, shredded pine wood, and pine wood chips using linear and quadratic regression.[z]

Container	Linear/ Quadratic	R^2	CC[y]	-1.0 MPa[x]	-1.5 MPa[w]	-2.0 MPa[v]	AW[u]
Coir	L	0.7301	75.2 b[t]	4.5	4.1	3.7	71.1
	Q	0.7955		4.7	4.0	3.7	71.2
Peat	L	0.6389	80.1a	4.6	4.4	4.1	75.7
	Q	0.6655		4.6	4.3	4.1	75.8
Pine Bark	L	0.7186	42.5 d	7.9	7.5	7.1	35.0
	Q	0.8087		7.9	7.3	6.9	35.2
SPW[s]	L	0.4595	52.8 c	5.5	4.9	4.4	47.9
	Q	0.5264		5.5	4.7	4.3	48.1
PWC[r]	L	0.4357	41.6 d	5.1	4.8	4.4	36.8
	Q	0.4574		5.1	4.7	4.4	36.9

[z] Procedures conducted in North Carolina State Horticultural Substrates Lab

[y] Container capacity values from porometer test (water held in substrate after drainage; by volume)

[x] Volumetric water content at -1 MPa.

[w] Volumetric water content at -1.5 MPa.

[v] Volumetric water content at -2 MPa.

[u] Availabel water is percent of container capacity above -1.5 MPa.

[t] Statistics preformed down columns using Tukey’s HSD.

[s] Shredded pine wood.

[r] Pine wood chips.

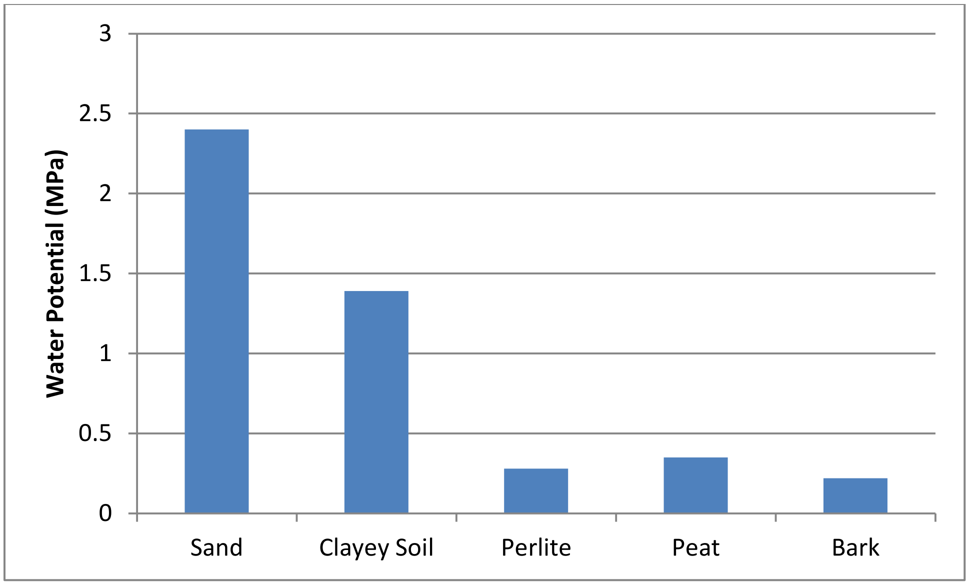
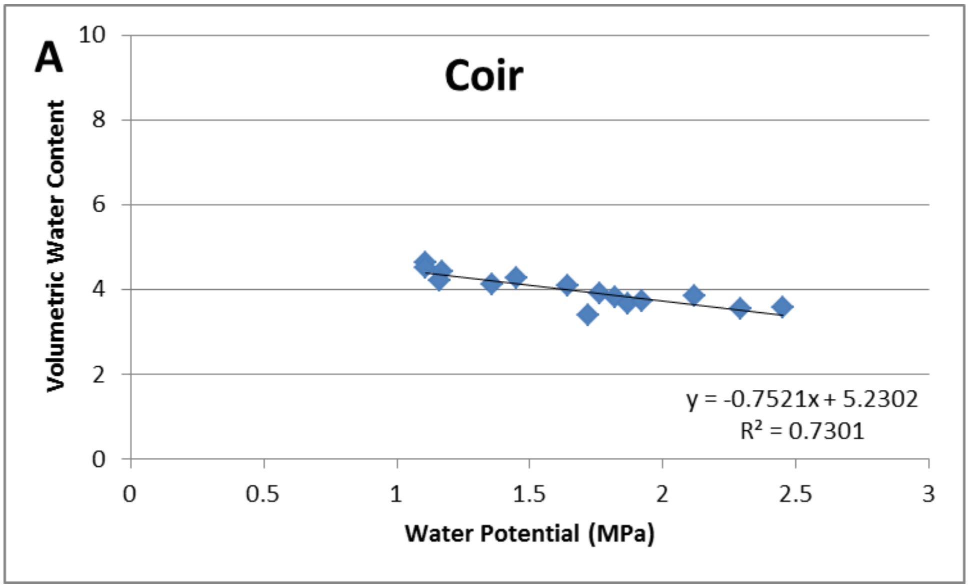
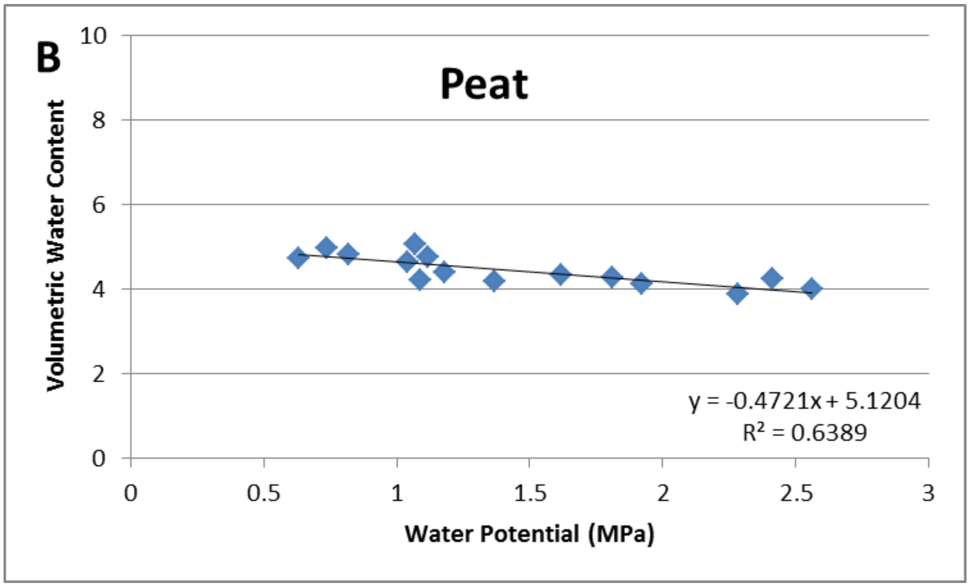
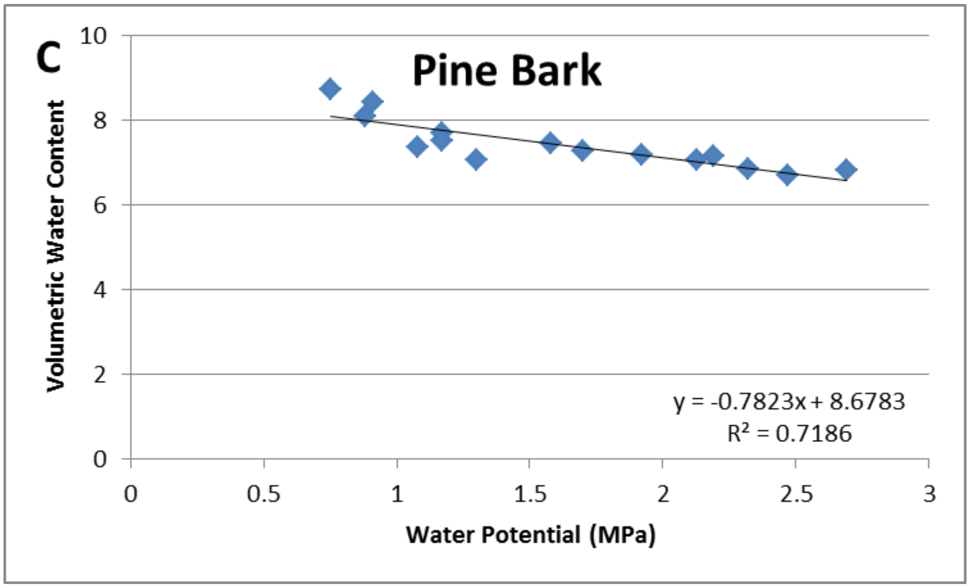


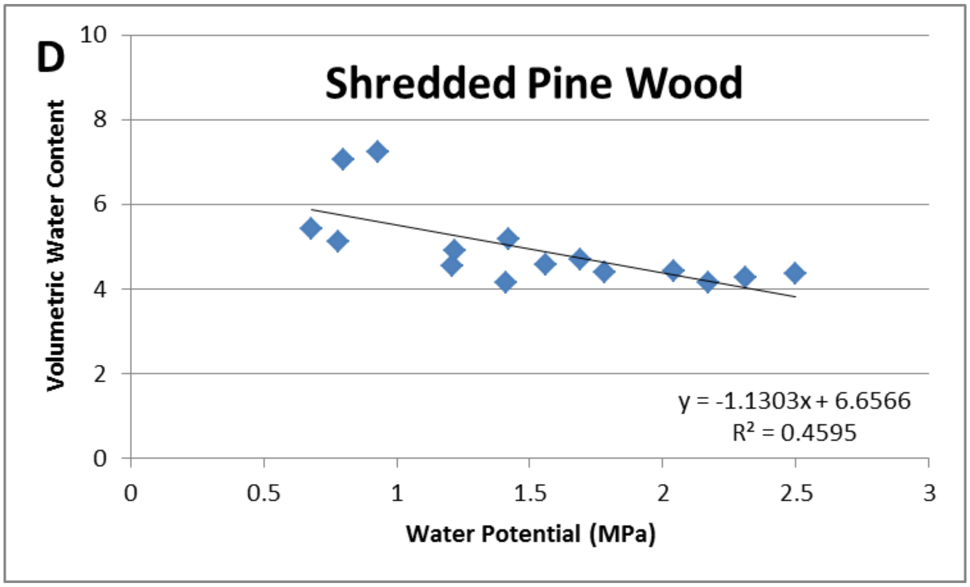
Figure 1. Water equilibrium potentials measured by WP4C dewpoint potentiameter on five materials after being exposed to a pressure of 1.5 MPa on a pressure plate.

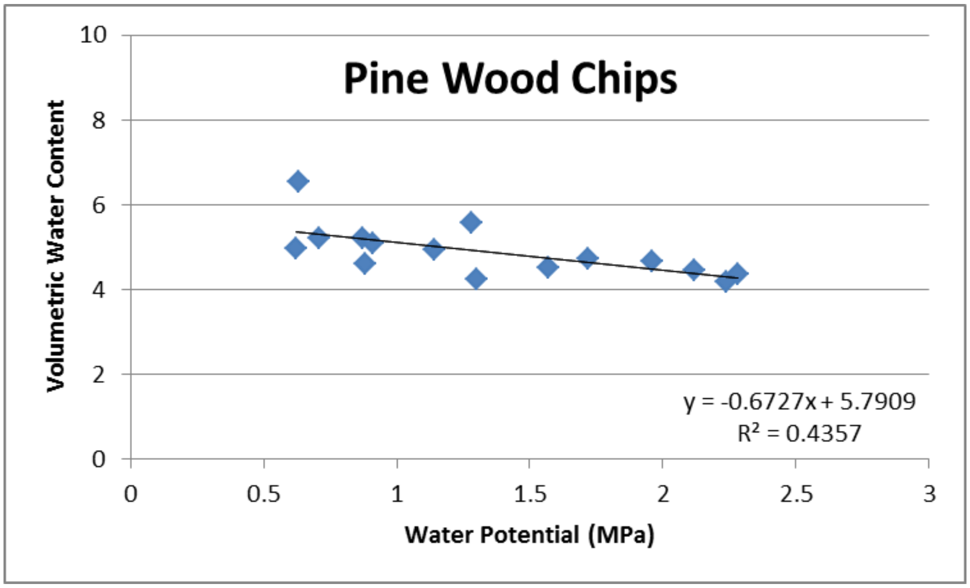
Figure 2. Permanent wilting ranges (bewtween -1 and -2 MPa) for attained with a WP4C Dewpoint Potentiameter for A) coir, B) peat, C) pine bark, D) shredded pine wood, and E) pine wood chips.


A
Coir
Volumetric Water Content
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
3
Water Potential (MPa)
y = -0.7521x + 5.2302
R² = 0.7301


B
Peat
Volumetric Water Content
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
3
Water Potential (MPa)
y = -0.4721x + 5.1204
R² = 0.6389


C
Pine Bark
Volumetric Water Content
10
8
6
4
2
0
y = -0.7823x + 8.6783
R² = 0.7186
0
0.5
1
1.5
2
2.5
3
Water Potential (MPa)


D
Shredded Pine Wood
Volumetric Water Content
10
8
6
4
2
0
y = -1.1303x + 6.6566
R² = 0.4595
0
0.5
1
1.5
2
2.5
3
Water Potential (MPa)


Pine Wood Chips
Volumetric Water Content
Water Potential (MPa)
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
3
y = -0.6727x + 5.7909
R² = 0.4357

CHAPTER 2

Moisture Retention and Drainage Profiles of Traditional and Alternative Greenhouse Substrate Components and Mixtures

Moisture Retention and Drainage Profiles of Traditional and Alternative Greenhouse Substrate Components and Mixtures

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Title: Moisture Retention and Drainage Profiles of Traditional and Alternative Greenhouse Substrate Components and Mixtures

Additional Index Words: peat, pine tree substrate, perlite, van Genuchten, model, tension, suction

Abstract

Water relations are becoming a focal of interest in the greenhouse industry, and much of that interest is being directed towards greenhouse substrates. Pine tree substrates (PTS) are relatively new greenhouse substrate components that may provide growers with more efficient use of water while remaining sustainable. Six greenhouse components, including two pine tree substrate components, along with mixtures consisting 10, 20, 30, 40, and 50% peat, shredded pine wood, or pine wood chips were tested for hydrophysical properties as well as their drainage profiles in order to "fingerprint" these materials and determine any differences occurring with using PTS in place of perlite in a greenhouse mix. It was determined that the two PTS components have a greater influence on substrate dynamics than does perlite. It was also determined that smaller portions of PTS can be used in place of perlite to achieve desired outcomes.

Introduction

Plants have been grown in containers for thousands of years for many reasons, but most notably, the ability to relocate the plant. Up until relatively recent times, the plant rooting environment was comprised primarily of field soils (Raviv and Lieth, 2008). Growers started using soilless media, otherwise known as substrates, in the 1960's to lower the weight of the containers and allow for increased drainage (Nelson, 2012). Since that time, soilless substrates have become the primary plant rooting media to be used in containerized crop production, and therefore there has been much research on the use and development of these container substrates. Some of the most studied aspects of container substrates for crop production are the hydrophysical properties. Hydrophysical properties include physical properties as well as hydrologic properties of a substrate, and provide a better understanding of substrate-water relations, water use efficiency, water availability, and drainage profiles.

One of the most important techniques for understanding substrate-water relations is the determination of a moisture release curve (MRC). Moisture release curves have been an integral way to characterize how water is held in field soils for over a century, as first described by Buckingham (1907). These curves also go by other names including water release curves, moisture characteristic curves, water characteristics curves, soil moisture tension curves, and soil water tension curves. A MRC is a plot that depicts relationships between the suction (moisture tension or water potential) exerted by a substrate on the moisture within, and the percent by volume of water left in the substrate (Childs, 1940). The tensions used in these MRCs are representative of pressure potential (Ψ_P) of a substrate. Total water potential (Ψ_T) is defined by the terminology committee of the International Soil Science Society as "the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water (at a specified point)" (Aslyng, 1963). Total water potential can be quantified as the sum of three different potentials including: 1) gravimetric potential (involving distance between two points); 2) osmotic potential (result of difference in solute concentrations across space or barriers); and 3) Ψ_P (either a positive pressure from presence of water or a negative pressure from the lack of water which is also described as matric tension). In field soils, tensions used for MRCs generally range from -10 kPa -1500 kPa. This range is observed as a result of -10 kPa tension being an accepted value for field capacity and -1500 kPa being the accepted level for permanent wilting point (PWP). Permanent wilting point is described by Taiz and Zeiger (1996) as the water content at which plants wilt and do not recover overnight, and generally classified as -1500 kPa. When a saturated field soil is allowed to drain, the term field capacity is used to describe the total volume of the porespace occupied by water, and is generally represented as either -10 kPa or -33 kPa depending on the texture of the soil.

The Ψ_P, which is plotted against volumetric moisture content (θ) for a MRC, is influenced by many physical and chemical aspects of the substrate, including water infiltration, redistribution, evaporation, plant uptake, and microbial activity (Bittelli and Flury, 2009). Proper soil or substrate Ψ_T is one of the most important factors that affect a crops quality and yield (Yuan et al., 2003). Understanding a soil or substrate's Ψ_T can aid in the determination of irrigation regimes, which when done properly, can effectively increase an operation's water use efficiency (Richards and Marsh, 1961; Morgan et al., 1966; Obreza et al., 1997). Therefore the determination of substrate MRCs is an important aspect of greenhouse or nursery crop management.

There are multiple ways to obtain a soil's MRC. The most commonly described method involves placing a soil sample of known volume on a porous ceramic plate, and saturating the sample. After saturation, pressures are applied incrementally forcing the water out of the soil sample and through the porous plate. Volumes of water desorbed out at each pressure are used to back calculate MC at each pressure (Klute, 1986). Porous plates are ceramic plates which are poured to have pores of a specific diameter, which is determined by the strength of the pressure plate, so water will only flow through when pressure is applied.

Moisture retention curves in soilless media were first described by Bunt (1961), and are obtained in a similar fashion to soils. However, the suction range is generally smaller for soilless media and conducted at lower tensions than in soils. This is because soilless mixes are more porous, and normally have larger diameter pores than field soils, enabling water to drain out of them at lower tensions. A soil at field capacity or a substrate at container capacity (CC) will not release any water until a suction or pressure is applied that exceeds the tension that water is being held at within the largest dia. pore. Soilless mixes are normally tested from 0 kPa (which is when the substrate is saturated) to -30 kPa because the majority water being released tends to do so within this range. There is also minimal change in θ from tensions of -30 kPa to -1500 kPa, as a result of the majority of the water being previously drained at lower pressures. Also, most greenhouse crops use water that is being held at pressures between -1 kPa and -10 kPa (Puustjarvi and Robertson, 1975), rendering it unnecessary to extend MRC's beyond -30 kPa.

More recent research has shown another method for developing MRCs in substrates, which uses gravitational force as opposed to applied pressure, similar to the way Buckingham (1907) first described the process. Dane and Hopmans (2002) use a method referred to as long column, in which a long column of soil or substrate is saturated, and stood upright allowing gravity to drain. A similar method, where a long column is fashioned and substrate packed within and saturated. After saturated the column is allowed to drain, while still oriented in a vertical orientation (Altland et al., 2010; Howard et al., 2010). Altland et al. (2010) then froze this column after drainage and cut into sections, allowing water content to be measured at each height, while Howard et al. (2010) fashioned the column with tensiometers to understand matric tension before disassembling column sections. Another method has been described by Retzlaff and South (1985), which involves measuring water potential with a tensiometer on a sample that is resting on a scale. The MCs at different tensions are determined by the weight of the sample.

Substrate hydrophysical properties are more clearly defined with the use of a MRC, by revealing some intuitive characteristics, including easily available water (EAW), water buffering capacity (WBC), and volume percentage of air (de Boodt and Verdonck, 1972). These three values, determined by differences of specific levels on the curve, can accurately predict how a substrate will hold and release at different tensions. White and Mastalerz (1966) were able to use MRCs to describe CC, which is related to field capacity for a field soil. Bilderback and Fonteno (1987) were then able to more accurately describe CC as being a function of container geometry.

Fonteno (1989) described how MRCs can be used to determine available and unavailable water for a substrate in a pot. Substrate water is not held evenly throughout the entire range of its availability, instead different amounts are released under different pressures (Karlovich and Fonteno, 1986). Moreover, different substrates release water differently from each other. Fonteno et al. (1981) showed that both a linear and a quadratic relationship between θ and Ψ_T exists at different pressure ranges. Many cubic models then followed suit which related θ to Ψ_T, including one discussed by Karlovich and Fonteno (1986). Nonlinear models had been used in soil science to determine relationship between θ and Ψ_T including the popular Brooks and Corey model (Brooks and Corey, 1964). A nonlinear model which was based on the Brooks and Corey model, with the inclusion of an inflection point was then presented by Van Genuchten (1980). The Van Genuchten model (Van Genuchten, 1980) was then modified from a four parameter nonlinear model to a five parameter nonlinear model, by removing relationship constraints between the curve fitting parameters n and m, which allowed for a better curve fit, and more accurate relationships between theta, $\Psi_{T,}$ unsaturated hydraulic conductivity (Van Genuchten and Nielsen, 1985). There has been much work dedicated to the comparison of the van Genuchten and Brooks and Corey models (Assouline and Tartakovsky, 2001; Morel-Seytoux et al., 1996; Russo, 1988). The nonlinear van Genuchten model was able to more accurately relate these two variables than was a cubic model. Cubic models had inaccuracies when describing MRC, causing them to not be as reliable as nonlinear models (Milks et al., 1989a). The five parameter Van Genuchten model (Van Genuchten and Nielsen, 1985) was then adapted for horticultural substrates by Milks et al. (1989a). Currently the most commonly used model for use with horticultural substrates is:

$$\theta = \theta_r + (\theta_s - \theta_r)/[(1+(\alpha \text{ x } h)\hat{}n]\hat{}m \qquad [1]$$

In this model, θ_s is the volumetric water content at saturation (0 kPa), θ_r is the residual water content (30 kPa), h is the height of the column or Ψ_T and α, n, and m are curve fitting parameters.

Values of θ_s and θ_r from Van Genuchten's model can be used in an equilibrium capacity variable (ECV) model to determine basic physical properties (TP, AS, and CC) of a substrate for a specific sized and shaped container (Bilderback and Fonteno, 1987; Milks et al., 1989b). It has been shown that container size significantly alters substrate properties, and in turn plant growth and development (Milks et al., 1989c; Bish et al., 1997; Owen and Altland, 2008).

The first objective of this experiment was to define the MRCs of two pine tree substrates (PTS), perlite and peat, as well as mixtures of peat and, perlite, shredded pine wood (SPW), and pine wood chips (PWC). Research is needed to determine hydrologic properties and water release behavior of substrates containing PTS, as they are currently being employed in greenhouse crop production, but have yet to have their hydrophysical properties evaluated. Identifying similarities and differences in behaviors between the two PTS components and the perlite will be an important step in not only fingerprinting these components but also furthering the use of PTS as greenhouse substrate components. The second objective of this research was to use the ECV models to determine any differences that the incorporation of the two types of PTS in a mix instead of perlite would have on the physical properties in different container types. It has been shown that many substrates that are used in larger containers do not provide desired properties when used in smaller volume containers such as plugs (Milks et al., 1989b; Milks et al., 1989c; Argo, 1998). Substrates in smaller sized containers tend to have problems with too little AS, which can cause desiccation of plant roots. The ECV models will be used to determine what stage of crop development in which the use of PTS mixes is best suited.

Materials & Methods

Substrate Preparation

Peat moss was acquired in a compressed bail (Premier Hort Tech, Canada), broken apart by hand (fluffed) and screened through a 6.35 mm screen on 27 Jan. 2012, in order to remove any clods and unwanted plant waste. Water was applied to the screened peat until a moisture content (MC) of 50% by weight was achieved. Peat was then combined with perlite to create seven 0.03 m^3 samples consisting of mixtures peat:perite in ratios of 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50 by volume.

Two PTS components were manufactured to be tested against perlite in these experiments. Loblolly pine trees were harvested on 9 Dec. 2011, and processed through a DR Chipper (18 HP DR Power Equipment, model 356447; Vergennes, VT) on 3 Jan. 2012, and hammer-milled through a 6.35 mm screen(Meadows Mills; North Wilkersboro, NC) on 5 Jan. 2012. Loblolly pine trees were also harvested on 12 Dec. 2011, but shredded (not chipped) in a Wood Hog shredder (Morbark; Winn, MI) on 9 Jan. 2012. The shredded pine wood was then hammer-milled as previously described above for the chipped wood on 10 Jan. 2012. The two PTS components had substantially different geometries. The trees first processed by a chipper then milled were “blockular” in nature and will be here on referred to as chipped wood (PWC), while the final product of the trees first processed through the shredder were more fibrous in nature and will be here on referred to as shredded wood (SPW). Six samples of both PWC and SPW were mixed volumetrically in ratios of peat:wood at 90:10, 80:20, 70:30, 60:40, and 50:50 respectively. Along with these 15 mixtures and the 100% peat that was being tested, 100% components of SPW, PWC, perlite, aged pine bark (PB), and coconut coir pith (Densu Coir; Canada) were also tested in order to attain characteristics of other traditionally used greenhouse substrate components. This rendered a total of 21 different substrates, which were used in this study (15 mixtures + 6 components).

Physical Properties

Physical properties were determined on three replications for each of the 21 substrates following procedures in the North Carolina State University Horticultural Substrates Lab Porometer Manual (Fonteno, et al., 1995). Total porosity (TP) values from physical properties were used as the starting point for the MRC or saturation (0 kPa), while CC values were used as initial drainage values. These substitutions were made to exclude inaccurate values directly affected by the resistance of the ceramic plates upon free drainage (occurring from gravitational forces only).

Particle Size Distribution

Samples equaling 2 L of each material were separated and placed in individual drying pans, and put in a forced air drying oven for 48 h. Each dried material was then separated into three 100 g samples. Patrticle size distribution (PSD) tests was conducted on each 100 g sample by fitting six sieves (MAKE - Fisher Scientific Co) with mesh sizes of 6.3, 2, 0.71, 0.5, 0.25, and 0.106 mm together with the larges mesh size on top and going down by mesh size. At the bottom of the sieve column a pan is connected, to collect all particles that pass through the bottom sieve (<0.106 mm). This column of sieves was then placed in a Ro-Tap® Shaker (WS Tyler Industrial Group, model B; Mentor, OH) and shaken for five min. Once completed, the sieves were separated and contents of each sieve were weighed. This process was repeated for every substrate. Particles that did not pass through the 6.3 mm sieve were classified as “extra-large,” particles that passed through the 6.3 mm sieve but not through the

2 mm sieve were classified as “large,” particles that passed through the 2 mm sieve and not through the 0.71 mm sieve were classified as “medium,” and particles that passed through the 0.71 mm sieve were classified as “fines.”

Moisture Retention Curves

Procedures for obtaining MRC’s were given in the North Carolina State University Horticulture Substrates Lab Manual (Fonteno & Harden, 2010). Equipment used in this experiment consisted of the 19 different substrates previously described, 7.5 cm tall x 7.5 cm i.d. aluminum cores, Volumetric Pressure Plate Extractors (VPPE; Soilmoisture Corp; Santa Barbara, CA) which are fitted with 50 kPa ceramic plates (Soilmoisture Corp; Santa Barbara, CA), compressed air connected to a pressure regulator and a manometer to observe pressures, graduated cylinders, and a forced air drying oven. The experiment was conducted in a controlled temperature chamber (North Carolina State University Horticultural Substrates Lab).

Each substrate was packed in four aluminum cores following procedures in North Carolina State University Horticultural Substrates Lab Manual (Fonteno and Harden, 2010), and placed on the 50 kPa ceramic plates. The VPPE’s then had their drainage tubes, where water is desorbed during the pressurizing process, clamped off to prevent leaking and samples were saturated from the bottom over the course of about 48 h. The saturation was done in a step-wise fashion, in which water was brought up 1/3 of the way from the bottom of the core and allowed to sit for one hour, water was then brought up 2/3 of the way from the bottom of the core and allowed to sit for 24 h to equilibrate. After equilibration the water was brought up to the top of the core and an additional 24 h are allowed for equilibration. After the second 24 h if the water level had dropped water was applied until the water level was to the top of the core and one additional hour was given to allow for equilibrium. Once fully saturated, excess water (water in VPPE but not in sample) was calculated by subtracting the volume of space occupied by the aluminum core (assuming it was solid) from the volume inside the VPPE. The VPPE's were then unplugged and allowed to drain for 48 h, until equilibrium was reached. Effluent was collected and the volume was measured. The suction given for this point was -0.38 kPa, as a result of an average of 0.38 kPa pressure due to gravity throughout the core (half the height of the core). The θ at this point was tentatively used as CC, until later replaced by values from porometer data. The lids to the VPPE's were then sealed with four bolts and wing nuts. Using the pressure regulator, compressed air from the air compressor, was moved into the VPPE until a pressure of 1 kPa was achieved in the center of the aluminum core. The samples were given 24 h to equilibrate and volumes of leachates were measured and recorded. This process was repeated for pressures of 2.0, 4.0, 5.0, 7.5, 10, 20, and 30 kPa respectively. After the samples had been exposed to 30 kPa and equilibrated the samples were removed from the VPPE's and weighed. The samples were then placed into a forced air drying oven at 105 C for 48 h. Once dry the samples were reweighed and θ was calculated, using equation [2].

$$[(\text{wet weight} - \text{dry weight}) / \text{volume of sample}] \qquad [2]$$

Using θ of sample at -30 kPa, individual θs at each point can be calculated by using equation [3].

$$[\{(\text{wet weight} + \text{total effluent up to specific point})\text{-dry weight}\}/\text{volume of sample}] \qquad [3]$$

Plotting the MRCs and Modeling

Once all desired suctions have a corresponding θ, a scatterplot was made to show the relationship between the two properties using Excel® 2010 (Microsoft Office; Redmond, WA). Values for 0 kPa (saturation) and -0.38 kPa (initial drainage) were replaced by TP and CC values from the porometer experiment respectively. This was done to overcome the resistance exerted by the ceramic plates, preventing free flow due to gravity. Values for EAW, and WBC, which categorize a substrate's water holding ability, were then calculated, as shown by de Boodt and Verdonck (1972), from points on the curve as indicated below.

$$\mathrm{EAW} = \theta_{10} - \theta_{50} \qquad [4]$$

$$\mathrm{WBC} = \theta_{50} - \theta_{100} \qquad [5]$$

Using SAS statistical software version 9.2 (SAS Institute; Cary, NC) with proc nlin, the means of each value, for each substrate were plotted, which allowed them to be fitted with the five parameter van Genuchten closed adapted for horticultural substrates [1]. However, this five parameter model did not converge and was deemed to not provide a good fit for the 100% substrate materials. For these materials, a restriction on one of the curve fitting parameters parameter (m=1) was used, which provided an adequate fit.

Equilibrium Capacity Variable Models

Using values attained by modeling the MRC curves with Van Genuchten's model, equilibrium capacity variable (ECV) models were rendered to demonstrate the physical properties of the substrate in different sized and shaped containers (Milks et al., 1989b). These models use θ_s and θ_r, and the three curve fitting parameters (α, n, and m) as well as individual container geometries and volumes to describe the differences in CC and air space (AS) as the container changes

Statistics were determined for the hydrologic properties in Table 1 and Table 2 using SAS version 9.2 (SAS Institute; Cary, NC) and Tukey's HSD with alpha = 0.05 to observe similarities and differences between different substrates for each property. Regression analysis was also tested for each property to determine the effects of amendment ratio within the peat. Table 3 was produced from mathematically derived modeling algorithms, which required means of repetitions to produce curve fitting parameters for use in the models. For this reason there were not multiple replications done on these models which rendered statistical comparisons impossible.

Results and Discussion

The MRCs were plotted for peat, coir, perlite, PB, SPW, and PWC (Figure 1) as well as all five ratios for each amendment (Figure 2). The MRCs for the 100% materials show well defined differences amongst all six materials (Figure 1). The peat and coir followed similar drainage patterns throughout the tension ranges. The two PTS components showed similar curve shapes to the perlite have characteristics similar to both peat and the PTS. The PB showed the steepest slope almost immediately, with almost all water being released (drained) over the entire tension range by -1 kPa. The peat:perlite mixes showed little variation amongst the different perlite ratios, and no difference is shape of the curve after -0.4 kPa (Figure 2A). The values for -0.38, -1.0, and -2.0 kPa were the only values with more than a 5% difference between different perlite ratios. This lack of variation can be explained by the inherent properties of the peat being more pronounced than the perlite (Figure 1). This also alludes to the similarities in shape of 100% peat and 100% perlite's curves, as when mixed they do not tend to cause a change in shape and therefore provide similar drainage patterns. Since the perlite is inert, there are no chemical or biological activities altering the water movement in the perlite. Also due to perlite's increased percentage of fine sized particles (PF; Table 1), as opposed to the two PTS components, much of the perlite is not being pronounced in the mixtures. The SPW (Figure 2B) and PWC (Figure 2C) do exhibit variation within aggregate ratios, as there is a significant difference between the high percentage of peat mixes (80 and 90% peat) and the lower peat mixes (50, 60, and 70% peat). At lower tensions (-1 kPa and less) and higher tensions (-10 kPa and up) larger differences are observed. The PTS mixes with high percentages of peat are also very similar to each other. This can be attributed to the individual manufacturing processes of the PTS not distinctly altering mix dynamics until there is a larger percentage of the material present. When the components are compiled into a mixture much of the individuality of the components is lost. The curves of the mixtures all resemble the 100% peat MRC as far as shape TP and MC at -30 kPa to a larger degree than that of the 100% amendment curves. This is another example of the inherent properties of the peat taking over the system, and lessening the effect on water retention caused by presence of amendments.

Total porosity for all ratios of perlite and PWC mixtures tended to decrease with increases in percentage of amendments to the peat, which was expected as these amendments had higher bulk densities and are much less porous than peat (Table 2) The TP for the different ratios of SPW did not change, with increasing amendment percent, however the proportion of CC and AS making up TP did. The 100% perlite had the lowest TP of all substrates in the experiment, about 10% and 12% lower than the next lowest substrates, PB and PWC respectively. Shredded wood had a 5% higher TP than PWC, but the TP ranges in the SPW and PWC mixes were similar except for the highest percentage mixes. Container capacity followed similar patterns for mixes with all three amendments, an increase in CC with a decrease in amendment, and 9 to 11% difference between the highest and lowest amendment rate. Shredded wood and perlite had the same CC, while PWC was 10% lower than both. This is likely due to a difference in surface area, and pore sizes between the two PTS components. The SPW being more fibrous would have a greater surface area and micropore volume than the chipped wood with larger particles and smoother edges. The perlite had 33 PF followed by PB (21.5%) and SPW (19.7%), with PWC being the lowest (6.8%; Table 1). This would result in correspondingly higher surface area and a higher percentage of smaller sized pores in perlite versus SPW versus PWC (Table 1; Hillel, 2008). Water is held with the highest tension on the surfaces of particles followed by the smallest diameter pores. Therefore, more water was held in the perlite and SPW than in PWC. The volumes of AS for all the substrates were inversely related to that of CC, with increasing AS resulting from an increasing percentage of amendment. The range of air space in all mixtures was 10 and 18% by volume. The 100 % PWC and PB had the same AS, alluding to both materials being viable for increasing drainage of a mixture. Air space in 100% perlite was about 1/3 that of SPW and PWC, but the same as 100% peat. Finer sized particles are able to fill in smaller voids, which allow them to pack more closely within themselves and create fewer macropores (Hillel, 2008)

The EAW also increased with a decrease in percentage of amendment, with peat and mixtures with high peat ratios having the highest EAW. The 100% PWC and PB had a much lower EAW than peat, coir, SPW, and perlite, which is likely due to a higher ratio of macropores which are formed as a result of a lower PF in the PWC (Table 1), and a high percentage of “extra large” sized particles in PB (unpublished data). The high number of macropores would also contribute to PWC having nearly a 50:50 split between CC and AS. There was almost no difference among components in EAW, while looking at similar mix ratios. The only instance where there was a difference was in 80:20 peat:SW, which did have a slightly higher EAW than the 80:20 peat:perlite (Table 2). There was no difference between ratios of peat:perlite in WBC, which is equal to that of 100% peat. The 100% peat and coir's WBC was significantly higher than that of any other component which means plants will be able to pull water between -5 and -10 kPa easier from these materials (Table 1). Figure 1 shows a similar downward slope for peat, coir, and perlite between -5 and -10 kPa, whereas both the PTS have a more gradual slope. This yields the inference that at this range peat and perlite are quite similar in percentage of water that is released. The SPW and PWC mixes lose less moisture in this pressure range than do the perlite mixes, however both the PTS mixes show a significant increase in WBC with decreasing amounts of PTS, whereas the perlite mixes do not. This explains the differences in the slopes of the PTS versus the peat and perlite. The SPW does not release much water after -4.0 kPa, and PWC does not release much water after -2.0 kPa, whereas perlite continues to release water steadily until -10 kPa and the peat does not stop losing moisture (Figure 1). The theta at -10 kPa, known from here on out as residual water (RW10), was also reported in Table 1, which allows for comparisons of the substrates at the higher tensions. There is a slight linear relationship for RW10 of peat:perlite mixes and a slight quadratic relationship for the peat:SW mixes with no significant relationship existing between the peat:CW mixes. This which shows while there are differences in MC at -10 kPa between the treatments, there is not an identified pattern that is followed. The RW for the WC mixes was significantly higher than the SPW mixes, which in turn was significantly higher than the perlite mixes. This is a result of a loss of connectivity in the WC at lower tensions, due to a lower PF. The lower the PF the less hydraulic conductivity a material has. This lower hydraulic conductivity causes the water column to break, thus not allowing moisture to drain easily. This is also the reasoning for the leveling off of the MRC curves for the 100% PTS (Figure 1). Also shown in Table 1 is the theta at -30 kPa (RW30), which shows what happens between -10 and -30 kPa. The PWC mixes do not lose much moisture from -10 to -30 kPa, while the perlite mixes do.

The ECV models (Table 3) show the change in physical properties of the mixtures as the container size changes. A 3.9 L Zarn pot, which is commonly used for larger plants in both greenhouse and nursery production was compared with two common greenhouse production containers of 10 and 16 cm tall, as well as single cell from a plug tray (273 cells per flat) and a single cell from a bedding plant flat (48 cells per flat). Regardless of container size and shape, the percentage of solids and therefore total pore space remains unchanged (Milks et al., 1989b). There is a change in the amount of water that can be held in the pore space. From the 273 cell plug tray (individual cells = l x w x h), to the 15 cm pots there is about a 20% difference in AS and CC, with the larger containers always having more AS. The excess drainage in the taller containers is a result of the increased gravitational forces drawing more water out of the smaller void spaces in taller containers, which was demonstrated by Spomer (1974). There is also increase hydraulic head in the taller containers, creating more positive pressure on the water in the pore space, causing increased drainage. There is little variation amongst substrates of equal ratios and containers. As the container size is decreased, the differences in AS and CC amongst ratios and aggregate type are diminished. In the smallest containers (plug trays) we see a larger (4.4) AS in the PWC mix, than we do in the perlite (2.8) and the SPW mix (2.2). As container size increases, the difference in AS between the three mixes diminishes, until there is relatively no difference between either of the substrates.

Conclusions

The two PTS types have a greater influence on substrate dynamics than perlite, when incorporated into a peat mixture. Percentages of perlite in a peat:perlite mixture do not create any statistical difference in substrate physical properties when used between 10 and 40% of a mixture. Pine tree substrates do tend to affect the dynamics of a substrate, with increasing influence coming from increasing percentages. This means that smaller proportions of PTS can effectively be used in place of larger amounts of perlite to achieve desired outcome. With both types PTS being cheaper to produce and incorporate into a substrate than perlite this can be a very significant discovery. The lowered hydraulic conductivity of the PTS also causes more water to be stored in a substrate at higher tensions than mixes with perlite as an amendment. Caron et al. (1998) showed that xylem stress is first observable when substrate water potential reaches -10 kPa. Kiehl et al. (1992) showed water stress in Chrysanthemums starts at -16 kPa. Looking closer at a standard ratio for substrate experimentation, 70:30 peat:amendment, there is a significant difference between the RW of the three different mixes at -10 kPa. Perlite, SPW, and PWC mixes at 30% yielded 29.2, 33.7, and 37.1 percent of pore space filled with water at -10 kPa respectively. In fact, the RW of a 30% PWC mix at -30 kPa was 32 percent, which is still higher than the 30% perlite mix at three times the tension (Table 3). Therefore a plant grown in a mixture containing PTS would have to exhaust less effort to achieve similar levels of water as opposed to a plant grown in a mixture containing perlite. Karlovich and Fonteno (1986) also described that the relationship between theta and tension being different for every substrate, the MC was more crucial in producing higher quality plants. Puustjarvi and Robertson (1975) reported that the majority of greenhouse crops are kept at tensions between 0 and -10 kPa which would render this unimportant, however once a plant leaves the greenhouse and is moved to a retail store there is a high likelihood that tensions beyond -10 kPa are achieved. For this reason, we can hypothesize that plants grown in peat amended with PTS would require higher tensions until stress symptoms start to develop, and therefore be potentially kept at higher quality longer at a market.

Irrigation regimes can be determined by monitoring soil or substrate moisture tension, and therefore the development of MRC's can be a very useful and important tool for greenhouse and nursery managers (Obreza et al., 1997). The use of PTS in place of perlite for substrates would require changes in irrigation schedules, which might cause some distress to growers. However, these changes would be to cut back slightly on irrigation, leading to more efficient water usage. The difference in irrigation would not be extreme, enabling a grower to forego altering irrigation regimes if desired.

The similarities in physical properties between PWC and PB are also very extensive, alluding PWCs possible use as a replacement or amendment for PB. Pine bark is generally used in a mix to increase drainage, but PB has been shown to vary significantly depending on source and cultural practices (Pokorny, 1975; Fields et al., 2012). This can cause a water holding issues with some PB which may be able to be prevented/lessened with the addition of PWC.

The ECV models provided a good representation of the differences in component physical properties in different stages of crop production. There are some slight differences between the amendments in smaller sized containers, however neither amendment used has been classified for use in plug containers. The representations of the larger sized containers, where these amendments are more likely to be found show that there is not much difference in physical properties regardless of which amendment is used.

The two PTS components used in this experiment were manufactured to exact specs. Altering one or more of the manufacturing process would lead to a change in hydrophysical properties, as well as drainage profiles of these materials. Jackson et al. (2010) demonstrated different ways to produce PTS, and the differences in physical properties rendered with different manufacturing processes for PTS. Therefore any further research may show differences in physical properties of PTS components if not manufactured using the same process.

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Table 1. Physical and hydrologic properties of six traditional and alternative greenhouse substrate components[z]

Component	TP[y]	CC[x]	AS[w]	Db[v]	EAW[u]	WBC[t]	RW100[s]	RW300[r]	PF[q]
Peat	91.0 a[p]	80.1 a	10.7 c	0.12 c	17.7 a	5.9 a	36.4 a	26.8 c	51.6 b
Perlite	66.4 d	54.3 c	12.2 c	0.17 b	10.4 b	3.6 b	30.6 c	29.5 b	33.2 c
SPW[o]	84.1 b	52.8 c	31.3 b	0.18 ab	13.9 a	2.1 c	33.8 b	33.9 a	19.7 d
PWC[n]	78.8 c	41.6 d	37.2 a	0.18 ab	05.6 c	0.5 d	33.9 b	33.7 a	06.8 e
Coir	88.7 a	75.2 b	13.5 c	0.09 d	16.5 a	6.0 a	26.0 d	22.8 d	64.0 a
Pine Bark	76.0 c	42.5 d	33.5 ab	0.21 a	03.2 c	0.2 d	22.6 e	22.2 d	21.5 d

[z] Physical and hydrologic properties determined using methods in North Carolina State University Horticultural Substrates Lab Manual (Fonteno and Harden, 2010).

[y] Total porosity is the total percentage of pore volume in a substrate.

[x] Container capacity is equal to the maximum water content a substrate can achieve after gravitational drainage has taken place.

[w] Air space which is the total percentage of porespace not filled with water at CC (TP=CC+AS).

[v] Bulk density is the weight of the oven dry material / total volume of sample.

[u] Easily available water is water lost between -1 kPa and -5 kPa.

[t] Water buffering capacity water lost between -5 kPa and -10 kPa.

[s] Volumetric water content of sample at -10 kPa.

[r] Volumetric water content of sample at -30 kPa.

[q] Percent of fine sized particles (>0.71 mm). Determination of PSD was done on 100% components only, X represents no data.

[p] Statistics were determined down column for individual properties using Tukey’s HSD with alpha = 0.05.

[o] Loblolly pine (*Pinus taeda* L.) trees processed through a shredder and then hammer-milled through a 6.35 mm screen.

[n] Loblolly pine trees processed through a wood chipper and then hammer-milled through a 6.35 mm screen.

Table 2. Physical and hydrologic properties of peat amended with 50, 40, 30, 20, 10, and 0% perlite, shredded pine wood, or pine wood chips.[z]

Mix Ratio	TP[y]	CC[x]	AS[w]	Db[v]	EAW[u]	WBC[t]	RW100[s]	RW300[r]
				Peat:Perlite				
50:50	85.6 e[q]	68.3 g	17.3 ab	0.12 ef	11.2 d	5.5 ab	27.8 g	18.8 h
60:40	85.7 e	72.5 defg	13.2 bcd	0.13 def	11.9 cd	5.8 ab	28.4 g	19.6 gh
70:30	87.1 abcde	74.8 def	12.3 bcd	0.13 de	14.3 abcd	5.2 bc	29.2 g	20.6 fgh
80:20	87.4 bcde	76.2 cde	11.1 d	0.12 ef	12.9 bcd	5.0 bc	28.6 g	20.3 fgh
90:10	88.3 bcde	77.0 bcd	11.3 d	0.12 ef	16.4 ab	5.1 bc	29.7 g	22.2 efg
100:0	91.0 abc	80.1 abc	10.7 d	0.12 f	17.7 a	5.9 ab	36.4 cd	26.8 d
Significance[p]	L***	L***	L***	NS	L***	NS	L**	L***
	Q**	Q***	Q***	NS	Q***	NS	NS	Q**
Mix Ratio				Peat:Shredded Pine Wood				
50:50	89.4 abcde	70.8 fg	18.7 ab	0.14 cd	11.3 d	3.1 e	32.3 f	27.4 cd
60:40	91.3 ab	72.4 efg	19.3 a	0.14 bc	10.2 d	3.4 de	34.9 cde	30.0 bc
70:30	90.5 abcd	76.2 cde	14.4 abcd	0.13 de	12.9 bcd	4.3 cd	33.7 def	27.1 d
80:20	92.5 a	80.6 abc	11.9 cd	0.12 ef	17.7 a	5.4 b	29.1 g	22.7 ef
90:10	92.1 a	80.9 ab	11.1 d	0.12 ef	17.8 a	6.5 a	32.5ef	23.8 e
100:0	91.0 abc	80.1 abc	10.7 d	0.12 f	17.7 a	5.9 ab	36.4 cd	26.8 d
Significance	NS	L***	L***	L***	L***	L***	NS	NS
	NS	Q***	Q***	Q***	Q***	Q***	Q*	NS
Mix Ratio				Peat:Pine Wood Chips				
50:50	86.1 de	69.1 g	17.0 abc	0.16 a	10.8 d	2.8 e	38.8 ab	36.6 a
60:40	89.5 abcde	71.0 fg	18.5 ab	0.16 a	11.3 d	2.7 e	39.6 a	36.2 a
70:30	89.1 abcde	73.8 def	15.3 abcd	0.15 ab	14.0 abcd	3.7 de	37.1 bc	32.0 b
80:20	90.9 abc	80.3 abc	10.6 d	0.13 cd	15.8 abc	4.9 bc	34.2 def	27.8 cd
90:10	91.8 ab	81.3 a	10.6 d	0.13 def	17.9 a	5.5 ab	34.3 def	26.6 d
100:0	91.0 abc	80.1 abc	10.7 d	0.12 fg	17.7 a	5.9 ab	36.4 cd	26.8 d
Significance	L***	L***	L***	L***	L***	L***	NS	L***
	Q***	Q***	Q***	Q***	Q***	Q***	NS	Q*

[z] Physical and hydrologic properties determined using methods in North Carolina State University Horticultural Substrates Lab Manual (Fonteno and Harden, 2010).

[y] Total porosity is the total percentage of pore volume in a substrate.

[x] Container capacity is equal to the maximum water content a substrate can achieve after gravitational drainage has taken place.

[w] Air space which is the total percentage of porespace not filled with water at CC (TP=CC+AS).

[v] Bulk density is the weight of the oven dry material / total volume of sample.

[u] Easily available water is water lost between -1 kPa and -5 kPa.

[t] Water buffering capacity water lost between -5 kPa and -10 kPa.

[s] RW100 is the volume percentage of water remaining in the sample at -10 kPa.

[r] RW300 is the volume percentage of water remaining in the sample at -10 kPa.

[q] Statistics were determined down column across all components and ratios for individual properties using Tukey's HSD with alpha = 0.05.

[p] Significance of the rate of amendment on the property with L being linear and Q being quadratic and NS= not significant, *** = $p \leq 0.001$, **=$p \leq 0.01$ *=$p \leq 0.05$.

Table 3. Mathematically derived physical properties of peat amended with 10, 20, 30, 40, and 50 percent perlite, shredded wood, and chipped wood, derived from modeling equilibrium capacity variable values.[z]

	Container Size									
Amendment	Plug[y]		BP Flat[x]		10 cm[w]		15 cm[v]		3.9 L Zarn[u]	
Percentage	CC	AS	CC	AS	CC	AS	CC	AS	CC	AS
	====================Perlite Mixes====================									
10%	85.4	1.9	79.1	8.2	73.9	13.4	65.4	21.9	60.7	26.6
20%	86.7	0.6	79.4	7.9	72.4	14.9	62.3	25.1	57.3	30.1
30%	85.3	2.8	77.8	10.3	72.3	15.8	63.6	24.5	59.0	29.1
40%	83.5	2.2	75.8	9.9	70.0	15.7	61.2	24.5	56.7	29.0
50%	80.4	6.6	72.0	15.0	66.9	20.1	59.3	27.6	55.3	31.7
	================Shredded Pine Wood Mixes================									
10%	90.1	4.7	83.0	11.8	78.3	16.5	70.6	24.2	66.2	28.6
20%	90.7	1.8	83.6	9.0	77.4	15.1	67.5	25.0	62.2	30.4
30%	88.4	2.2	80.2	10.3	74.0	16.5	65.0	25.6	60.4	30.1
40%	89.0	2.7	78.4	13.3	71.5	20.2	62.4	29.3	58.1	33.6
50%	86.6	2.8	76.4	13.0	69.6	19.8	60.4	29.0	56.1	33.4
	================Pine Wood Chips Mixes================									
10%	89.2	2.6	83.1	8.7	78.4	13.4	70.6	21.2	66.1	25.7
20%	89.4	1.5	83.0	7.9	77.4	13.5	68.4	22.5	63.7	27.2
30%	84.7	4.4	77.4	11.7	72.8	16.3	65.7	23.4	61.9	27.2
40%	83.6	5.9	75.6	13.9	70.8	18.7	64.0	25.5	60.6	28.9
50%	81.1	5.0	73.4	12.7	68.9	17.2	62.3	23.8	59.0	27.1

[z] Properties derived by modeling Van Genuchten curve fitting parameters from moisture retention curves determined in the North Carolina State University Horticultural Substrates Lab.

[y] Individual cell from a plug tray containing 273 individual cells (l x w h).

[x] Individual cell from a bedding plant flat tray containing 48 individual cells (l x w x h).

[w] Container 10 cm tall commonly used in greenhouse crop production (vol).

[v] Container 15 cm tall commonly used in greenhouse crop production (vol).

[u] Zarn container with volume of 3.9 L used in greenhouse crop production

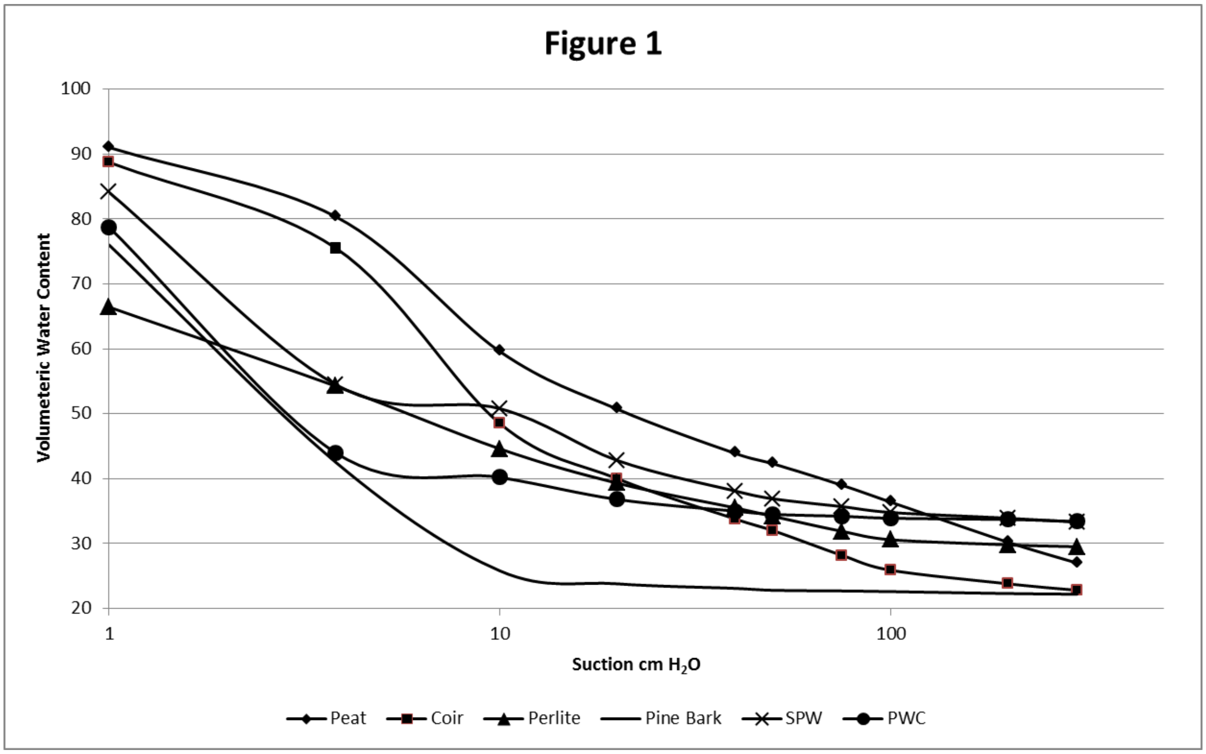

Figure 1. Moisture retention curves of six traditional and alternative greenhouse substrate components.

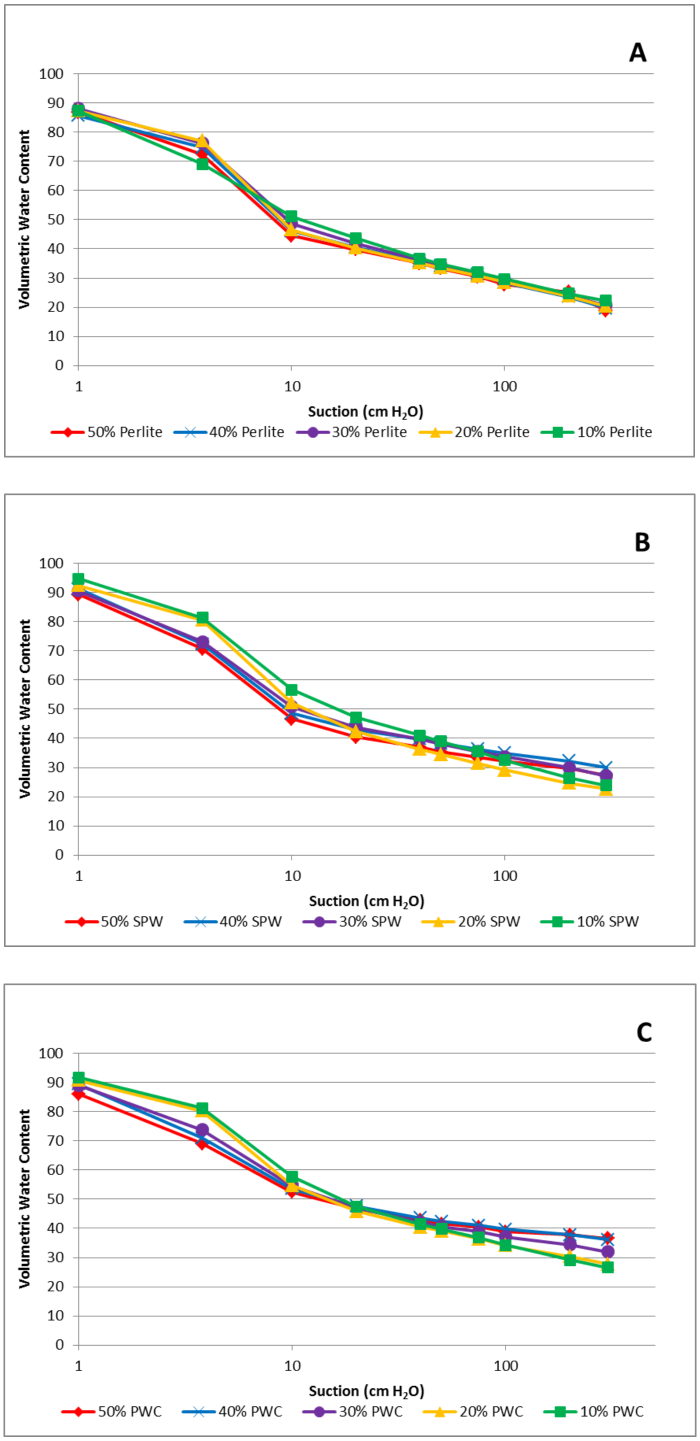

Figure 2. Moisture release curves of peat amended with 10, 20, 30, 40, and 50% of A) perlite, B) SPW, and C) PWC.

CHAPTER 3
Hydration Efficiency of Traditional and Alternative Greenhouse Substrate Components

Hydration Efficiency of Traditional and Alternative Greenhouse Substrate Components

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Abstract

A material's wettability can determine whether or not it can be efficiently used in a greenhouse substrate. Poor wettability can lead to water use inefficiency as well as poor plant growth and development. This experiment was designed to test the wettability and hydration efficiency of some traditional and alternative components of substrates under different moisture contents (MC) and wetting agent (WA) levels. Peat, perlite, coconut coir, pine bark, and two differently manufactured pine tree substrate components were tested at 50% and 25% initial MC by weight. Each of these components received WA treatments of high, medium, low, and none. It was determined from this experiment that hydration efficiency is influenced primarily by initial MC. Wetting agent can aid in hydration efficiency however may not always be enough to overcome all cases of hydrophobicity.

Introduction

Wettability of a material has been defined by Letey et al. (1962) as the ability of a liquid to spread over a surface. Proper wettability ensures even distribution of water and therefor nutrients throughout the entirety of the substrate. Appropriate wettability also leads to greater water holding capacity, which has been shown to be an important factor for proper plant growth (Plaut et al., 1973). Horticultural substrates often have wettability problems due to the high percentage of organic matter (OM) components in them. The OM in substrates, primarily being of sphagnum peat moss and pine bark, can become hydrophobic, thus creating a lack of wettability (Dekker et al., 2000a). The organic molecules of OM contain many organic acid functional groups on their exterior, which include carboxylic acids and phenolic acids, among others. These acidic functional groups tend to repel water from the particle surfaces when in a neutral state with hydrogen cations bound to oxygen anions (Ellerbrock et al., 2005). When allowed to air dry these hydrophobic properties of the OM, such as peat, can be intensified and the wetting and rewetting process can be complicated during plant culture (Valat et al., 1991). When allowed to dry out many organic substrates can develop hydrophobicity issues that hinder proper rewetting (Beardsell and Nichols, 1982).

There are several factors that can influence a substrates wettability, including but not limited to, moisture content (MC; de Jonge et al., 1999), substrate pH (Gautam and Ashwath, 2012), hydrophobicity of the substrate (Fonteno et al., 2012), and preferential flow (Ritsema and Dekker, 1994).

Measurement of substrate wettability has been difficult to assess, with the most commonly used method in the literature, being the measurement of contact angles (Michel, 2009). The process of measuring contact angles to infer wettability was first described by Letey (1969), and was primarily used for measuring wettability of mineral soils. Contact angles are the angles that form at the contact points between the three phases of a soil or substrate, water, solids, and air (Hillel, 2008). The angle that forms at the terminal end of a water droplet, when first coming in contact with a surface, is considered the contact angle. The angle is primarily determined by the surface energy of the solid particle. As a surface becomes more wettable, or less hydrophobic, the surface tension is reduced. As a result, water is allowed to spread out across the surface, reducing the contact angle. Hydrophobic surfaces, with high surface energies, do not allow the water droplet to spread across the surface, resulting in larger contact angles greater than 50-60^{o} (Shirtclliffe et al., 2006). Determination of wettability by measurement of contact angles is a complex task that requires a high level of precision. As a result, machines have been created to undertake this task, however these machines are expensive and have to alter the material's physical state by grinding the material before it is tested.

Another commonly used method for measuring substrate wettability described by Letey (1969) and reevaluated by Dekker and Ritesma (2000b), is known as the water drop penetration time (WDPT) test. To test WDPT a drop of water is placed on the surface of the substrate and the time it takes for the drop of water to completely penetrate the substrate is measured. This method is less expensive to preform, however results can be varied as a result of the subjective properties of this test. A more recent method described by Fonteno et al., (2012) for determining the wettability of a substrate is known as the hydration efficiency test. In this method, known quantities of water are passed through a substrate and effluents are collected to determine the quantity of water sorbed by the substrate.

Wetting agents are chemicals which increase the wettability of substrates. Wetting agents are a type of surfactant, which in turn is a type of adjuvant. The word surfactant is a combination of the words “surface active agents”. Wetting agents are used to change the properties of water by allowing the individual water molecules to break some of their hydrogen bonds and spread out more evenly over the surface of a substrate. Wetting agents, like all surfactants, are chemically composed of two parts, a hydrophilic hydrocarbon tail and a hydrophobic lipid head. The hydrophobic end will adsorb to the surface of the substrate particle leaving the hydrophilic end exposed. The water molecules will then bind to the hydrophilic end and spread out across the surface of the particle. This reduces surface energy of the solid particle and promotes a more uniform distribution of water over the surface. Wetting agents are commonly used in many substrates to achieve proper MC with fewer irrigation events. Thus, they are an important aspect in a substrate’s hydration efficiency.

Wetting agents enable substrates to be more uniformly wet, as they ensure that water spreads throughout a substrate by reducing surface tension (Moore, et al, 1983). As a plant pulls water from the substrate, the forces from the substrate act on the water and the tension is increased. Wetting agents alleviate this tension and ensure that more water is available to plants (Miller and Westra, 1998). Wetting agents are used in the horticultural industry to increase wettability and penetration of water through a substrate, without altering substrate physical properties (Powell, 1987). Due to the limited volume of substrate in a container, and in turn limited amount of water that can be held in a plant, maximization of water retention, and minimization of leaching is a critical aspect to the horticultural industry (Yeager et al., 2007). Studies have shown that plants not only grow well in substrates amended with wetting agents, but sometimes better than substrates not amended with wetting agents (Bilderback et al., 1997; Bhat et al., 1992). Wetting agents have also been reported to chemically increase water holding capacity in some substrates (Elliott, 1992; Blodgett et al., 1993). Wetting agents are also used to aid in rewetting substrate surfaces that dry out between irrigation events during plant production (Boodley and Sheldrake, 1977). Another use for wetting agents in horticultural substrates is to overcome hydrophobicity or water repellency of a substrate.

The first objective of this work was to survey the wettability of traditional substrate components and for the first time, characterize pine tree substrate (PTS) components now being used in greenhouse substrate mixes. Research is needed to determine the hydrologic properties of PTS in order to understand how to properly wet them and increase their water storage efficiency. The second objective of this research was to determine hydration efficiency of two types of PTS as well as traditional greenhouse substrate components. The third objective was to test the hydration efficiency procedure on widely used commercial substrates, and evaluate the hydration efficiency procedure's ability to accurately determine wettability and hydration efficiency of horticultural substrates.

Materials and Methods

Hydration Efficiency of Substrate Components

Substrate components tested were coconut coir (Densu Coir, Canada), sphagnum peat moss (Premier Tech, Canada), aged pine bark, perlite, and two types of hammer-milled loblolly pine wood (*Pinus taeda* L). Freshly harvested loblolly pine logs were hammer-milled through a 6.35 mm screen after initially being processed through either a wood chipper or a wood shredder. The pine logs destined for chipping were harvested on 9 Dec.

2011, and passed through a DR Chipper (18 HP DR Power Equipment, model 356447; Vergennes, VT) on 3 Jan. 2012, and hammer-milled (Meadows Mills, North Wilkersboro, NC) on 5 Jan. 2012. The pine logs destined for shredding were harvested on 12 Dec. 2011, and shredded in a Wood Hog shredder (Morbark©; Winn, MI) on 9 Jan. 2012. The shredded pine wood was then hammer-milled as previously described above for the chipped wood on 10 Jan. 2012.

Each of the six components was hydrated to 50% MC by weight. To do this each component had subsamples of about 150 mL weighed then dried and then reweighed. This gives wet weight and dry weight. MC = [(wet weight – dry weight)/wet weight x 100] by attaining material's initial MC and calculating volume of water needed to raise MC to 50% by weight. Each component was separated into four subsamples of equal volume (4 L). Each subsample was treated with AquaGro®-L (Aquatrols, Paulsboro, NJ) wetting agent at either 0 (none; NWA), 116 (low rate; LWA), 232 (medium rate; MWA), and 348 (high rate; HWA) ml m^{-3} respectively. The amount of wetting agent required to achieve the four testing levels for each sample was pre mixed with the water required to bring the sample to 50% MC. The six components each with the four WA levels yielded 24 treatments. The amount of water required to bring each substrate up to 50% MC and the amount of wetting agents required for each respective subsample were mixed in a 4 L SureSpray™ sprayer (Chapin; model 20010; Batavia, NY). Components were individually spread out at a depth of 1 cm on a metal tray, and wetting agent/water mixture was evenly applied (sprayed from sprayer). Water was thoroughly mixed in each component immediately after application by turning and mixing until entirety of solution had been applied. To test the effect of MC on WA levels and wettability, substrate components were also tested at 25% MC. To do this, all 24 samples were then split in half by volume (2 L each). One half was placed into a plastic bag and sealed to prevent water loss and allow for moisture equilibrium. The second half was spread on a tray and allowed to air dry until 25% MC was attained. Initial MC and total weight of each sample was used to calculate how much water needed to be lost to reach 25% MC. Water's specific density is 1g/cm^3, each ml lost is equal to a 1 g. Therefore, the precise volume of water that needed to be lost to achieve 25% MC was calculated. Samples were allowed to air dry until weight (g) loss equals number of ml's needed to be removed. Once target MC was attained samples were sealed in plastic bags to prevent further water loss, while allowing for moisture equilibrium. The addition of the 25% MC treatments resulted in a total of 48 treatments in this study (6 components x 4 WA levels x 2 MC).

This experiment was conducted following the procedures described by Fonteno et al., 2012. The equipment required consisted of a transparent cylinder, 5 cm i.d. x 15 cm h, with a mesh screen (mesh size 18x16; New York Wire; York, PA), attached to one end, using rubber pressure plate rings (Soilmoisture Equipment Corp.; Santa Barbara, CA); a 250 ml separatory funnel; a 250 ml beaker; and a 10 ml plastic vial (4 cm dia.), referred to in this work as a diffuser. The diffuser had five evenly spaced holes in the bottom (2.38 mm dia.), which enabled it to diffuse the force of water as it is released and falls to the surface of the substrate. As water moves from the funnel into the diffuser, it slowly drips out of the five holes onto the substrate surface, thus simulating a drip irrigation system in a greenhouse production setting. A rubber O-ring is placed around the outside of the diffuser, which allowed it to sit precisely atop the transparent cylinder.

The transparent cylinders were packed with each substrate component to achieve a bulk density (Db) within 5% of other samples of the same components. To do this, cylinders were filled with substrate and gently packed by holding filled cylinders 10 cm off a flat surface and dropping 3 times, so the top of the sample was even with a line 10 cm from the bottom and 5 cm from the top of the cylinder, which represents 200 ml of substrate. Four replications were produced for each of the 48 treatments, totaling 192 different samples. Once packed, cylinders were fitted with a diffuser, and placed under a separatory funnel. Each water application is referred to as a hydration event. Each hydration event consisted of passing 200 mL water through the substrate filled cylinders at a rate of 3 liters per hour. Due to hydrophobicity issues of some of the substrate components at 25% MC, water flow rate into the diffuser was slowed in order to prevent water from filling the cylinder and spilling over the top. The water was passed from the funnel, through the diffuser, onto the substrate, with a 2.5 cm distance between the bottom of the diffuser and the surface of the substrate. As the water percolated through the substrate, it was either sorbed into or onto the substrate or it leached through the substrate and out of the column and was collected into a beaker below. Ponding, which is the accumulation of hydraulic head, occurs when water levels on the surface of substrate buildup before water infiltrates the substrate. Ponding was controlled by keeping hydraulic head to a maximum of 2 cm, by adjusting the stop cock on the funnel. Hydraulic head is the depth of water column present on top of the surface. After the entire 200 ml had been applied and passed through samples, equilibration was allowed until dripping ceased (about 3 min). Effluent water collected in the beakers located below the cylinders was recorded and water retained by the substrate was calculated by subtracting leached water (effluent) from total water applied (200 ml). This procedure was repeated 10 times for each sample.

After the 10th hydration event was completed, cylinders were reweighed and new sample heights were measured, in order to observe any changes in volume due to shrinking or swelling. Container capacity (CC) was then needed to determine maximum hydration. To determine CC, the cylinders were then placed into a Bucher funnel with holes as described in the North Carolina State University Porometer Manual (Fonteno and Harden, 1995). The samples were saturated from below by adding water to the funnels between the cylinder and the funnel wall, until water reached 1/3 of the height of the sample (3 cm from bottom of cylinder). After two min water was added again until it reached 2/3 of the height of the sample (6 cm from bottom of cylinder). After two additional min, water was applied until the water level was even with the top of the sample (10 cm from bottom of cylinder). After saturating for 15 min, the stopper was pulled from the bottom of the funnel and water was allowed to drain for 30 min. Samples were reweighed and new sample heights were again measured to observe any changes in volume. Samples were then placed into a forced-air drying oven for 48 h to dry. Once dry, samples were reweighted and dry weight was used to determine MC and total water retained.

Follow-up - Testing on Mixes

A follow up experiment was conducted on readily available commercially produced mixes, in order to test the viability of the hydration efficiency test. Three mixes were used: 1) Mix A was a commonly used commercial grower mix, composed of Canadian sphagnum peat moss (45%), processed pine bark, perlite, vermiculite, starter nutrients, wetting agent & dolomitic limestone; 2) Mix B was commercially available retail mix, composed of Canadian sphagnum peat moss (between 55 and 65%) composted softwood bark, perlite, wetting agents, and fertilizer; and 3) Mix C was a standard research and grower control mix, consisting of 60:20:20 peat:perlite:vermiculite (v:v:v), containing appropriate lime and wetting agents. No additional wetting agents were added to these mixes. The three mixes were moistened following the same procedures as in experiment one, packed in the cylinders, and 10 hydration events were applied as previously described. Similar to the substrate components in experiment one, the three mixes were tested at 50% MC and 25% MC, with four replications of each totaling six treatments and 24 replications.

Wettability curves were produced for each of the samples tested in this experiment. These curves plot the volumetric water content of the sample after each hydration event. The CC, which is the highest MC attained by volume of each sample after drainage had occurred, was also plotted on the chart to show relationships between CC and sample after each hydration event. Each treatment had its hydration efficiency rated by an initial hydration percentage (IHP) rating and a hydration efficiency index (HEI) system. Initial hydration percentage was the percentage of CC that was attained by a sample after one hydration event, and the HEI system determined the number of hydration events required to bring the system to CC. For example, if CC was reached after the first hydration event a IHP of 100 and HEI of 1 would be achieved. If the sample reached CC after the third hydration event, this would result in a HEI of 3 and an IHP under 100. If CC was not attained in the 10 hydration events by a treatment, that treatment was given a “x” in Table 1 to denote lack of achievement.

Statistics were determined on data using SAS v. 9.2 (SAS Institute; Cary, NC). A Tukey’s HSD test with alpha = 0.05 was used to determine differences and similarities between the components at individual MCs and WA levels. A Tukey’s HSD test with alpha = 0.05 was also used to determine the differences in the HEI values across all treatments in the experiment. Container capacity and IHP within each component at individual MCs had regression analysis conducted to determine the effect of the rates of WA on each component at each MC. Both linear and quadratic regression was determined and significance was determined using *p*-values, with significance ranging from >0.001 to 0.05. An ANNOVA test was also conducted to test effects of WA and MC on CC and IHP among all components and within individual components.

Results

Coir: Regardless of the WA level, coir at 50% MC received an HEI of 1. However, at 25% MC, coir failed to reach CC after the initial hydration. In fact, coir samples with MWA and HWA reached after three hydrations, while Figure 1B shows a steady intake of water in the MWA and HWA treatments, without ever reaching CC in the 10 hydrations. The CC for coir at 50% MC is unaffected by WA levels, but at 25% MC there is a significant relationship for CC and WA level (Table 1). The IHP (Table 1) values do show a significant interaction with WA level, especially in the 25% MC coir. This shows that the addition of WA does not greatly affect CC of coir, but does play a significant role in coir's hydration efficiency, especially at lower MCs.

Peat: *F*igure 1C shows that no wetting agent application rate prevents peat from attaining CC. Like in coir, no significant interaction was observed between WA level and CC for 50% MC, with a strong linear interaction (*p* = .0006) between IHP and WA level (Table 1). Peat at 25% MC does show a positive linear relationship with both CC and IHP and WA level, however, the peat at 25% was being affected strongly by hydrophobicity issues, causing the values for CC of NWA peat at 25% MC to be so low that a linear relationship resulted. Peat at 25% MC attained CC in the 10th hydration event for NWA, MWA, and HWA, and never attained CC in LWA. The fact that the CC was so significantly low in the NWA compared to the other treatments is the only causation for the NWA to achieve CC at all.

Pine Bark: At 50% MC, PB achieved an HEI value of 1 for all WA levels. In fact, PB at 50% MC showed a slight negative linear relationship between CC and WA level, as an increase in WA level tended to lower the CC (Table 1). This is attributed to the wetting agent lowering the surface tension of the water and allowing more drainage from a material with no observable hydrophobicity issues (Blok et al., 2008). At 25% there is a significant relationship between WA and IHP, while having no significant relationship between CC and WA, and NWA samples never reached CC. This coincides with previous work which shows that pine bark requires proper MC (>35% MC) and WA in order to achieve acceptable wetting (Airhart et al., 1980).

Perlite: Perlite was completely unaffected by any WA level or MC (Table 1). Perlite reached CC after one hydration event in every treatment, and there was no relationship between WA level and CC. This is likely due to perlite being an inert mineral (Bunt, 1988) unlike the rest of the components in this experiment, which are biological in nature and have organic molecules influencing their hydration.

Shredded Pine Wood: Shredded pine wood (SPW) had a linear and quadratic relationship with WA level and IHP at both 50% and 25% MC (Table 1). Any addition of WA, at 50% MC, caused the SPW to reach CC in one irrigation event (Figure 1I). The CC also showed a slight relationship between CC and WA level, with an increase in WA level causing a slight increase in CC. However, the SPW at 25% MC showed no relationship between WA level and CC, but a strong linear and quadratic relationship between WA level and IHP (Table 1). The HEI values for SPW at 25% MC show that the increased levels of

WA caused the CC to be reached in fewer hydration events. Unlike more common materials, like coir, which is considered to be very easy to wet, and peat, which is the most commonly used component for greenhouse substrates (Nelson, 2012), SPW required just three hydration events to reach CC at 25% MC and NWA. Lower MC and less WA is considered to be where hydrophobicity is most likely to occur, however an IHP value of 63.8 for SPW, is much greater than that of both coir (14.2) and peat (34.3).

Pine Wood Chips: Pine wood chips (PWC) at 50% MC did show a linear and quadratic relationship between CC and WA level, however the maximum fluctuation in CC was just 2% (Table 1). At 25% MC there was no significant relationship between CC and WA level. The chipped wood was manufactured to be more blockular, in order to increase aeration and drainage in a container substrate, and therefore is more closely compared to perlite, which is the most commonly used component for this purpose (Nelson, 2012). Figure 1K, shows that at 50% MC, PWC reaches CC after just one hydration event, just like that of perlite. At 25% MC, there is no relationship between WA level and CC, however there is a linear and a slight quadratic relationship between IHP and CC. Chipped wood and perlite also share the same CC at 25% MC in all WA levels except for LWA, in which case PWC has a higher CC.

Discussion

An ANNOVA was done to determine the effects of WA levels, MC, and their interactions on both CC and IHP (Table 2). From this, it was determined that across all substrates, CC was unaffected by MC, WA, and their interaction. Moisture content did have a significant effect on IHP, with WA and the interaction between MC and WA having no effect. From this data we can determine that while both WA and MC do have effects on hydration efficiency of the components (Table 1), MC has a strong effect on the IHP for all components.

At 50% MC the only material that does not wet up is peat at NWA. At all levels with WA, every component at 50% MC has an IHP of 1, which denotes a high hydration efficiency. Based on this, the 25% MC, a relatively low MC that has been associated with hydrophobicity issues (Fonteno, et al., 2012), is where most of the differences in hydration efficiency occur. Coir has been shown to have a high wettability, much higher than peat (Abad et al., 2005), but at 25% MC at NWA and LWA coir does not reach CC, while peat at NWA does. This is attributed to the extremely low CC of peat at 25% MC and NWA. At 25% MC both the SPW and the PWC had the highest IHP and HEI values amongst the organic materials. Perlite, which achieved CC in one hydration regardless of MC and WA level, has no issues with wettability. This is a result of perlite being chemically inert (Hanna, 2005), and therefore having no organic acid functional groups, which restrict water movement in organic materials (Ellerbrock et al., 2005). However, perlite and the PWChad very close CCs across all treatments. Pine wood chips had an equal or higher CC than perlite in all treatments except for 50% MC at NWA and MWA. Chipped wood also had the same CC as PB in all treatments except for 50% MC HWA, wherein the CC of PWCwas 5.2% higher than that of PB. When amended to a dry mix, wood aggregates are able to draw the ponded surface water through the mixture at a higher rate than perlite (personal observation). This is hypothesized to be a result of increased percentage of fine sized particles in the perlite causing "nesting" to occur within the peat. Nesting is a term used to describe particles fitting into internal pore spaces or other materials, causing a change in physical properties of the mixture (Bachman and Metzger, 2007).

Shredded wood had a higher CC than PWC, PB, and perlite in all treatments, except 50% MC NWA, in which SPW was equal with perlite. As a result of the manufacturing process, SPW is a fibrous material, with rough edges. These edges result in a higher percentage of fines (Table 2) and therefore a higher water holding capacity (Handreck, 1983; Richards et al., 1986). Fine sized particles have much higher surface area than larger diameter particles, as well as a larger volume of micropores as smaller sized particles tend to clog larger pores, restructuring them into smaller pores. The greater surface area along with the larger micropore volume results in SPW having an increased CC. The geometry of the SPW allows it to not only have good aeration qualities like perlite and PWC, but the increased PF allow for a higher CC, resulting in peat-like properties.

As for the differences in treatments, WA level played a slight role in CC in 50% MC PB and SW, as well as 25% MC coir. It also played a strong role in 25% peat, as the presence of WA greatly helped the peat overcome they hydrophobicity issues. IHP was significant in all WA levels across both MCs except for perlite, which had not wettability issues and 50% MC PWC. So WA level had a much stronger effect on IHP than CC. When comparisons are made across the entire experiment, we see that MC has a significant effect on IHP, while WA does not, and CC is unaffected by either. When comparisons are made to HEI values across all treatments, there are slight differences between WA levels and a strong difference between MCs. All this points to both WA level and MC having a strong effect on hydration efficiency, but initial MC having the predominate effect.

Examining the results of the follow up experiment, it is evident that the hydration efficiency test does have validity, as the statistics show that similarities between treatments in the mixes are present in the commercial substrates. This allows the individual components to be compared to one another, without major issues of individual components testing differently than mixes. All three substrates received an HEI value of 1 at 50% MC (Figure 2a). When tested at lower MCs, each substrate took longer to achieve CC (Figure 2b), similarly to the components.

This test examines hydration efficiency of substrate components using a drip system. From personal observation, the authors have observed differences in results when not using a diffuser. This diffuser absorbs some of the kinetic energy from the liquid as it is poured onto the sample. The water is then allowed to gently drip onto the surface of the samples, much like a drip emitter system. Pouring the water directly onto the sample, as previously described by Fonteno (2010) caused a difference in initial hydration and would therefore lead to excess water passing through the sample (personal observation). This method, which would more represent an overhead boom irrigation system, would create excess wasted water, and therefore have a lower hydration efficiency. When measuring hydration efficiency with a sub irrigation system, it was observed that CC was never attained, and most mixes reached only about 80% (unpublished data). The authors have hypothesized from this that when properly conditioned, substrates will be at the highest water efficiency levels when used in a drip irrigation system, as opposed to an overhead or sub irrigation system.

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Table 1: Container capacity (CC), initial hydration percentage (IHP), and hydration efficiency index (HEI) of six substrate components at two volumetric moisture contents (MC) amended with either none (NWA), low (LWA), medium (MWA), or high (HWA) levels of wetting agents.[z]

	50% Moisture Content						25% Moisture Content					
	NWA	LWA	MWA	HWA	L[t]	Q[s]	NWA	LWA	MWA	HWA	L	Q
Coir												
CC[y]	75.6a[v]	69.5 a	75.4 a	70.1 a	NS	NS	70.5 a	74.0 a	73.0 a	74.9 a	*	*
IHP[x]	97.7 a[v]	97.8 a	99.9 a	100.0 a	*	*	14.2 d	24.8 d	45.1 d	43.4 d	***	*
HEI[w]	1 a[u]	1 a	1 a	1 a	-	-	x	x	3 c	3 c	-	-
Peat												
CC	66.6 b	63.7 b	65.8b	66.8 b	NS	NS	25.5 e	68.1 b	69.2 a	72.9 a	***	*
IHP	27.0 c	96.2 a	97.5 a	95.4 a	***	*	34.3 c	12.5 e	12.9 e	13.4 e	**	*
HEI	X	1 a	1 a	1 a	-	-	10 f	x	10 f	10 f	-	-
PB[r]												
CC	35.9 d	33.7 de	34.7 e	32.7 e	**	*	31.5 de	38.6 d	41.4 c	34.6 c	NS	NS
IHP	93.9 a	99.4 a	98.8 a	100.0 a	**	*	43.5 c	53.4 c	72.5 c	65.2 c	**	*
HEI	1 a	1 a	1 a	1 a	-	-	x	4 d	2 b	x	-	-
Perlite												
CC	47.2 c	32.1 e	43.8 d	39.6 d	NS	NS	40.5 c	30.8 e	41.9 c	37.9 c	NS	NS
IHP	100.0 a	100.0 a	98.9 a	100.0 a	NS	NS	98.8 a	97.1 a	100.0 a	99.7 a	NS	NS
HEI	1 a	1 a	1 a	1 a	-	-	1 a	1 a	1 a	1 a	-	-
SPW[q]												
CC	44.3 c	40.7 c	47.4 c	47.6 c	**	**	48.9 b	54.5 c	46.7 b	52.1 b	NS	NS
IHP	81.9 b	94.6 a	95.4 a	96.1 a	***	**	63.8 b	61.3 c	90.6 ab	87.9 b	***	***
HEI	X	1 a	1 a	1 a	-	-	3 c	4 d	2 b	2 b	-	-
PWC[p]												
CC	35.9 d	35.3 d	36.3 e	37.9 d	**	**	36.6 cd	36.3 d	38.1 c	36.8 c	NS	NS
IHP	97.2 a	97. 8 a	95.3 a	97.1 a	NS	NS	59.5 b	76.0 b	76.1bc	74.7	**	*
HEI	1 a	1 a	1 a	1 a	-	-	5 e	5 e	2 e	2 b	-	-

[z] Wetting agent used was AquaGro®-L at either 0 (none; NWA), 116 (low; LWA), 232 (medium; MWA), and 348 (high; HWA) ml m^{-3}.

[y] CC= maximum MC by volume attained by sample.

[x] IHP= The percentage by volume of CC water that is sorbed in the substrate after the initial hydration event.

[w] HEI = number of hydration events required to bring treatment to CC.

[v] Statistics using a Tukey HSD with a=0.05 are given down columns for a given WA level and MC.

[u] Statistics using a Tukey HSD with a=0.05 are compared throughout the entire table.

[t] Linear regression significance test, NS= not significant, *** = p≤0.001, **=p≤0.01 *=p≤0.05.

[s] Quadratic regression significance test. NS= not significant, *** = p≤0.001, **=p≤0.01 *=p≤0.05.

[r] PB= loblolly pine (*Pinus taedea* L.) bark.

[q] SPW = Shredded loblolly pine (*Pinus taedea* L.) wood hammer-milled through 6.35 mm screen.

[p] PWC = Chipped loblolly pine wood hammer-milled through a 6.35 mm screen

Table 2. Particle size distribution of six traditional and alternative greenhouse substrate components[z].

	Substrate Component					
	Coir	Peat	Pine bark	Perlite	SPW[y]	PWC[x]
X-large[w]	0.2 c[u]	2.7 b	18.2 a	0.2 c	0.0 e	0.0 e
Large[t]	5.6 e	18.1 d	35.0 c	45.2 b	34.7 c	66.1 a
Medium[s]	30.2 b	27.6 bc	25.3 bc	21.4 c	45.6 a	27.1 bc
Fines[r]	64.0 a	51.6 b	21.5 d	33.2 c	19.7 d	6.8 e

[z] Particle size distribution determined by sieving through column of sieves for five minutes in a shaker.

[y] Shredded wood produced from hammer milling shredded loblolly pine (*Pinus taeda* L.) trees.

[x] Chipped wood produced from hammer milling chipped loblolly pine trees.

[w] X-large particles are larger than 6.3 mm in diameter.

[v] Values are means of percentages of total sample.

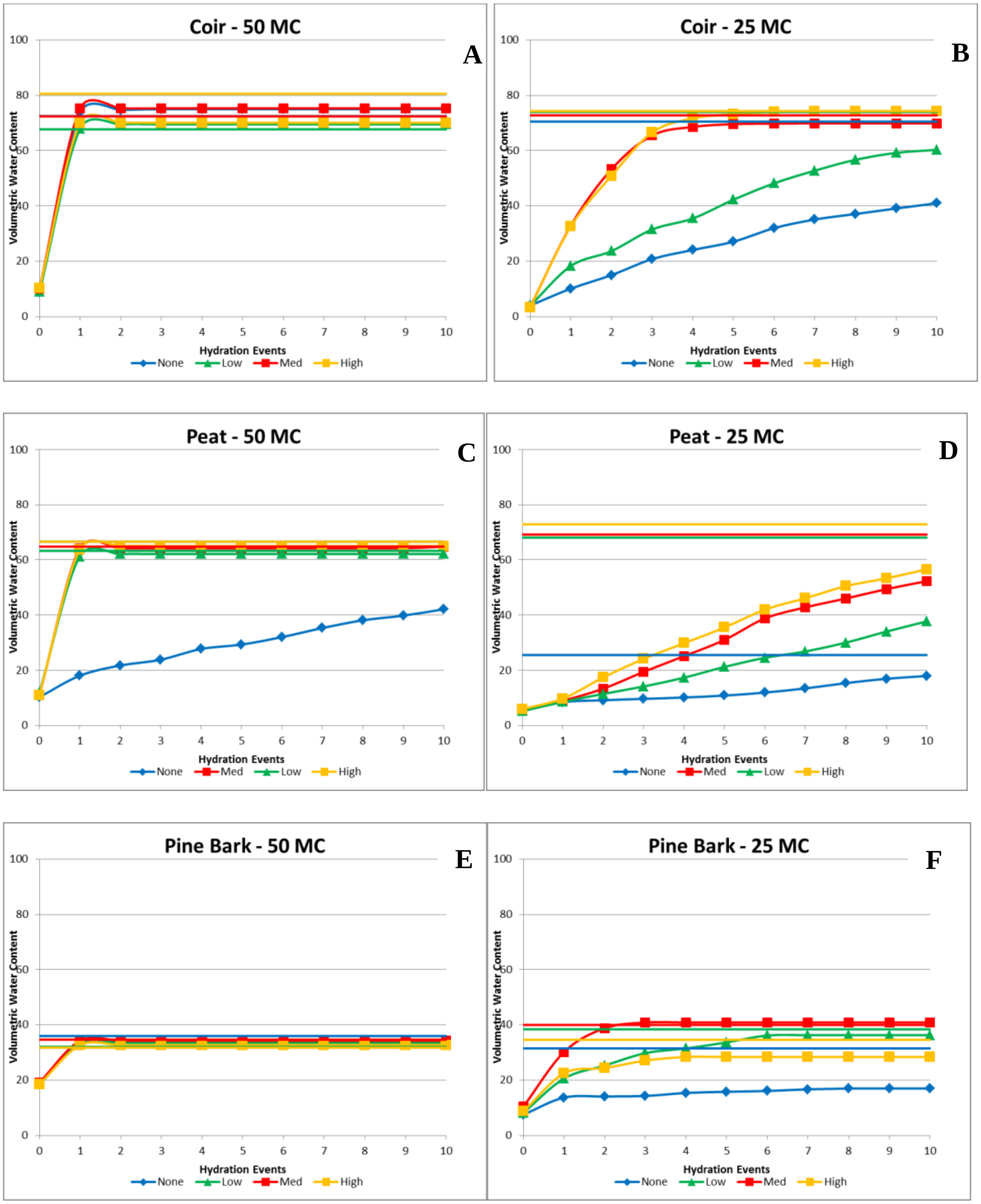
[u] Statistics are determined across rows using a Tukey's HSD in order to determine differences and similarities amongst different components within a particle size fraction

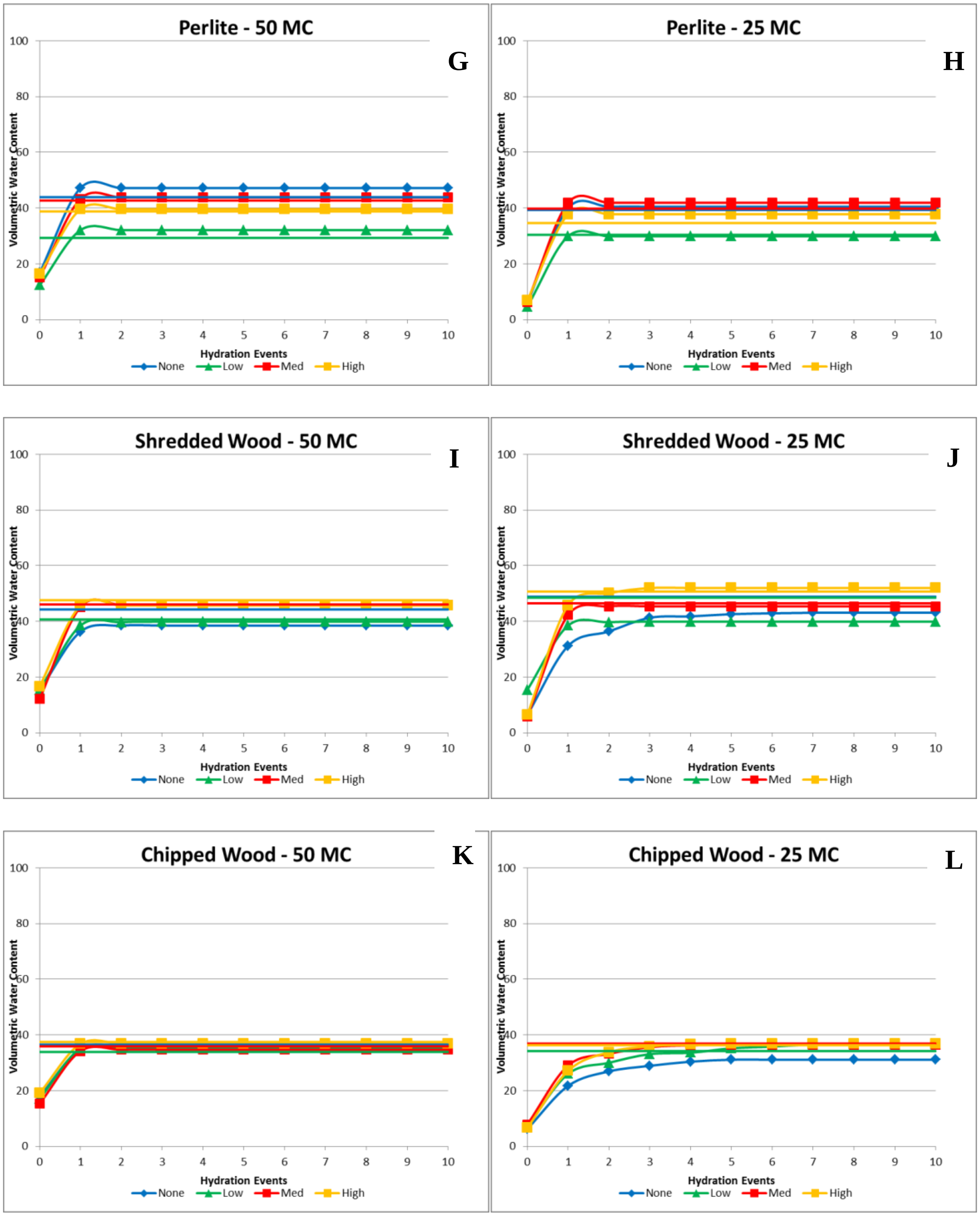
[t] Large particles are smaller than 6.3 mm and larger than 2 mm in diameter.

[s] Medium particles are smaller than 2 mm and larger than 0.5 mm in diameter.

[r] Fine particles are under smaller than 0.5 mm in diameter.

Figure 1. Wettability curves at four different wetting agent levels (none, low, medium, and high) and container capacity lines for A) Coir at 50% MC, B) Coir at 25% MC, C) Peat at 50% MC, D) Peat at 25% MC, E) Pine bark at 50% MC, F) Pine bark at 25% MC, G) Perlite at 50% MC, H) Perlite at 25% MC, I) Shredded wood at 50% MC, J) Shredded wood at 25% MC, K) Chipped wood at 50% MC, and L) Chipped wood at 25% MC.

Coir - 50 MC
A
Coir - 25 MC
B
Peat - 50 MC
C
Peat - 25 MC
D
Pine Bark - 50 MC
E
Pine Bark - 25 MC
F
Volumetric Water Content
Hydration Events
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10
None
Low
Med
High


Perlite - 50 MC
G
Perlite - 25 MC
H
Shredded Wood - 50 MC
I
Shredded Wood - 25 MC
J
Chipped Wood - 50 MC
K
Chipped Wood - 25 MC
L
Volumetric Water Content
0
20
40
60
80
100
Hydration Events
0 1 2 3 4 5 6 7 8 9 10
None
Low
Med
High

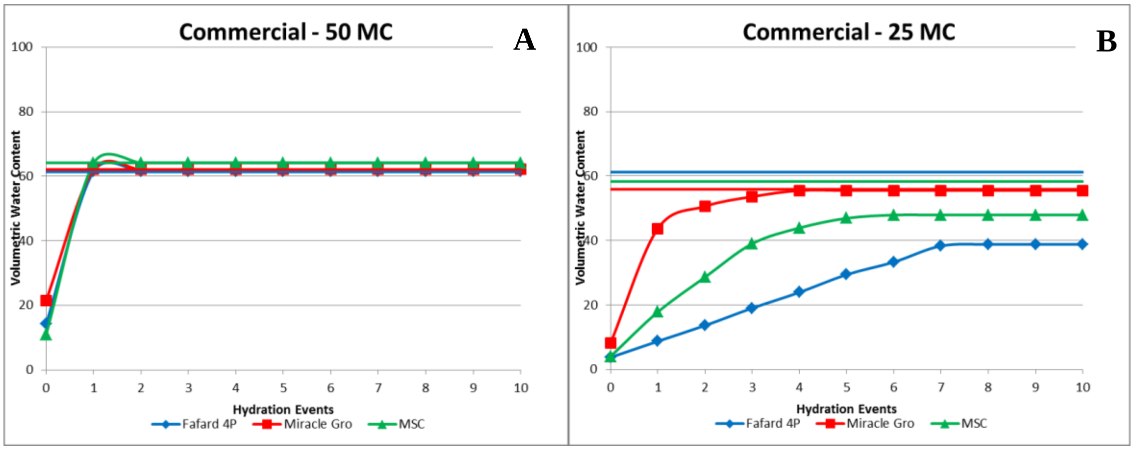


Figure 2. Wettability curves for three substrate mixes at (A) 50% initial moisture content, and (B) at 25% initial moisture content