ABSTRACT

EDWARDS, RACHEL MARIE. Hydrology and Plant Response to Wood Products in Soilless Substrates (Under the direction of Dr. Brian Jackson).

The floriculture, greenhouse, and nursery industries all rely on quality horticultural substrates to produce optimal crops in containerized production systems. The horticulture production industry research priorities focus on identifying alternatives to the traditional substrate materials of peat moss and perlite. The restrictions for harvesting peat moss from peat bogs tighten as the concern with climate change and greenhouse gases increase. These wetland peat bogs only take up 3% of the earth’s surface but they hold 15-30% of the world’s soil carbon.

One alternative material that has been proposed in areas with a significant timber industry is wood based substrates. In order to answer questions surrounding wood-based potential substrate materials, twenty different materials and mixtures were analyzed for physical and hydrological properties. The main substrate materials analyzed were three different types of wood substrates, two different types of peat moss, and horticultural grade perlite. ForestGold is a disk-refined wood substrate from Pindstrup, GreenFibre is a screw extruded wood substrate from Klassman-Deilmann, and the other wood substrate was a hammermilled pine tree substrate (PTS) produced on the campus of NC State University with freshly harvested Pinus taeda L. (loblolly pine). The Sphagnum peat moss utilized in these trials was sourced from Canada, as well as one source from Europe (Germany). Horticultural grade perlite was also evaluated individually as well as in mixtures with 80% and 60% Canadian sourced peat moss. The wood substrates were mixed with the Canadian peat moss at ratios of 20%, 40%, 60%, and 80% and evaluated. The ForestGold and PTS were mixed with Canadian peat moss at 15% and 30% wood substrate and compared to the same ratios of peat and perlite mixes in mini-horhizotrons. Root growth of
*Euphorbia pulcherrima* Willd. ex Klotzsch (poinsettia) ‘Astro Red’ and ‘Charon Red’ was evaluated as well as *Chrysanthemum morifolium* L. (mum) “Gigi Yellow” and “Kathleen Dark”.

The results show that the wood substrates have different properties and effects on plant grown depending on their processing techniques, but all substrates can effectively serve as a substitute for perlite in a peat:perlite (peatlite) mixture for adequate root growth. The results also suggest that the source of peat moss will greatly determine its physical properties because of different harvesting techniques and chosen particle size during processing. Of all the wood substrates tested in this study, the greater ratio of hammermilled PTS had the most water holding capacity and had the fastest root growth for the *Euphorbia pulcherrima* Willd. ex Klotzsch in mini-horhizotrons for the first four weeks of root growth. This suggests that wood substrates, specifically PTS, can produce similar if not optimal crop growth to peatlite substrates.
Hydrology and Plant Response to Wood Products in Soilless Substrates

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Horticultural Science

Raleigh, North Carolina
2020

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DEDICATION

I want to dedicate this work to my family.

My grandparents, Herbert and Joy Frazier, have been dedicated to bringing fresh produce to our family my entire life, and I greatly admire that. Growing up, I wanted to be just like grandpa and know all the names of all the trees in the forest. The summertime was for road trips to Raleigh, NC, to harvest grandpa’s vegetables and see grandma’s flowers thriving and blooming. They shaped me into who I am today by fostering my love for nature and botany.

To my mother, Angela Edwards, for instilling a scientific curiosity in me from a young age and always answering my endless “Why?” questions about the natural world around me. On my 8th birthday, my mom bought me a microscope which I used to observe samples of pond water from down the street. I was fascinated with the concept of the microscopic world because of your enthusiasm for your field of science and I knew that one day, I wanted to be just like you.

To my father, Michael Edwards, who has always taught me so much about appreciating life and the beauty in it. From protecting the 1 strawberry in our backyard garden, to the 1 sunflower we got to bloom the summer before I left for college, thank you for always supporting me and helping me grow my own happiness.

And lastly, to my grandparents Clarence and Doris Edwards whom are greatly missed. My grandmother Doris’s love for plants certainly rubbed off on me before I even knew it.
BIOGRAPHY

In the 1980’s Angela Frazier and Michael Edwards went to NC State University together. After graduation Angela pursued a Masters in Microbiology and Michael pursued his Masters in Architecture. After school, they married, and a few years later in 1996, Rachel Marie Edwards was born in Charleston, South Carolina. Rachel was a mixture of her parents with a passion for both art and science. She enjoyed living by the beach for 18 years until she went to college at Clemson University in 2014. After 2 years of spending some time as a general biology major and in nutrition sciences, Rachel went to speak with a career counselor at the Clemson career center in search of something more fulfilling. Once she was introduced to department of Horticulture Science and toured through the campus greenhouses, she switched her major the next day. In her second semester in Horticulture science Rachel not only became Clemson Horticulture club president, but also began working as a floriculture research assistant for Dr. Jim Faust. This three-semester long experience sparked her love for horticultural research. She aspired to focus on medicinal plants and in her last semester of undergrad she went to the New England Cannabis Conference in Boston where she realized there was a huge need for horticultural research in this industry. Rachel graduated from Clemson University with her Bachelor of Science in Horticulture Science with two minors in Biological Sciences, and Sustainability in the spring of 2018. When she got the opportunity to pursue graduate school and work under Dr. Brian Jackson, who has an active role in current cannabis cultivation research, she was thrilled to start her Master of Science at NC State University in the fall of 2018. Excited about the opportunity to work with the new Hemp crop, Rachel also knew her passion for sustainability would be fostered through this program that provides essential research for the use of more environmentally
friendly horticultural substrates. She had an interest in hydrology with hopes of understanding water conservation within containerized horticultural production.
ACKNOWLEDGMENTS

To my incredible family, thank you for all your love, support, and encouragement. Mom, thank you for being the scientist I have always looked up to, for being a great role model, and for always proof-reading my writing! Dad, thank you all your love, support, and for teaching me about art and how it affects people, much like the art of horticulture. My big brother, Anthony, thank you for spending our childhood outside with me and always being there for me. Papa and Gram, I have cherished these two years living in Raleigh with you, thank you for sharing your garden with me and for all the lunch dates! To my boyfriend, Jason Porter, and our dog, Storm; my little family, thank you for welcoming me home each day with open arms and wagging tails, always supporting me through it all. Jason, thank you for helping me collect data, and proof reading my writing. Also, thank you to Jason’s family for all their love and support!

To Dr. Helen Kraus and Emily Anderson with the Flourish Horticultural Therapy program, thank you for introducing me to this amazing outreach opportunity, exposing me to a new passion of mine, and for all your friendship and support this past year. Also, thank you to Kimberly McAllister and Diane Mayes for being a part of Flourish, I will always cherish our friendship and times in the NCSU conservatory! Thank you to Amalie Lyday for her friendship and shared interest in the new hemp crop. Thank you to Dr. Lori Snyder for fostering my passion through mentoring me in hemp seed research. Thank you to Elisabeth Meyers for your friendship, support, and being the best teaching mentor; I am so grateful that I was your TA. Thank you to Kerry Olive, William Reece, and Diane Mayes for their assistance in the greenhouses. A big thank you to Brian Schulker and Jake Hudgins who helped me collect data, as well as Lesley Judd and Laura Barth who helped me with statistical analysis! Thank you to
Dr. Gunter and Dr. Heitman for their guidance and support with being on my committee. Finally, and most of all, thank you to Dr. Brian Jackson for making this opportunity possible!
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CHAPTER ONE

Literature Review
Containerized Horticultural Production

Containerized plant production dates back as far as the Egyptians almost 4,000 years ago when they would bring different species of citrus trees to the king and containerize the non-native species that would struggle in the native soil (Naville, 1913; Raviv et al., 2019). In the temple of Hatshepsut, Deir el-Bahari, near Thebes, Egypt, there is an image of citrus trees being brought to the temple in containers (Naville, 1913; Matkin et al., 1957; Raviv et al., 2019). Even though containerized plant production has been practiced/utilized for centuries to bring the wealthy peoples of the time specialty food crops, they mostly utilized mineral soils as their container medium. Research and development of specialized horticultural substrates to be utilized in these modern containerized production systems has only recently begun. Modern horticultural substrates do not contain mineral soils and are rather highly engineered organic and inorganic materials. It wasn’t until the 1970’s that research began to use and explore the properties of soilless substrates such as air space, water holding capacity, and chemical properties that effect nutrient absorption and overall plant growth (Cooper, 1975; Raviv et al., 2019; Verwer, 1976).

Floriculture is a major economic driver in the United States with a 4.77 billion dollar valuation in 2018 from just the 15 top producing states of floriculture crops (U.S. Department of Agriculture; USDA, 2019). This is up 9% since the 2015 valuation of the top 15 floriculture crop producing states which reported 4.37 billion dollars (USDA, 2019). The money made from sales of specialty horticultural crops (including vegetables, sod, transplants, floriculture crops, etc.) in 2014 was 13.8 billion dollars. The actual number of floriculture producers has also increased by 8% and the actual area of land being utilized for floriculture production in the United States has increased by 12% since 2015 (USDA, 2019). All these thriving industries are
utilizing soilless substrates in order to produce optimal crops in these containerized production settings. These large industries are why horticultural substrate research is so applicable and necessary as more commercial products appear on the market. It is essential for growers to understand the properties of horticultural substrates and how they may need to alter their growing practices in order to transition to different substrate materials in their container production system.

**Horticultural Substrates**

Traditional substrate materials include inorganic materials such as perlite and vermiculite, and organic materials such as sphagnum peat moss, and pine bark (Baker, 1957). The University of California began introducing these types of organic substrates for containerized crop production in the 1950’s (Baker, 1957). This type of containerized production with organic substrates became known as the ‘UC System’ (Baker, 1957). The first substrate to be made and sold in America as an alternative to topsoil for container crops was developed as a ‘peat-lite’ mix at Cornell University in 1960, which has today become a common substrate for the floriculture industry (Baker, 1957; Owen et al., 2012). Pine bark has been utilized specifically in outdoor nursery production systems for decades and is typically aged to increase the number of fine particles. This alters the substrate physical properties to increase the water holding capacity (Bilderback et al., 2013).

Peat moss is harvested from wetlands of organic rich, decaying plant material called peat bogs. Today there is much concern with the protection of peat bogs because of their vital role in the carbon sequestration and possible role in combating climate change (Limpens et al., 2008). There are tightening restrictions on how peat can be harvested in order to preserve the peat bog itself. More floriculture and greenhouse growers are looking for more reliable and sustainable
alternatives. New research on horticultural materials for alternative substrates must be provided to the industry of greenhouse growers as they start to change their substrates to something more economically and environmentally friendly.

*Organic substrate: peat moss*

Sphagnum peat moss consists of decomposed plant matter in large wetland bogs that are located in specific parts of the world such as Canada (Bragg, 1990; Jones, 2012). This material has become the main substrate in the horticultural industry for years because of its ideal physical properties such as air space, water holding capacity, and total pore space (Bragg, 1990). The chemical properties are also ideal for horticultural production because dissolved salts and electric conductivity (EC) are naturally low, and this means that a specific fertilizer regime can be implemented for specific crop nutrition needs (Bragg, 1990). The only alteration that sphagnum peat moss requires in order to produce successful crops is a pH adjustment by adding limestone to counteract the natural acidity of the material (Boodley & Sheldrake, 1973). The wetland peat bogs only take up 3% of the earth’s surface but they hold 15-30% of the world’s soil carbon (Limpens et al., 2008). In order to preserve these bogs, there are tight restrictions on how and when peat moss can be harvested. The floriculture and greenhouse industries will seek out more reliable horticultural substrates as alternatives that may be economically beneficial.

*Inorganic substrate: perlite*

Perlite is heat-expanded volcanic rock that is made in a similar process to popcorn where the rock is heated until it expands. It is similar to pumice in that it comes from a volcanic rock, however, a heat treatment makes perlite much lighter in weight (Dunn and Billinghurst 1954; Morrison et al., 1960; Thompson and Read 1954). Morrison et al., 1960 studied plant growth in substrate containing 100% perlite and found that with its adequate air space and water holding
capacity combined with an adequate nutrient supply, perlite provided a suitable root environment for short term crops. (Morrison et al., 1960). The structure of perlite when included in substrate mixes increases air space, drainage, and porosity so naturally it became a popular additive to sphagnum peat moss in order to avoid over saturated containers with inadequate air space for root growth (Savvas et al., 2013). Perlite has become increasingly expensive in recent years since the cost of transportation has gone up and the main producers of perlite are not in the United States (Owen et al., 2012). This has caused some growers to seek cheaper alternative horticultural substrates for their floriculture or greenhouse operations.

*Alternative organic substrate: coconut coir*

Coconut coir is an alternative substrate to sphagnum peat moss made from the mesocarp of *Cocos nucifera* L. (coconut) and is a natural byproduct of the coconut industry. This material must be processed multiple times with different treatments to become suitable for plant growth and can be heavy therefore difficult and expensive to transport (Carlile et al., 2015). Coconut Coir can be sourced from many different areas of the world, but primarily it comes from Sri Lanka, India, the Philippines, Indonesia, Mexico, Costa Rica, and Guyana (Konduru et al., 1999). Konduru et al. (1999) found that the chemical properties of coconut coir vary vastly across the different sourcing areas. Not only does the area that coconut coir is sourced from effect its properties, but the way it is processed is very important to the substrate performance as well. Konduru et al. (1999) found that when coconut coir is processed with a screen it has significantly different physical properties such as total pore space, total air space, water holding capacity, bulk density, etc, when compared to waste grade coconut coir which is unscreened. This shows the importance of substrate sourcing, processing, and engineering to the physical and chemical properties that will ultimately determine the success of plant growth.
Wood-based horticultural substrates

Drotleff (2018) showed that organic wood substrates mixed in at the ratio of 20% - 40% with other types of horticultural substrates are gaining popularity in the United states. Gruda (2012b) notes that wood fiber substrates are more advanced than ever, with chemical and physical properties being optimized for plant growth over the last 10 years in Europe. Gruda & Schnitzler (2000) examined transplants grown in 100% wood fiber substrate and found that the bio-morphological characteristics of the plants were the same of the control substrate, as long as adequate irrigation was supplied as with any course substrates. Wood fiber substrate manufacturers should be able to assist growers in utilizing and managing their specific product in container crop production depending on their products physical, structural, and chemical characteristics (Jackson, 2018). This is why further research to fully understand the differences between these products is so important to the horticulture industry.

Tree species utilized

*Plantanus occidentalis* L., also known as sycamore trees have been chipped and used as a horticultural substrate for many years in Europe (Gruda & Schnitzler, 2004). Many different species of wood have been analyzed to find the optimal species for horticultural substrate use. Murphy et al. (2011) preformed a study on three different species of economically low-value trees. These species included *Liquidambar styraciflua* L. (sweet gum), *Carya tomentosa* (Poir.) Nutt. (hickory), and *Juniperus virginiana* L. (eastern red cedar) and they found that the eastern red cedar preformed comparably to perlite, while the others exhibited a lesser performance (Murphy et al., 2011). When other tree species were analyzed for their suitability as a substrate, plant growth was found to be lowest in *Acer rubrum* L. (red maple) and *Quercus alba* L. (white oak), intermediate in sycamore and *Pinus strobus* L. (white pine), and highest in *Pinus taeda* L.
loblolly pine) (Rau et al., 2006). Sycamore was similar to that of loblolly pine for the first two weeks but then declined due to decomposition of the wood fiber, which lead to nitrogen immobilization (Rau et al., 2006). Bilderback et al. (2013) suggest that loblolly pine can be utilized without processing or aging and still avoid phytotoxic effects that could potentially damage plant growth. This ideal characteristic combined with the easy accessibility of loblolly pine in the southeastern united states makes it an optimal horticultural substrate.

Pine bark versus whole pine tree

Loblolly pine is a suitable species for plant growth, but there is a difference in physical properties depending on which part of the tree is being utilized. Pine bark has been used in nursery systems for many years (Bilderback et al., 2013). Whole pine tree substrate is made ustalizing the entire tree (limbs, pine needles, bark, wood, etc.) When pine bark substrates were compared to whole pine tree substrates for plant propagation, it was found that a range of species of plants can be propagated in 100% pine tree substrates whether it be pine bark or whole pine tree substrate (Witcher et al., 2014). However, the addition of peat moss to either wood fiber greatly increased the root length, likely due to the water holding capacity of peat moss (Witcher et al., 2014). They also found that pine bark substrate combined with peat moss would increase container capacity and produce the most shoot growth compared to whole pine tree mixed with peat or the wood substrates alone (Witcher et al., 2014). Pine tree substrate (PTS) referrers to wood that has been processed from only pine wood, and this is the main material this thesis is focused on.

Processing Horticultural Wood Substrates

Jackson (2018) states that the three most common ways wood substrates are being process are 1) single or twin-screw extrusion 2) twin disk-refined or 3) hammermilled which all
produce completely unique products of wood fiber. The differences between products include
different fiber thickness, chemical, and physical properties (Jackson, 2018). Wood fiber made
through screw-extrusion is typically easier to blend with other substrate materials, while the
wood fiber made with a twin disk refiner is more difficult to blend because of the way it is
compressed (Jackson, 2018). However, the twin disk refined wood substrate can be more easily
compressed into bales for shipping or can be pressed into sleeves for hydroponic production
(Jackson, 2018).

Whether the pinewood is shredded into fiber-like cotton material or made into individual
chips will have a big impact on its properties. When pinewood is shredded it has a higher total
porosity and provides more easily available water to plants when compared to pinewood chips
(Fields et al., 2014). The shredded pinewood was designed to retain water like peat while the
pine chips acted similar to perlite to allow drainage. However, it was found that the drainage of
both substrates was greater than coir or peat because of the lack of fine particles (Fields et al.,
2014). When the different pine tree substrates were individually mixed with peat as a perlite
replacement and compared to peat-lite mixes, it was found that the pine tree substrates had a
larger impact on water retention dynamics and drainage (Fields et al., 2014).

A study was done to analyze pine chips ground with different size screens, which create
different size pine chips (Saunders et al., 2006). Marigolds were grown in different pine chip
substrates and the pine chips with the 1.59 mm screen had the highest dry weights while the pine
chips made with a 6.35 mm had dry weights that were significantly lower (Saunders et al., 2006).
Substrates made with a smaller screen typically had a higher pH, EC, and nutrient holding
capacity compared to those made with a larger screen (Saunders et al., 2006). The finer material
wood made with a smaller screen had a much higher affinity for water which leads to better
nutrient holding capacity and more plant available water (Saunders et al., 2006). This study showed that pine chips that are processed properly in the right size range could be an appropriate substrate for short-term crops.

Besides the difference in the physical part of wood that is being used as a substrate, the way the wood is processed is very important for physical and hydrological properties. When thinking about wood substrates, it is difficult to define what exactly a wood “fiber” substrate is vs other wood substrates. Maher et al., (2008) defined wood fiber as any wood material that undergoes secondary processing after the initial wood chipping process. The initial wood chipping process can be performed with a variety of screen sizes for a variety of particle sizes. This initial process created extremely high temperatures and produces output that is completely stable and sterile (Gruda and Schnitzler, 2004; Maher et al., 2008; Schmilewski, 2008).

**Production alterations for wood substrates**

When looking at pine tree-based substrates, some traditional horticultural practices may need to be slightly altered for optimal plant production, especially depending on the production time. Chrysanthemums were grown to compare peat lite mixes with pine wood mixes, and it was found that EC and nutrient levels were significantly higher in peat lite mixes when given equal amounts of fertilizer (Wright, Jackson, B. E., Browder, & Latimer, 2008). The pine tree substrate is more susceptible to microbial decomposition and immobilization of nitrogen due to the high organic content. When pine wood substrates were analyzed over time and compared to pine-bark substrates, it was found that nutrient levels and EC levels were generally higher in pine bark (Jackson, Wright, & Seiler, 2009). The pine wood substrate also had a higher CO₂ flux that showed a greater microbial decomposition over time, which could explain the lower CEC and nutrient concentrations. However, the fertilizer rates did not exacerbate the decomposition of the
wood-based substrates over two growing seasons (Jackson et al., 2009). The shrinkage of both
the pinewood and pine bark substrates was the same with plants grown in it over the two full
growing seasons as well (Jackson et al., 2009). Another chemical component of wood-based
substrates to take into consideration is the pH. Even though wood materials have an inherently
higher pH than peat or perlite, when mixed with majority peat moss it is still necessary to add the
proper amounts of limestone to adjust the pH to the appropriate level for plant growth (Jackson
et al., 2009). However, this lessens the amount of lime needed for a wood–peat mix to become
the proper pH when compared to the more acidic peat-perlite mix (Jackson et al., 2009).

With proper adjustments, the wood fiber substrates have been shown to provide an
equally comparable root environment to traditional horticultural substrates (Gruda & Schnitzler,
2004). Gruda & Schnitzler (2006) saw that wood fiber substrate have suitable physical and
chemical properties to be a peat moss substitute. Gruda & Schnitzler (2004) suggest that the
wood fiber substrate should be compressed slightly into the container when filling in order to
increase the bulk density of the substrate and provide more water holding capacity. Gruda &
Schnitzler (2006) suggest that 30% wood fiber should be used with other substrate materials to
prevent degradation. Further research can provide many practical adjustments such as these that
can greatly assist growers in transitioning to new wood fiber horticultural substrates.

**Hydrological properties of substrates and plant growth**

Substrate material greatly influences hydraulic plant relations through chemical and
physical characteristics. Root hydraulic conductance is defined as the effort it takes for water to
move throughout a plants root system depending on pressure and water potential (Judd et al.,
2016). Judd et al., (2016) evaluated hydraulic conductivity in container crops with a hydraulic
conductance flow meter, which is traditionally used in intact root systems of field crops. When
tested on chrysanthemums, it was found that different substrates did create a difference in root biomass but no difference in hydraulic conductivity of the root systems (Judd et al., 2016). This shows that even though the hydraulic conductivity doesn’t necessarily change between substrates, the substrate can still cause differences in the overall growth of the plant root system. Another study examined aged *Pinus taeda* that was processed into different size particles and combined with sphagnum peat or coir to make 7 different substrates that were studied during the production cycle of *Hibiscus rosa-sinensis* ‘Fort Myers’ (Fields et al., 2018). The purpose of this study was to examine the differences in substrate hydraulic conductivity and its effect on plant water usage. The higher the hydraulic conductivity the more water the plant’s roots can pull from the substrate, therefore the substrates with higher hydraulic conductivities are able to utilize more of the substrate solution (Fields et al., 2018). When water potential was monitored to stay in the optimal range of -50 to -100 kPa, they found that plants could be produced with less than 18L of water (Fields, Owen et al., 2018). This suggests that substrates can be engineered to reduce the amount of irrigation needed for production.

Yap et al., (2013) grew *Catharanthus roseus* 'Cooler Deep Orchid' and *Tagetes patula* 'Janie Deep Orange' in different substrates and then analyzed for their water potential at three different stages of wilting. Water potential was determined with a dew point potentiometer. *Catharanthus roseus* went to much lower tensions of water potential before wilting compared to marigolds. All plants were re-hydrated after they reached the 3rd wilting stage and all plants were able to recover after 24 hours, even though they had reached tensions equivalent to their permanent wilting points (Yap et al., 2013). There is also a great deal of variation for permanent wilting point between species, which is why it is important to further research the role of substrate in post-harvest environments with different crops. A study by Guo et al., (2018)
examined the differences in post-harvest quality of poinsettias when grown with substrate sustained at 20% moisture content and with 40% moisture content. The plants grown in 20% moisture content had shorter bracts and stems when compared to the 40% but total bract, leaf number, and bract thickness were not affected (Guo et al., 2018). The 40% moisture plants abscised more bracts during post-harvest and had more bract edge burn. Overall, it was found that not only did the reduced moisture content produce more compact plants with better postharvest quality, but it could also cut irrigation, fertilizer and labor costs almost in half. More research should be done to fully understand proper irrigation ranges for different soilless substrates so that growers can be more conscious of their water usage and general inputs.

**Physical and Chemical Substrate Properties**

Many studies have been conducted to identify the qualities that make a substrate suitable for plant growth. These qualities include physical characteristics such as pore space, air-holding capacity, bulk density, and particle size distribution, as well as hydraulic conductivity and water retention (Barrett et al., 2016). Ideal substrates for plants will also have proper chemical interactions typically measured by pH, cation exchange capacity (CEC), and nutrient availability. A good substrate also has to be practical for the grower to obtain and use, which is why peat is a common material used for substrates. Not only is it abundant and very easily transportable due to its low bulk density, but it requires very little processing to obtain these ideal physical and chemical characteristics (Barrett et al., 2016).

Container capacity (CC) of a substrate is the amount of water a substrate can hold within a specific container size. The plant available water (PAW) referrers to the water that exist before permanent wilting point (PWP = -1.5Mpa) is reached in the rhizosphere during the substrate dry-down process. The PAW and CC of a substrate greatly
depend on the geometric shape of the container (Bilderback and Fonteno, 1987; Milks et al., 1989). The physical properties of a substrate such as CC, air space, and total porosity can be found for any substrate material or mix using the NCSU porometer method (Fonteno et al., 2010). These are good parameters to understand the physical properties of a substrate that will affect PAW.

**Root Growth Evaluation Techniques for Substrate Research**

The root system of a plant is an essential part of plant health and there are many different methods developed to observe plant roots. There are large underground glass windows that allow viewing of root structures of plants in the landscape called “Rhizotrons” as well as tiny glass tubes with a viewing device that can be stuck underground to observe the roots called a “mini-rhizotron” (Taylor et al., 1990). The advantage of this type of observation method is being able to see root length increases over time with successive measurements and applying sensors to monitor conditions and tracking the root growth with time-lapse photography can provide a lot of information about optimal crop production (Taylor et al., 1990). These are examples of subjective root measurements and these often depend on the root-system examiner (Wright and Wright, 2004). The only non-subjective way to evaluate roots is to get a physical dry weight of the root system after removing it from the field or container. The traditional root-washing technique has challenges since it is nearly impossible to collect every root while also trying to fully wash away the substrate or soil intertwined in the roots themselves (Aung, 1974). It has been shown that when using this method of dry weight measurements there can be a 20% - 40% loss of dry weight material in the washing process depending on the researcher doing the root washing procedure (Oliveira et al., 2000; van Noordwijk and Floris, 1979). This method of root
evaluation is not only destructive but it only allows for evaluation at the end of the growing process rather than allowing for observation over time.

Another disadvantage of the rhizotron is the expense of the construction and operation of the facility itself, and that the roots against the glass may not be completely representative of the full root system (Taylor et al., 1990). The Horhizotron™ was developed as a smaller, more manageable and representative way to observe early root development over time in nursery or greenhouse container crops by Auburn University and Virginia Tech University (Wright and Wright, 2004). This device has eight clear side walls that have shade panels which can be lifted up to reveal the undisturbed root system underneath. Two of the glass walls on each side of the quadrant represents the root structure of that quadrant of the rhizosphere (Wright and Wright, 2004). The researcher can observe and record the length of the 5 longest roots on each glass panel in order to analyze the root growth over time (Jackson et al., 2005; Price et al., 2009; Wright and Wright, 2004). This method was later developed into a smaller box with six glass panels in a triangular shape designed for smaller floriculture crops grown in six-inch containers. This is known as the mini-horhizotron, similar to the name and design of the original horhizotron™ (Wright and Wright, 2004). Judd (2014) used these mini-horhizotrons to study early root growth over time of three different crops in three different substrates. It was found that the plants grown in mini-horhizotrons had little to no differences between plants that had been grown in six-inch containers. (Judd et al., 2014). It was also found that the early root growth did differ between substrates but would have been undetectable at the end of the production cycle if the roots had only been evaluated with a root-wash dry weight (Judd et al., 2014). This shows that the observation method utilizing the mini-horhizotron is a good tool to study different types
of horticultural substrates since the root system can be observed as it develops over time after transplantation of the plug, rather than one destructive harvest at the end for root-washing.
Literature Cited


CHAPTER 2

Characterization of hydro-physical properties for substrate mixes containing various types of pine tree substrate produced by different processing methods.
Abstract

The nursery, greenhouse, and floriculture industries mainly involve containerized plant production. For decades, peat moss and pine bark have been the principle substrates used in these industries but recent advancements in wood fiber engineering have led to many commercial wood-based substrate offerings. The type of processing method performed on these different wood products will greatly affect their physical and hydrological properties. Two common commercial wood substrates from Europe were analyzed in this study and included ForestGold (disk-refined) and GreenFibre (screw-extruded). A hammermilled pine tree substrate (PTS) was also evaluated. These wood substrates were analyzed at 100%, as well blended with peat moss in ratios of 80%, 60%, 40%, and 20%. Canadian peat moss was evaluated individually at 100% and compared to 100% European sourced peat. A 100% perlite was also evaluated individually as well as in mixtures with 80% and 60% Canadian sourced peat moss. A total of 20 substrates were analyzed through the NCSU porometer method for physical properties, and the saturated hydraulic conductivity (Ksat) was obtained utilizing the procedure and equipment described by Drzal (1994). Moisture retention curves were created for each substrate utilizing Volumetric Pressure Plate Extractors. The results showed that the European peat and GreenFibre wood were the most similar to perlite, while PTS was more similar to Canadian peat in its water release patterns. Canadian peat had the highest water holding capacity of all the substrates, and ForestGold had the least water holding capacity. ForestGold also had the most air space, total porosity, and highest saturated conductivity. The reason the Canadian peat had a higher water holding capacity compared to European peat was because it contained significantly more fine particles than European peat. These results also display how the differences in wood substrate
processing techniques will greatly affect the physical and hydrological properties of horticultural substrates.
**Introduction**

Floriculture production in the United States has recently increased by 8% and the actual area of land being utilized for floriculture production in the United States has increased by 12% since 2015 (USDA, 2019). Over 85% plants grown in the greenhouse and nursery industries are grown with soilless substrate in containers (USDA, 2009). These industries are utilizing substrates in order to produce optimal crops in a containerized production setting. There is current interest in developing new sustainable, organic substrate materials for the horticultural industry. One of the main products of interest and promise being wood materials. Gruda (2012b) explores the advancement of wood fiber substrates throughout the decade and highlights the improvements and physical and chemical characteristics. Bilderback et al. (2013) suggest that the species *Pinus taeda* L. (loblolly pine) is an ideal substrate medium, especially for the southeastern United States with an active timber industry. Gruda & Schnitzler (2000) showed that wood substrates were a suitable alternative to traditional substrate materials for horticultural production. Gruda & Schnitzler (2006) suggested that 30% wood fiber should be combined with other types of substrates to optimize production and prevent degradation. However, more research needs to be conducted in order to characterize the effects of these percentages and ratios on hydrophysical properties of wood-based substrates.

The part of the tree that is processed for substrate also has to be considered when thinking about wood substrates. When pine bark substrates were compared to whole pine tree substrates, it was found that pine bark substrate combined with peat moss would produce a greater container capacity (CC) compared to whole pine tree mixed with peat (Witcher et al., 2014). Besides the difference in the physical part of wood that is being used as a substrate, the way the wood is processed is very impactful on physical and hydrological properties. It is difficult to define what
exactly a wood “fiber” substrate is vs other wood substrates. Maher et al., (2008) defined wood fiber as any wood material that undergoes secondary processing after the initial wood chipping process. This further processing creates extremely high temperatures and produces output that is completely stable and sterile (Gruda and Schnitzler, 2004; Maher et al., 2008; Schmilewski, 2008). In 2018, Jackson stated that the three most common ways that wood substrates are being processed for horticultural use are 1) single or twin-screw extrusion 2) twin disk-refined or 3) hammermilled and each method of processing produces completely unique products of wood fiber substrate. These unique structures create unique different hydro-physical properties that have yet to be distinctly defined for different types of processing methods of wood substrates. Jackson (2018) says that the screw extruded, and disk refined wood substrates are already being utilized throughout Europe. As the horticultural industry searches for sustainable alternative substrates, more research is needed to determine the physical and hydrological properties influenced by the different processing methods of wood-based substrates.

Pine wood that is processed by shredding has a higher total porosity and provides more easily available water to plants when compared to pinewood chips (Fields et al., 2014). It was found that the drainage of both substrates was greater than coir or peat because of the lack of fine particles (Fields et al., 2014). It was also found that pine tree substrates had greater water retention compared to perlite in a peat moss mixture (Fields et al., 2014). Different size pine chips can be created with different screen sizes and this causes difference in the physical properties of the substrate due to the particle size distribution (Saunders et al., 2006). Substrates made with a smaller screen typically had a higher pH, electrical conductivity (EC), and nutrient holding capacity compared to those made with a larger screen (Saunders et al., 2006). This is because the larger materials create macro pores which allow more drainage and less water.
retention. The finer material wood made with a smaller screen had a much higher affinity for water which leads to higher CC (Saunders et al., 2006). This study showed that pine chips which are processed properly in the right size range could be an appropriate substrate for short-term crops, and more research should be done on horticultural substrate particle size distribution to understand their hydrological properties.

Several substrate hydro-physical properties can be explained with the generation of a moisture retention curve (MRC) which were first described by Bunt (1961). MRC’s show the amount of moisture released by the substrate when subjected to suction forces and shows the amount of tension created by the adhesion and cohesion forces of the water. MRC’s allow for the observation of many important hydro-physical properties such as CC, air space (AS) easily available water (EAW), and water buffering capacity (WBC; de Boodt and Verdonck, 1972). Saturated hydraulic conductivity ($K_{sat}$) refers to the steady infiltration rate (cm/min) at which water percolates through the substrate during complete saturation. A head of water accumulates on the surface of the soil or substrate due to gravitational forces and free drainage is occurring from the bottom (Handreck and Black, 2010). It is a result of the cohesive and adhesive nature of water in that when the volumetric water content increase there are higher proportions of capillary water, which fills more pores and allows for more paths in which water can move (Fields, 2016). Raviv et al. (1999) discussed the importance of measuring in situ hydraulic conductivity and deemed decreasing conductivity as the primary limiting factor for water uptake by roots in soilless substrates. This means that predictions can be made for irrigation schedules if you understand these types of physical and hydrological properties that influence water movement and plant growth.
The term available water (AW) in reference to soilless substrates is the amount of water held between CC and permanent wilting point (PWP; -1.5 MPa). CC and AW of a substrate will vary depending on container size and geometries (Bilderback and Fonteno, 1987; Milks et al., 1989). Unavailable water (UW) is defined as the water that is adsorbed to the particle surface of the substrate held at a tension equal to or less than PWP (-1.5 MPa), therefore making it unavailable for the plant to utilize. As more water is removed from the substrate, greater tensions (suction) are needed to remove the remaining water. Plant unavailable water exist when plant roots can no longer take up the water left in the soil due to high tensions of suction to soil particles. PWP and UW varies depending on substrate type and the crop, therefore there the point at which water is truly unavailable for plant use is not always the same (Fields et al., 2014). The volumetric fraction of UW is larger in organic substrates than that of mineral soils, due to an increase in particle surface area which means more area for the water to adhere and therefore a greater amount of UW.

MRCs describe the changes in substrate volumetric water content correlated with increasing matric suction throughout the dry down process. Using the differences in water content at specific tensions on a MRC, EAW, which is defined as water held at tensions between -1.0 to -5.0 kPa, and WBC, water held at tensions between -5.0 and -10.0 kPa (de Boodt and Verdonck, 1972), can be measured. How much water is released under each amount of pressure (tension or suction) depends greatly on hydro-physical properties of the material. Different amounts of water are released under different pressures and this creates a unique MRC for every soilless media material (Karlovich and Fonteno, 1986), which can accurately predict how a substrate behaves when drying down and how often they will need to be irrigated. MRCs may also be used to describe the structural effects of substrates with regards to air and water.
relationships and can be used to model these relationships in containers of different sizes (Drzal et al., 1994; Fonteno, 1989; Milks et al., 1989; and Tilt et al., 1987). This allows for a full understanding of hydrological properties depending on a specific substrate media and container size/shape being utilized.

The objective of this study is to characterize the hydrological and physical properties of the differently processed types of wood substrates (1. hammermill, 2. disk-refined, and 3. screw-extruded) in varying ratios compared to other commonly utilized substrate materials including sphagnum peat moss and perlite.

Materials and Methods

Substrate materials

Sphagnum peat-moss (Pro-Moss Sphagnum Peat, Quakertown, PA) was taken from a compressed bale, loosened/fluffed and moistened (by hand) to a moisture content of 50% (by weight). The peat moss used was Premier Pro-moss (Pro-Moss Sphagnum Peat, Quakertown, PA) source from Canada (Can. Peat). Five of the mixes included ForestGold which is a disk refined pine wood material (Pindstrup, Denmark). ForestGold was analyzed at 100%, and in volumetrically mixed ratios with Can. peat of 80%, 60%, 40%, and 20% for a total of five samples. The same five ratios of wood to peat were applied to the next two types of wood substrates; GreenFibre, a screw-extruded pine tree substrate (Klassman; Geeste, Germany) and a hammermilled pine tree substrate (PTS) that was hammermilled at NC State University Substrate Processing and Research Center (SPARC; at the NCSU horticulture field lab, Raleigh, NC) through a 9.5 mm screen. The last five substrates consisted of 100% Premier Pro-moss sphagnum peat, 100% European Peat (Klassman Germany), 100% medium grade horticultural grade perlite (Carolina Perlite Company, Gold Hill, NC), as well as mixes of peat and perlite in
ratios of 80:20 and 60:40 peat perlite utilizing the Can. Peat and the perlite from Caroline Perlite Company. A total of 20 substrate samples were prepared to be evaluated for hydro-physical properties.

Water additions

The amount of water to be added was calculated by weighing each volumetric substrate mixture for a “full weight” (g), and then getting the moisture content (MC) of the initial substrate using the Ohaus MB45 moisture analyzer (Parsippany, NJ). Once the initial MC and substrate full weight are known, the (MC*full weight) gives you the existing water (g) in the substrate. The dry weight of the substrate can be found through calculation:

\[
\text{full weight} - \text{(existing water)} = \text{dry weight (g)}.
\]

Ideal moisture content of 75% to 80% can be achieved with this calculation;

\[
\text{dry weight} \times 0.75 \text{ to } 0.85 = \text{total water} - \text{(existing water)} = \text{additional water (g) needed}.
\]

Finally, substrates were sealed in plastic bags for 48 hours to allow for moisture and lime equilibrations.

Physical properties

Physical properties including CC, AS, total porosity (TP), and bulk density (BD) were determined using the NC State University Porometer method, using procedures in the North Carolina State University Horticulture Substrates Laboratory Manual (Fonteno and Harden, 2010). This is accomplished by utilizing specialized base plates for soil sample aluminum cores. These allow the substrate to be completely saturated and then water being held in the sample’s air space pores to be drained into a graduated cylinder, representing the AS. Next the wet weight
of the sample is recorded, then the sample is dried completely in a Lindberg/Blue mechanical oven (Asheville, NC). The dry weight is recorded to allow for calculation of water held at CC;

\[ \text{wet weight} - \text{dry weight} = \text{water (g) held at CC} \]

The CC and AS are added together to calculate the TP of the substrate sample.

*Saturated hydraulic conductivity*

\( K_{\text{sat}} \) was determined for all samples using the procedure and equipment described by Drzal (1994). Five replications of each substrate were packed into five 347.5 mL aluminum cores as described in the North Carolina State University porometer method and each core was fitted with an individual funnel adaptor ring on the bottom and a plastic cylinder with a spout on the top. Each core assembly was secured onto an individual stationary funnel mounted on the \( K_{\text{sat}} \) unit. A constant head reservoir, mounted to laboratory jacks, was filled with water and maintained at a constant level by a recirculation system. Rubber tubing was connected from the reservoir to the bottom of the stationary funnel, allowing water to saturate each core unit from the bottom. A hydraulic head was created by raising the reservoir a measured distance above the sample. Saturation of the samples was achieved by slowly raising the reservoir in 1 cm increments from the base of the sample until the water level in the reservoir was at an equal level with the sample surface. The samples were then allowed to equilibrate for 15 min before initiating flow. Flow was initiated by imposing a hydraulic head of 0 cm, followed by a hydraulic head of 1 cm which was used for \( K_{\text{sat}} \) measurement. The system was allowed to equilibrate for 15 min at each selected hydraulic head. After equilibration, a volume of water was collected in a 1 L flask placed under the spout of each core assembly and the time taken for the water to reach
that volume was recorded. Piezometers mounted to the reservoir and each core assembly were used to precisely measure hydraulic head differences (ΔH). \( K_{\text{sat}} \) (cm/min) was determined using Darcy’s Law equation:

\[
Q = K_{\text{sat}} \frac{dH}{dx}
\]

where \( Q \) (cm³/min) is the volume flux density (the volume of liquid phase passing through unit cross-sectional area of soil in unit time), \( dH \) is the head difference (cm), and \( dx \) is the distance (cm²; area of aluminum core).

**Particle size distribution**

The particle size distribution (PSD) was determined for each substrate. Two liters of each substrate were spread at a depth of 2 cm on a drying pan and placed in a forced air dryer for 48 hr at 105 °C. PSD for four fractions (X-large: > 6.3 mm, Large: between 6.3 mm and 2.0 mm, Medium: between 2.0 mm and 0.5 mm, and Small: < 0.5 mm) was determined by passing three replications of the dry material through a column of six sieves (W.S. Tyler, Mentor, OH). Screen sizes utilized were: 6.3, 2.0, 0.71, 0.5, 0.25, and 0.125 mm with a pan to collect the particles that passed through the 0.125 mm sieve. 200g samples were used for the Canadian peat and the perlite, and 100g samples were used for the European peat which had a lower bulk density and was inherently lighter in weight. The column of sieves was placed in a Ro-Tap Shaker (W.S. Tyler, model B; Mentor, OH) and shaken for five minutes. The sieves were separated, and the contents of each sieve were weighed separately. Particle size was expressed as a percentage of the total weight of the sample. Three replications were analyzed from each substrate.

**Moisture retention curve**

MRCs were obtained using procedures in the NC State University Horticulture Substrates Laboratory Manual (Fonteno and Harden, 2010). Each sample was placed in a 7.5 cm
tall × 7.5-cm inch diameter aluminum cylinder and placed in Volumetric Pressure Plate Extractors (VPPE; Soilmoisture Corp., Santa Barbara, CA) fitted with 50-kPa ceramic plates (Soilmoisture Corp.). The experiment was conducted in a controlled-temperature chamber (NCSU Horticultural Substrates Laboratory) held at 22 °C. Samples were saturated by adding tap water to the VPPEs in a stepwise fashion and were allowed to equilibrate for 48 h before drainage. Samples were covered to prevent evaporation, drained for an additional 48 h, and water effluent volumes were recorded. Metal lids were fitted onto the top of each VPPE and pressures of 1.0, 2.0, 4.0, 5.0, 7.5, 10, 20, and 30 kPa were applied over the course of 16 days. Each pressure was applied for 24-48 h, and drainage from each sample was recorded. After drainage from the last applied pressure was recorded, the cores were removed from the VPPEs, weighed, and placed in forced air dryer for 48 h at 105 °C. The dried samples were weighed, and Θ (volumetric water content) was calculated. This allows for the development of a MRC and which will show the hydrological properties of wood-based substrates in increasing ratios with peat.

**Plotting the MRCs and modeling**

Once all desired suctions had a corresponding Θ, a scatterplot was made to show the relationship between the two properties. Values for 0 kPa (Θs; water content at saturation) were the TP values from the porometer data. Θ at -0.38 kPa (initial drainage) was taken from the CC values from the porometer data.

**Equilibrium capacity variable models**

Equilibrium capacity variable modeling was performed for each substrate to determine simulated physical properties of that substrate in different geometrically sized and shaped containers. This was done using values obtained by modeling the MRCs with Van Genuchten models (Milks et al., 1989). These models use Θs, Θr (residual water content at -0.30 kPa), a (the
inverse of AS) and curve fitting parameters n and m. These variables allow for specific container dimensions to describe total pore space, CC and AS of the substrate in each individual container size and shape.

Statistics

Physical properties (TP, CC, AS, and BD), K\text{sat}, and the particle size distribution were all analyzed through SAS 9.4. There were three replications used for the particle size distribution data and physical properties data, while four replications were used for the K\text{sat} data. Data was analyzed as a completely randomized design by analysis of variance (ANOVA) using a GLIMMIX procedure. Treatment means were separated using Tukey’s honestly significant differences (HSD) test at p < 0.05 significance level. Fisher’s Least Significant Difference (LSD) was run on the physical properties, K\text{sat}, and particle size distribution data. Table 3 was produced from mathematically derived modeling algorithms, which required means of repetitions to produce curve-fitting parameters for use in the models. To validate the model, means of moisture retention data were compared to points of corresponding $\Theta$ and to model predictions using the 7.6 cm aluminum cylinder as the container.

Results / Discussion

Particle size distribution

European peat had more extra-large (greater than 6.3 mm) and large (less than 6.3 mm, greater than 2.0 mm) particles compared to Canadian peat (Table 2.1). Over 50% of the perlite particles were classified as large, and over 20% were medium (less than 2.0 mm, greater than 0.5 mm) size particles. However, the perlite had almost no extra-large particles (Table 2.1). Canadian peat has the most fines (less than 0.5 mm) and medium particles compared to European
peat or perlite, and almost 30% of Canadian peat particle were fine (specifically 0.25 mm) (Table 2.1).

Physical properties

The TP increased as the amount of ForestGold or GreenFibre wood substrate is increased in percentage, while there was no clear pattern in TP for PTS ratios with peat (Table 2.2). The TP of 100% PTS was significantly similar to the TP of 100% Canadian and European peat (Table 2.2). The TP of 100% Forest Gold was the highest and similar to the TP of 100% GreenFibre. The CC generally went up as wood substrate percentage went down (Table 2.2). The CC was the same for 100% ForestGold as it was for 100% perlite, and that the CC of 100% GreenFibre was the same as 100% Canadian peat. The CC of 100% GreenFibre was somewhere in the middle of ForestGold / Perlite, and PTS / Canadian peat. The AS increased as the percentage of ForestGold and GreenFibre wood substrates increased, while again there was no clear pattern for the PTS ratios (Table 2.2). European peat had three times the amount of AS compared to the Canadian peat, the European peat had 28% AS while Canadian peat had 8% AS (Table 2.2). 100% ForstGold had the most air space, then 100% GreenFibre, and then 100% PTS. The BD varies depending on substrate material (Table 2.2). The 100% ForestGold had the lowest BD, then 100% GreenFibre, and then 100% European peat. The highest BD was seen in 100% Perlite and 100% PTS, then followed by 100% Canadian peat. Overall the BD of the PTS ratios were higher than the other wood substrate ratios, which was possibly what lead to the difference in CC and AS (Table 2.2).

Saturated hydraulic conductivity

Figure 2.3 shows the distribution between the replicates of substrate samples. The distribution of the $K_{sat}$ value seemed to decrease with increasing amounts of peat-moss. In Table
it is shown that for all wood substrate ratios, as more peat was added the $K_{\text{sat}}$ decreased. The 100% ForestGold substrate has the highest $K_{\text{sat}}$ value. 100% GreenFibre substrate and 100% PTS substrate had similar $K_{\text{sat}}$ values as 100% perlite (Table 2.3). European peat had four times the $K_{\text{sat}}$ value of Canadian peat. There was no difference in $K_{\text{sat}}$ values between 60:40 and 80:20 peat:perlite (Table 2.3). The ratio of 80:20 peat:wood was similar between all three different wood substrates and 80:20 peat:perlite was the same as the 80:20 peat:wood ratios as well (Table 2.3). The 60:40 ratio of the peat:wood mixtures were all significantly similar. However the 60:40 ratio of the peat:perlite mixture was the same as the same GreenFibre and PTS 60:40 peat:wood ratios, but not the 60:40 peat:ForestGold ratio (Table 2.3).

The $K_{\text{sat}}$ value is correlated with the AS value seen in the physical properties data because the more AS the more pores are available for easy saturated water flow. The ForestGold material had the highest AS values and it also had the highest $K_{\text{sat}}$ values (Table 2.3). Generally, the $K_{\text{sat}}$ values of the wood substrates in the 20% or 40% ratios were higher than the peat:perlite ratios.

*Moisture retention curves*

Figure 2.1 compares all the 100% materials with MRCs that show the water holding capacity (WHC) of these substrates as they released water with increased tension of suction. Canadian peat had the most WHC while ForestGold had by far least amount of WHC at suctions greater than -100 kPa. At -10 kPa ForestGold only had about 30% volumetric water content left, while perlite, GreenFibre, and European peat had about 45%, PTS had 57% and Canadian peat had 70% volumetric water content left at -10 kPa (Fig 2.1) Overall, GreenFibre, perlite and European peat were very similar in their WHC. However, PTS showed to have more WHC than the other wood substrates, but still less than Canadian peat moss at 10hpa. This is likely due to the high bulk density of the PTS material. At -100 kPa PTS still had 10% higher volumetric
water content compared to the other wood substrates and held more water than the Canadian peat (Fig 2.1). On the other hand, ForestGold showed less WHC compared to the other wood substrates. At -100 kPa Forest Gold was still holding the least water with only 10% volumetric water content left, compared to the other substrates which all still contained at least 30% volumetric water content at – 100 kPa (Fig 2.1).

Figure 2.2 compares the mixtures of materials at rates of 20%, 40%, 60%, and 80% additions of wood substrate to Canadian peat and 20% and 40% perlite with Canadian peat. Those moisture retention curves showed that as the percentage of wood increased the WHC decreased. In the 20% addition graph (Fig 2.2A), the curves acted very similarly, GreenFiber was holding the most water, and ForestGold was holding the least. This trend continued for the 40% additions as well. 60% wood additions (Fig 2.2B; Fig 2.2C) highlights the changes in physical properties likely caused by the processing differences of the materials. ForestGold held the least amount of water as suction tensions increased, GreenFibre was in the middle, and the PTS held the most water as suction tensions increased. This trend also continues into the 80% additions (Fig 2.2D)

The PTS had a larger WHC overall because of its higher bulk density compared to the other wood materials. Similarly, this is probably also why European peat held much less water than Canadian peat, along with the greater number of fine particles in Canadian peat compared to European peat (Table 2.1). It can be seen in Table 2.1 that European peat had more air space than Canadian peat, which explains why it would have less WHC and a more dramatic slope on the MRC (Fig 2.2). ForestGold 100% material had the greatest amount of AS (Table 2.2) and the highest Ksat value shown in (Table 2.3). Therefore, the fact that it has the least WHC makes sense with those physical and hydrological properties.
ECV Models

These models are simulated physical property values for each substrate based on specific container size. This can be especially useful when choosing between different substrates for a production situation utilizing a specific container size. Total porosity was not affected by container size as long as bulk density is constant (Milks et al., 1989b). Therefore, it was not included in the ECV models. Although total porosity remains constant, the AS and CC have a negatively correlated relationship. Since larger containers allow for more drainage, as the container size goes up the AS increases and CC decreases. In the smallest container size, the European peat had a 0.26 ratio for Can. peat AS / European peat AS, while in the largest container size that same ratio was 0.4 (Table 2.4). As the container size increases those differences were diminished in the two-gallon container with European peat now only around having double the amount of AS compared to Canadian peat, rather than quadruple (Table 2.4). As the container size increase, the CC decreases and the AS increases.

Conclusion

The reason the Canadian peat had such a higher water holding capacity compared to European peat was because it contained significantly more fine particles than European peat. These results also displayed how the differences in wood substrate processing techniques will greatly affect the physical and hydrological properties of horticultural substrates. These properties will determine the success of the plant growth within the containerized system. Disk refined wood produces had a CC similar to perlite for additional drainage and AS. The hammermilled PTS had the largest CC while the ForestGold material had the smallest CC of all the wood materials. GreenFibre was a balanced material compared to these two wood substrates, with a CC in the middle of the two other common wood substrates. This trend was duplicated in
the MRC with the distinction between wood types becoming clearer with increasing amount of wood substrate in a mixture.
Literature Cited


Bilderback T. E., W. C. Fonteno. 1987. Effects of container geometry and media physical properties on air and water volumes in containers J. Environ. Hort. 5180182


www.nass.usda.gov/Publications/AgCensus/2012/Online_Resources/Census_of_Horticulture_Specialties/HORTIC.pdf


Table 2.1 Particle size distribution of sphagnum peat moss sources from Canadian (Can Peat), and European (Euro Peat), and Perlite.

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Substrate</th>
<th>X-large</th>
<th>Large</th>
<th>Medium</th>
<th>Fines</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>Euro Peat</td>
<td>13.4 a</td>
<td>51.3 b</td>
<td>15.7 c</td>
<td>6.0 b</td>
</tr>
<tr>
<td></td>
<td>Can Peat</td>
<td>2.0 b</td>
<td>17.0 c</td>
<td>21.9 a</td>
<td>13.0 a</td>
</tr>
<tr>
<td></td>
<td>Perlite</td>
<td>0.1 c</td>
<td>54.9 a</td>
<td>19.6 b</td>
<td>5.3 b</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.125</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>&lt;0.125</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

X-large particles are greater than 6.3 mm in diameter.
Large particles are less than 6.3 mm and greater than 2.0 mm in diameter.
Medium particles are less than 2.0 mm and greater than 0.5 mm in diameter.
Fine particles are less than 0.5 mm in diameter.
Means separated within column by Tukey’s HSD with α ≤ 0.05. Means followed by the same letter are not significantly different (n=3).
LSD = Fisher’s Least Significant Difference
Table 2.2 Physical and hydrologic properties of Canadian peat amended with 20%, 40%, 60%, and 80% of three wood substrate components as well as 100% wood substrates, Canadian peat, European peat, perlite, and peat:perlite (PeatLite) mixes.

<table>
<thead>
<tr>
<th>Percent</th>
<th>Substrate</th>
<th>TP&lt;sub&gt;y&lt;/sub&gt;</th>
<th>CC&lt;sub&gt;x&lt;/sub&gt;</th>
<th>AS&lt;sub&gt;w&lt;/sub&gt;</th>
<th>Db&lt;sub&gt;v&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>ForestGold</td>
<td>93.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>50.3&lt;sup&gt;l&lt;/sup&gt;</td>
<td>43.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.05&lt;sup&gt;j&lt;/sup&gt;</td>
</tr>
<tr>
<td>80%</td>
<td>ForestGold</td>
<td>88.3&lt;sup&gt;bcd&lt;/sup&gt;</td>
<td>64.0&lt;sup&gt;fghi&lt;/sup&gt;</td>
<td>24.3&lt;sup&gt;de&lt;/sup&gt;</td>
<td>0.06&lt;sup&gt;i&lt;/sup&gt;</td>
</tr>
<tr>
<td>60%</td>
<td>ForestGold</td>
<td>88.9&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>67.3&lt;sup&gt;def&lt;/sup&gt;</td>
<td>21.6&lt;sup&gt;e&lt;/sup&gt;</td>
<td>0.08&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>40%</td>
<td>ForestGold</td>
<td>81.1&lt;sup&gt;fgh&lt;/sup&gt;</td>
<td>67.3&lt;sup&gt;def&lt;/sup&gt;</td>
<td>13.8&lt;sup&gt;hi&lt;/sup&gt;</td>
<td>0.10&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>20%</td>
<td>ForestGold</td>
<td>77.1&lt;sup&gt;i&lt;/sup&gt;</td>
<td>66.2&lt;sup&gt;efgh&lt;/sup&gt;</td>
<td>10.9&lt;sup&gt;jk&lt;/sup&gt;</td>
<td>0.11&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>100%</td>
<td>GreenFibre</td>
<td>89.7&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>57.1&lt;sup&gt;k&lt;/sup&gt;</td>
<td>32.7&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.07&lt;sup&gt;h&lt;/sup&gt;</td>
</tr>
<tr>
<td>80%</td>
<td>GreenFibre</td>
<td>88.2&lt;sup&gt;bcd&lt;/sup&gt;</td>
<td>61.8&lt;sup&gt;ij&lt;/sup&gt;</td>
<td>26.5&lt;sup&gt;cd&lt;/sup&gt;</td>
<td>0.08&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>60%</td>
<td>GreenFibre</td>
<td>84.0&lt;sup&gt;efg&lt;/sup&gt;</td>
<td>63.7&lt;sup&gt;ghi&lt;/sup&gt;</td>
<td>20.3&lt;sup&gt;f&lt;/sup&gt;</td>
<td>0.09&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>40%</td>
<td>GreenFibre</td>
<td>83.2&lt;sup&gt;efgh&lt;/sup&gt;</td>
<td>68.0&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>15.1&lt;sup&gt;h&lt;/sup&gt;</td>
<td>0.10&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>20%</td>
<td>GreenFibre</td>
<td>81.7&lt;sup&gt;fgh&lt;/sup&gt;</td>
<td>69.7&lt;sup&gt;cd&lt;/sup&gt;</td>
<td>12.0&lt;sup&gt;ij&lt;/sup&gt;</td>
<td>0.11&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>100%</td>
<td>PTS&lt;sub&gt;s&lt;/sub&gt;</td>
<td>84.6&lt;sup&gt;ef&lt;/sup&gt;</td>
<td>63.4&lt;sup&gt;hi&lt;/sup&gt;</td>
<td>21.2&lt;sup&gt;f&lt;/sup&gt;</td>
<td>0.14&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>80%</td>
<td>PTS</td>
<td>85.7&lt;sup&gt;cde&lt;/sup&gt;</td>
<td>67.3&lt;sup&gt;def&lt;/sup&gt;</td>
<td>18.4&lt;sup&gt;g&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>60%</td>
<td>PTS</td>
<td>87.0&lt;sup&gt;bcde&lt;/sup&gt;</td>
<td>67.1&lt;sup&gt;defg&lt;/sup&gt;</td>
<td>19.9&lt;sup&gt;fg&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>40%</td>
<td>PTS</td>
<td>87.0&lt;sup&gt;bcde&lt;/sup&gt;</td>
<td>67.1&lt;sup&gt;defg&lt;/sup&gt;</td>
<td>19.9&lt;sup&gt;fg&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>20%</td>
<td>PTS</td>
<td>81.5&lt;sup&gt;fgh&lt;/sup&gt;</td>
<td>71.4&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>10.0&lt;sup&gt;fk&lt;/sup&gt;</td>
<td>0.12&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>100%</td>
<td>Canadian Peat</td>
<td>82.9&lt;sup&gt;efgh&lt;/sup&gt;</td>
<td>73.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.0&lt;sup&gt;ml&lt;/sup&gt;</td>
<td>0.13&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>100%</td>
<td>European Peat</td>
<td>87.3&lt;sup&gt;bcde&lt;/sup&gt;</td>
<td>58.3&lt;sup&gt;jk&lt;/sup&gt;</td>
<td>28.8&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.08&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>100%</td>
<td>Perlite</td>
<td>76.7&lt;sup&gt;i&lt;/sup&gt;</td>
<td>52.2&lt;sup&gt;i&lt;/sup&gt;</td>
<td>24.4&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.14&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>80:20</td>
<td>PeatLite</td>
<td>80.7&lt;sup&gt;gh&lt;/sup&gt;</td>
<td>74.3&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>6.4&lt;sup&gt;m&lt;/sup&gt;</td>
<td>0.13&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>60:40</td>
<td>PeatLite</td>
<td>80.0&lt;sup&gt;hi&lt;/sup&gt;</td>
<td>71.1&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>8.8&lt;sup&gt;jkl&lt;/sup&gt;</td>
<td>0.13&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>LSD&lt;sub&gt;s&lt;/sub&gt;</td>
<td></td>
<td>3.72</td>
<td>3.56</td>
<td>2.91</td>
<td>0.004</td>
</tr>
</tbody>
</table>

<sup>z</sup>Physical and hydrologic properties determined using the methods of Fonteno and Harden (2010).
<sup>y</sup>TP = total porosity; total percentage of pore volume (TP = CC + AS).
<sup>x</sup>CC = container capacity; maximum water content after free (gravitational) drainage.
<sup>w</sup>AS = air space; total percentage of pore space not filled with water at CC
<sup>v</sup>BD = bulk density; substrate dry weight/total sample volume.
<sup>u</sup>Means separation down column for individual properties using Tukey’s HSD with α = 0.05, means followed by the same letter are not significantly different (n=3).
<sup>t</sup>PTS = Pine tree substrate
<sup>s</sup>LSD = Fisher’s Least Significant Difference
Table 2.3 Saturated hydraulic conductivity (K$_{sat}$) values of Canadian peat amended with 20%, 40%, 60%, and 80% of three wood substrate components as well as 100% wood substrates, Canadian peat, European peat, perlite, and peat:perlite mixes.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>K$_{sat}$ (cm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% ForestGold</td>
<td>177.4 a y</td>
</tr>
<tr>
<td>80% ForestGold</td>
<td>119.6 bc</td>
</tr>
<tr>
<td>60% ForestGold</td>
<td>81.5 cde</td>
</tr>
<tr>
<td>40% ForestGold</td>
<td>43.7 defg</td>
</tr>
<tr>
<td>20% ForestGold</td>
<td>19.0 h</td>
</tr>
<tr>
<td>100% GreenFibre</td>
<td>124.0 bc</td>
</tr>
<tr>
<td>80% GreenFibre</td>
<td>118.6 bcd</td>
</tr>
<tr>
<td>60% GreenFibre</td>
<td>82.7 bcde</td>
</tr>
<tr>
<td>40% GreenFibre</td>
<td>68.8 def</td>
</tr>
<tr>
<td>20% GreenFibre</td>
<td>50.7 efgh</td>
</tr>
<tr>
<td>100% Pine Tree Substrate</td>
<td>125.5 bc</td>
</tr>
<tr>
<td>80% Pine Tree Substrate</td>
<td>103.2 bcd</td>
</tr>
<tr>
<td>60% Pine Tree Substrate</td>
<td>83.5 cde</td>
</tr>
<tr>
<td>40% Pine Tree Substrate</td>
<td>51.1 efgh</td>
</tr>
<tr>
<td>20% Pine Tree Substrate</td>
<td>32.8 fgh</td>
</tr>
<tr>
<td>100% Canadian Peat</td>
<td>15.0 h</td>
</tr>
<tr>
<td>100% European Peat</td>
<td>66.0 defg</td>
</tr>
<tr>
<td>100% Perlite</td>
<td>126.1 b</td>
</tr>
<tr>
<td>80:20 Peat:perlite</td>
<td>18.5 h</td>
</tr>
<tr>
<td>60:40 Peat:perlite</td>
<td>22.9 gh</td>
</tr>
<tr>
<td>LSD$_x$</td>
<td>24.23</td>
</tr>
</tbody>
</table>

*$_{K_{sat}}$ values determined using the methods of Drzal (1994).*

*$_{Means separation down column using Tukey’s HSD with a = 0.05, means followed by the same letter are not significantly different (n=8).}$

*$_{LSD = Fisher’s Least Significant Difference}$*
Table 2.4 Mathematically derived physical properties of Canadian (Can.) peat amended with 20%, 40%, 60%, and 80% wood substrate, as well as 100% wood substrates, Can. Peat, European peat, perlite, and peat:perlite(PL)

<table>
<thead>
<tr>
<th>Container size</th>
<th>3” Core</th>
<th>4” pot</th>
<th>6” pot</th>
<th>8” pot</th>
<th>1 gal pot</th>
<th>2 gal pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>CC</td>
<td>AS</td>
<td>CC</td>
<td>AS</td>
<td>CC</td>
<td>AS</td>
</tr>
<tr>
<td>----------------</td>
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<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>20%</td>
<td>68.4</td>
<td>10.8</td>
<td>67.3</td>
<td>11.9</td>
<td>61.1</td>
<td>18.1</td>
</tr>
<tr>
<td>40%</td>
<td>69.9</td>
<td>12.3</td>
<td>68.7</td>
<td>13.5</td>
<td>61.6</td>
<td>20.6</td>
</tr>
<tr>
<td>60%</td>
<td>72.1</td>
<td>16.8</td>
<td>70.6</td>
<td>18.3</td>
<td>62.5</td>
<td>26.4</td>
</tr>
<tr>
<td>80%</td>
<td>64.7</td>
<td>20.8</td>
<td>62.6</td>
<td>22.9</td>
<td>52.5</td>
<td>33.0</td>
</tr>
<tr>
<td>100%</td>
<td>56.1</td>
<td>20.6</td>
<td>54.8</td>
<td>21.9</td>
<td>50.0</td>
<td>26.7</td>
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</tr>
<tr>
<td>GreenFibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>59.1</td>
<td>22.6</td>
<td>58.3</td>
<td>23.4</td>
<td>55.8</td>
<td>25.9</td>
</tr>
<tr>
<td>40%</td>
<td>68.8</td>
<td>14.4</td>
<td>67.7</td>
<td>15.5</td>
<td>63.1</td>
<td>20.1</td>
</tr>
<tr>
<td>60%</td>
<td>71.8</td>
<td>12.2</td>
<td>70.9</td>
<td>13.1</td>
<td>66.5</td>
<td>17.5</td>
</tr>
<tr>
<td>80%</td>
<td>65.9</td>
<td>22.4</td>
<td>64.6</td>
<td>23.7</td>
<td>59.0</td>
<td>29.3</td>
</tr>
<tr>
<td>100%</td>
<td>64.3</td>
<td>25.5</td>
<td>62.9</td>
<td>26.9</td>
<td>57.4</td>
<td>32.4</td>
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</tr>
<tr>
<td>Hammermilled PTS</td>
<td></td>
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</tr>
<tr>
<td>20%</td>
<td>67.1</td>
<td>18.9</td>
<td>65.8</td>
<td>20.2</td>
<td>60.4</td>
<td>25.6</td>
</tr>
<tr>
<td>40%</td>
<td>65.6</td>
<td>21.4</td>
<td>64.1</td>
<td>22.9</td>
<td>57.6</td>
<td>29.4</td>
</tr>
<tr>
<td>60%</td>
<td>80.1</td>
<td>6.0</td>
<td>79.4</td>
<td>7.6</td>
<td>75.4</td>
<td>11.6</td>
</tr>
<tr>
<td>80%</td>
<td>75.8</td>
<td>11.2</td>
<td>75.0</td>
<td>12.0</td>
<td>71.0</td>
<td>16.0</td>
</tr>
<tr>
<td>100%</td>
<td>67.5</td>
<td>17.1</td>
<td>66.4</td>
<td>18.2</td>
<td>62.1</td>
<td>22.5</td>
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<td>-----------</td>
</tr>
<tr>
<td>Peat, Perlite, and peat-lite mixes</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Euro Pq</td>
<td>61.8</td>
<td>23.9</td>
<td>60.4</td>
<td>25.3</td>
<td>54.8</td>
<td>30.9</td>
</tr>
<tr>
<td>Can Pp</td>
<td>77.2</td>
<td>6.4</td>
<td>76.6</td>
<td>7.0</td>
<td>73.4</td>
<td>10.2</td>
</tr>
<tr>
<td>Perlite</td>
<td>56.1</td>
<td>20.6</td>
<td>54.8</td>
<td>21.9</td>
<td>50.0</td>
<td>26.7</td>
</tr>
<tr>
<td>80:20PL</td>
<td>72.6</td>
<td>8.1</td>
<td>71.8</td>
<td>8.9</td>
<td>66.7</td>
<td>14.0</td>
</tr>
<tr>
<td>60:40PL</td>
<td>70.0</td>
<td>10.0</td>
<td>69.1</td>
<td>10.9</td>
<td>64.2</td>
<td>15.8</td>
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</table>
Table 2.4 Continued

<table>
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<tr>
<th>Properties derived by modeling Van Genuchten curve fitting parameters from moisture retention curves determined in the North Carolina State University Horticultural Substrates Laboratory. Data were produced from mathematically derived modeling algorithms, which required means of repetitions to produce curve-fitting parameters for use in the models.</th>
</tr>
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<tr>
<td>Standard 3in Core for soil and substrate property analysis as described in the Porometer Manual (Fonteno and Harden, 2010).</td>
</tr>
<tr>
<td>Standard 4 inch pot size for container production (0.47L)</td>
</tr>
<tr>
<td>Standard 6 inch pot size for container production (0.95L)</td>
</tr>
<tr>
<td>Standard 8 inch pot size for container production (3.78L)</td>
</tr>
<tr>
<td>Standard 1 gallon pot size for container production (4.00L)</td>
</tr>
<tr>
<td>Standard 2 gallon pot size for container production (7.50L)</td>
</tr>
<tr>
<td>CC = container capacity; maximum water content after free (gravitational) drainage.</td>
</tr>
<tr>
<td>AS = air space; total percentage of pore space not filled with water at CC</td>
</tr>
<tr>
<td>Euro P = European peat from Klassman Germany</td>
</tr>
<tr>
<td>Can. P = Canadian peat Premier Pro Moss</td>
</tr>
<tr>
<td>PL = Canadian peat and perlite mixture with perlite being the lesser portion</td>
</tr>
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Figure 2.1 Moisture retention curves of 100% materials: Canadian Peat, European Peat, Perlite, ForestGold, GreenFibre, and Pine Tree Substrate (PTS).
Figure 2.2 Moisture release curve of ForestGold, GreenFibre, and Pine tree substrate incorporated into Canadian peat at additions of 20% (A), 40% (B), 60% (C), and 80% (D), along with 20% (A) and 40% (B) perlite amended into Canadian peat moss.
Figure 2.3 $K_{sat}$ distribution between 4 sample replications. As the percentage of Canadian peat increases, the distribution or variability between same sample replications decreases.
CHAPTER 3

Effect of Wood Substrates on Poinsettia and Chrysanthemum Quality and Root Growth
Abstract

In recent years the floriculture and greenhouse industries have grown in the United States, and these industries are looking for advanced and highly engineered horticultural substrates that are both environmentally and economically friendly. The horticultural substrates in this evaluation included mixtures of peat moss, with additives of perlite, ForestGold and a hammermilled pine tree substrate (PTS). Substrates were mixed volumetrically in ratios of 15% and 30% additives. The objectives of this study were to investigate the effect of two types of wood substrate materials on plant root growth and overall plant performance. The mini-horhizotron was utilized to study root growth of poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch ‘Astro Red’ and ‘Charon Red’) for six weeks. Separate plants replicated in standard containers were also included for chemical properties monitoring and bract measurements at anthesis.

The addition of the wood substrates altered the physical properties of the mixture compared to the traditional perlite mixes with increased total porosity. Container capacity was also increase with wood substrates compared to the traditional peat:perlite mixes, except for 70:30 peat:PTS which had the exact same container capacity as 70:30 peat:perlite. The longest root growth was seen in 70:30 peat:PTS during the first four weeks of plant growth. The highest bract area index measured on the “Astro Red” cultivar was seen in 85:15 peat:perlite, followed by 70:30 peat:PTS and peat:ForestGold. The experiment was repeated in the mini-horhizotrons the following year with mums (*Chrysanthemum morifolium* L. ‘Gigi Yellow’ and ‘Kathleen Dark’) which were more vigorous than the poinsettia cultivars and showed no difference in root growth between substrates. There were also no differences in plant dry weights after production
in these different substrates. Wood based substrates can be a suitable alternative to perlite in containerized production setting and produce similar plant growth as traditional substrates.
Introduction

The floriculture and greenhouse industry had a 4.77 billion dollar valuation in 2018 from only the 15 top producing states of floriculture crops (U.S. Department of Agriculture (USDA), 2019). This valuation is up 9% since the 2015 (USDA, 2019). Also, the actual number of floriculture producers has increased by 8% and the actual area of land being utilized for floriculture production in the United States has increased by 12% since 2015 (USDA, 2019). These thriving industries are utilizing horticultural substrates in order to produce optimal crops in a containerized production setting. Over 85% plants grown in the greenhouse and nursery industries within our nation are grown with soilless media in containers (USDA, 2009). The mixture of peat moss and perlite is the traditional substrate for the floriculture industry (Baker, 1957; Owen et al., 2012). As container production gains popularity, more specific substrate materials are being developed and engineered as horticultural substrates.

As the industry explores new alternative substrates, there will be an increase in demand for research of those materials. Different types of horticultural substrates will provide different types of physical, hydrological, and chemical properties that effect root growth. Gilman and Beeson (1996) showed that container grown plants develop a greater number of fine roots which support a healthier plant allowing them to be more easily transplanted than a field grown plant and have a higher rate of success. Mathers et al. (2007) showed that plants with larger root systems were able to better withstand transplant stress. The type of substrate material utilized will greatly affect the development of the root system through the substrates unique physical properties, particle size distribution, and chemical properties (Mathers et al., 2007). This is why it is important to understand root growth difference between the different types of substrate materials being produced.
Today there are a number of ways to observe, evaluate, and measure root growth. One example is subjective root measurements, such as observations made through a large underground glass windows that allow viewing of root structures of plants in the landscape called “Rhizotrons” (Taylor et al., 1990). Another way to observe roots is with tiny glass tubes with a viewing device that can be stuck underground to observe the roots called a “mini-rhizotron” (Taylor et al., 1990). Subjective root measurements often depend on the root-system examiner (Wright and Wright, 2004). Another way to non-subjectively evaluate roots is to get a physical dry weight of the root system after removing it from the field or container. The traditional root-washing technique has challenges since it is nearly impossible to collect every root while also trying to fully wash away the substrate or soil intertwined in the roots themselves (Aung, 1974). It has been shown that when using this method of dry weight measurements there can be a 20% - 40% loss of dry weight material in the washing process depending on the researcher doing the root washing procedure (Oliveira et al., 2000; van Noordwijk and Floris, 1979). However, this is one of the easiest ways to quantify root growth since all it involves is the washing process and a forced air drier. This is why root washing for root dry weights are so commonly utilized for root growth evaluation.

The Horhizotron™ is a non-evasive way to evaluate root growth and transplant success of container crops that can be observed over time (Wright and Wright, 2004). This is accomplished by providing a strategic design of a container, or root-box, with four arms and eight glass faces for observing roots over time which are covered by removable shade panels. The Horhizotron™ allows for post-transplant root growth and establishment evaluation in a variety of soils or substrates (Wright and Wright, 2004). The Horhizotron™ can be used easily in a greenhouse or field due to its lightweight materials and transportability. However, there are
limitations such as the size of the container restricted the size of the type of plant to be studied, so only larger container plants could be properly analyzed (Wright and Wright, 2004). Thus, a smaller version of the Horhizotron™; the mini-horhizotron was developed with a similar design and concept for smaller container crops. This root-box is a similar strategic design with three arms, and six glass panels to observe roots which are covered by removable shade panels. The mini-horhizotron was developed as a non-destructive way to examine and analyze root growth over time and was specifically designed to study the early stages of root growth for floriculture nursery container crops (Judd et al., 2014). This is an ideal tool for analyzing root growth after plug or rooted cutting transplant in the floriculture production process. The mini-horhizotron provides an accurate way to research different types of substrates for container crops. Root growth rates can also be quantified by measuring the length of the longest roots against the transparent walls. The five longest roots identified on each side of a quadrant is often used in analysis with the Horhizotron™ (Jackson et al., 2005; Price et al., 2009; Wright and Wright, 2004) with the roots of two sides of one quadrant averaged to obtain the experimental value for that quadrant (Wright and Wright, 2004).

In order to reduce the concern for accuracy of subjective ratings, rhizotrons, minirhizotrons and other transparent wall/container designs commonly use digital imaging to measure root systems rather than having a person take measurements themselves. Digital imaging includes photographs or videos, scanned images of exposed roots, or scanned root tracings (Judd et al., 2014). Some of these programs include RootLM (Utah State University, Logan, UT) RootReader 2D (Robert W. Holley Center for Agriculture & Health, Ithaca, NY.), EZ-Rhizo (University of Glasgow, Scotland, UK), WinRHIZO and WinRHIZO Tron (Regents Instruments, Quebec City, Canada). Measurements produced by WinRHIZO include total length,
projected area, surface area, root tips, and branching points (Arsenault et al., 1995). These digital tracers can have their limitations too such as difficulty deciphering between the root structure and substrate materials, which means the researchers must manually trace the root system for the software. WinRHIZO requires the roots to be excavated completely and washed, which risks losing root material in the process (Judd et al., 2014).

Drotleff (2018) claims that wood-based substrates are gaining popularity in the United States mixed in at the ratio of 20% - 40% with other soilless media. Bilderback et al. (2013) suggested that loblolly pine *Pinus taeda* L. can be utilized without phytotoxic effects that could potentially damage plant growth. This ideal characteristic combined with loblolly pine’s easy accessibility in the southeastern United States makes it an optimal horticultural substrate. Jackson (2018) discusses processing of the most common wood substrates which are 1) single or twin-screw extrusion, 2) twin disk-refined, or 3) hammermilled which all produce completely unique products of wood fiber with unique characteristics. The type of processing which pinewood undergoes is a large factor in the physical and hydrological properties of the substrate, and these properties can determine the success of root development. Shredded pinewood has a higher total porosity and provides more easily available water to plants when compared to pinewood chips (Fields et al., 2014). The shredded pinewood was designed to retain water like peat while the pine chips acted similar to perlite to allow drainage. However, it was found that the drainage of both substrates was greater than coir or peat as a result of fewer fine particles (Fields et al., 2014). More horticultural research should be done to examine these types of products that are now being produced commercially to determine their different properties and how those effect plant growth.
Judd et al., (2014) studied the root growth of one species applying the mini-horhizotron method with *Rudbeckia hirta* L. ‘Becky Yellow’ in three different substrates in a 70:30 ratio with peat moss being the dominant material. The substrates non-dominant materials that were mixed in at 30% included perlite as a control, pine wood chips, and shredded pine wood. The results indicate that the wood-based substrates compared were similar or slightly improved when compared to the perlite mix. Judd et al., (2014) also verified that the mini-horhizotron is a useful and accurate apparatus for greenhouse horticultural substrate research by testing it with a variety of species. However, this research only examined one species for root growth against different wood-based substrates and with rising interest in wood substrates, there is a need for more research.

The objective of this project was to examine the effect of the different types of processed wood materials (specifically hammermilled and twin disk refined) on root growth and overall plant growth of two varieties of poinsettias (*Euphorbia pulcherrima* Willd. ex Klotzsch ‘Astro Red’ and ‘Charon Red’) in fall 2018 and chrysanthemums (*Chrysanthemum morifolium* L. ‘Gigi Yellow’ and ‘Kathleen Dark’) in the fall of 2019.

**Materials and Methods**

*Substrate and plant materials*

The six mixes chosen for this study consisted of two ratios utilizing sphagnum peat moss combined with perlite, and two different types of wood substrate. Premier pro-moss sphagnum peat moss sourced from Canada. Sphagnum peat-moss (Pro-Moss Sphagnum Peat, Quakertown, PA) was taken from a compressed bale, loosened/fluffed, and moistened (by hand) to a moisture content of 50% (by weight). This peat was used in the larger portion of two different mix ratios
of 85:15 and 70:30 with the lesser of the ratios consisting of three different materials including perlite, pine tree substrate (PTS) hammermilled wood, and ForestGold. ForestGold is a disk refined wood material (Pindstrup, United Kingdom). The PTS material was produced at the Substrate Processing And Research Center (SPARC) at the NCSU horticulture field lab (Raleigh, NC) with a hammermill with a screen size of 9.5 mm using pine tree mulch from Parker Bark (Rose Hill, NC). The perlite was supplied by the Carolina Perlite Company (Gold Hill, NC). Three replications of each substrate were analyzed for each of the two cultivars of poinsettias and chrysanthemums in the mini-horhizotron root boxes. The poinsettias used were rooted cuttings of *Euphorbia pulcherrima* Willd. ex Klotzsch ‘Astro Red’ and ‘Charon Red’ (Dummen Orange, Costa Rica). A second experiment was with rooted cuttings of *Chrysanthemum morifolium* L. ‘Gigi Yellow’ and ‘Kathleen Dark’ (Raker-Roberta’s Young Plants; Litchfield, MI).

**Preparing substrates**

Substrates were hand mixed and measured by their volume. Utilizing a clear cubic foot box, each 70:30 ratio with 70% of peat measured on the rulers in the box and 30% of perlite, Forest Gold, or PTS material. The 85:15 ratio was made in the same manner by using the same materials. After each mixture was measured (v/v), it was mixed thoroughly by hand. A pulverized dolomitic carbonate limestone (85% CaCO3MgCO3; Rockyardale Quarries Corp., Roanoke, VA) was added at a rate of 2.72 kg/0.91m to each mix in order to raise the pH to 5.5. Finally, the moisture content was raised to the appropriate level for each substrate mix by adding a certain amount water. The amount of water to be added was calculated by weighing each volumetric substrate mixture for a “full weight”(g), and then getting the moisture content (MC) of the initial substrate using the Ohaus MB45 moisture analyzer (Parsippany, NJ). Once the
initial MC and substrate full weight are known, the (MC*full weight) gives you the existing water in the substrate. The dry weight of the substrate can be found through calculation;

\[
\text{full weight} - \text{(existing water)} = \text{dry weight.}
\]

Ideal moisture content of 75% to 80% can be achieved with this calculation;

\[
\text{dry weight} \times 0.75 \text{ to } 0.85 = \text{total water} - \text{(existing water)} = \text{additional water (g) needed.}
\]

Finally, substrates were sealed in plastic bags for 48 hours to allow for moisture and lime equilibrations.

*Poinsettia; experiment 1*

The poinsettia rooted cuttings were transplanted on 5 Sept., 2018, pinched on 11 Sept., and the first day of root measurement was 12 Sept. Plants were fertilized at each irrigation with 200 mg L-1 nitrogen (N) formulated from Peters Professional 20N-10P-20K Peat-Lite Special (Israeli Chemicals Ltd, Israel) containing 8.1% ammonical- (NH4-N) and 11.9% nitrate-Nitrogen (NO3-N) and injected by a Dosatron injector ((D14MZ2); Dosatron International, Inc., Clearwater, FL). There were three replications of the mini-horhizotrons for each substrate. Once six weeks of root growth was recorded for the mini-horhizotron plants they were harvested for shoot dry weights. There were four replications of each poinsettia cultivar in each substrate treatment in a 0.95L green plastic container (AZA0600 from Landmark Plastic Corporation, Akron, OH). Each container was weighed as it was filled with substrate to ensure the same amount of substrate in each replication. Three of these reps were used to monitor chemical properties of pH and electrical conductivity (EC) using the pour through method (Wright, 1986) and measured with a HANNA portable pH/EC meter (HI9813-6 pH meter; Hanna Instruments, Woonsocket, RI). These measurements were conducted once a week for nine weeks starting on 20 Sept. Container plants had drip irrigation and the mini-horhizotron plants received the same
rate of daily fertigation through overhead hand watering to ensure even moisture distribution throughout the root box. Experiment concluded at anthesis on December 3rd and plants were destructively harvested for bract measurements.

**Root and bract measurements**

The root measurements were started once the first roots began to appear on the glass and the measurements were taken once a week for six weeks. Each week root count and measurements were assessed. The root measurements included the number of roots per side (flat face) of the six root box arms and the length of the 5 longest roots, as performed on the Horhizotron™ (Jackson et al., 2005; Price et al., 2009; Wright and Wright, 2004). Once the six weeks of root growth measurements were obtained and the roots had reached the end of the glass panel, the plants were harvested, and dry weights were recorded.

Bract measurements were taken of these container plants to analyze flower quality on December 5th and the plants were harvested. The measurements included the length and width of every bract on the four largest flowers per plant. Each bract that was under 1 cm long was excluded.

The measurements were used to create a bract area index for each plant using the equation using the formula for an ellipse \[(\text{long axis} \times \text{short axis} \times \pi) \div 4\] and averaged (Lopez & Camberato, 2011).

**Chrysanthemums; experiment 2**

A second experiment was with rooted cuttings of *Chrysanthemum morifolium* L. ‘Gigi Yellow’ and ‘Kathleen Dark’ (Raker-Roberta’s Young Plants; Litchfield, MI). Rooted cuttings were transplanted on 7 Aug. 2019 into three mini-horhizotrons and four replications of 0.95L green plastic containers (AZA0600 from Landmark Plastic Corporation, Akron, OH) with the same six substrate mixes described in Expt. 1. These mixes were made again using the same
methods except the lime rate was adjusted to 3.63 kg/0.91m for all the mixes except 100% peat
which required a lime rate of 4.08 kg/0.91m to get the target pH of 6.0 according to Larson
(2013) Introduction to Floriculture book. The same dolomitic lime as described above for the
poinsettia mixes was used. Plants were fertilized at each irrigation with 300 mg L-1 nitrogen (N)
formulated from Peters Professional 20N-10P- 20K Peat-Lite Special (Israeli Chemicals Ltd,
Israel) containing 8.1% ammonical- (NH4-N) and 11.9% nitrate-Nitrogen (NO3-N) and injected
by a Dosatron injector ((D14MZ2); Dosatron International, Inc., Clearwater, FL).. The pH and
EC was monitored through-out the production process on three replications of plants growing in
the plastic containers through the same methods as in experiment 1. The root growth was
analyzed in the mini-horhizotron root boxes for four weeks utilizing the same methods listed
above. Plants in the plastic containers were grown to anthesis and dry weights were collected of

Physical properties

Physical properties such as total porosity (TP), container capacity (CC), air space (AS),
and bulk density (BD) were determined using the North Carolina State University Porometer
method, using procedures in the North Carolina State University Horticulture Substrates
Laboratory Manual (Fonteno and Harden, 2010).

Statistics

Physical properties, bract area measurements, plant dry weights, and pH/EC were all
analyzed through SAS 9.4. Data were analyzed as a completely randomized design by analysis of
variance (ANOVA) using a GLIMMIX procedure. Treatment means were separated using
Tukey’s honestly significant differences (HSD) test at p < 0.05 significance level. Fisher’s Least
Significant Difference (LSD) was run on the physical properties and bract area index data.
The mini-horizotron experiment was a completely randomized split-plot design, with boxes as whole plot units, cultivar and substrate two whole plot factors, arranged in a full-factorial layout with one root box per cultivar-by-soil combination, and time as a split-plot factor. This analysis averages over roots and sides to a box. Log$_{10}$ of the total root length is estimated for each cultivar across all substrates for each week and the lsmeans estimate is reported in separate graphs to show substrate and cultivar effects separately. Treatments of substrates estimated means were separated using Tukey’s honestly significant differences (HSD) test at p < 0.05 significance level.

**Results / Discussion**

*Physical properties*

The substrate with the highest reported TP was 70:30 peat:ForestGold which was also similar to 85:15 peat:PTS (Table 3.1). The substrates with the lowest TP were the 85:15 and 70:30 peat:perlite mixtures. The CC reported (Table 3.1) of the substrates was not significantly different between any of the substrates except for the 85:15 peat:perlite which had less container capacity than the other substrates. The AS shows no clear pattern, the substrates with the least air space were 70:30 peat:perlite and 70:30 peat:PTS (Table 3.1). The highest BD was seen in the 70:30 peat:PTS mixture (Table 3.1).

*Bract area index*

‘Charon Red’ had no differences reported for the bract area measurements that were taken after poinsettia’s reached anthesis (Table 3.2). ‘Astro Red’ showed differences with the highest bract area index being reported as 85:15 peat:perlite followed by 70:30 peat:ForestGold and 70:30 peat:PTS (Table 3.2). The substrates that produced the lowest bract area index for
‘Astro Red’ was 70:30 peat:perlite and 85:15 peat:ForestGold (Table 3.2). Overall, ‘Charon Red’ had a greater bract area index than ‘Astro Red’ for all substrate treatments.

*Root growth in the mini-horhizotron*

The poinsettias ‘Astro Red’ and ‘Charon Red’ were not different in root growth except in week 5, but generally ‘Charon’ had a more vigorous root growth (Fig 3.1). The substrate with the highest root growth was 70:30 peat:PTS which had the highest reported root growth for the first four weeks of measurements (Table 3.3, Fig 3.2). For the first three weeks of root growth 70:30 peat:ForestGold had the lowest root growth of all the substrates, but its quickly caught up with the others on week 4 and 5 (Table 3.3, Figure 3.2.) After the first four weeks of root growth the substrate treatments were not significantly different (Table 3.3).

The chrysanthemums ‘Gigi Yellow’ and ‘Kathleen Dark’ were significantly different for all four weeks of recorded root growth with ‘Kathleen Dark’ having more vigorous root growth (Figure 3.3). Over the four weeks of recorded root growth the substrate treatments showed no significant differences for either cultivar of chrysanthemum (Table 3.4, Fig 3.4). Compared to the poinsettias, the chrysanthemum had faster and more vigorous root growth overall which is why the measurements should have been taken more frequently to capture the significance of the substrate treatments.

*Plant dry weights*

There was no difference in shoot dry weights for any substrate treatments for either cultivar of poinsettias or chrysanthemums (Tables 3.7 and 3.8).

*Chemical properties*

Figure 3.5 shows the pH of the poinsettia plants over the time of plant growth, and the substrate with the highest pH for both cultivars was 70:30 peat:PTS. This was possibly because
wood inherently had a higher pH than most other substrate materials, and the PTS had the highest BD so it had the greatest amount of wood substrate (Jackson et al., 2009; Fig 3.1). The lowest pH is 85:15 peat:perlite and peat:ForestGold. The EC had no clear trend between substrates (Fig 3.5).

For the Chrysanthemums, the highest starting pH is 70:30 peat:perlite and the lowest starting pH was 85:15 peat:perlite and peat:ForstGold (Table 3.6). The final pH had a similar trend except that the 85:15 peat:ForestGold was no longer lower than the other substrate treatments. The starting and final EC measurements show no significant difference between any substrate treatment.

**Conclusion**

The substrate mix 70:30 peat:PTS had the most root growth in the first four weeks of poinsettias growth. The fifth and sixth week of root growth there was not significant difference between substrates for the poinsettias. The chrysanthemums showed no difference in root growth between substrate over the four weeks of recorded growth. The poinsettia ‘Astro Red’ had the greatest bract area in the 85:15 peat:perlite which was very similar to the bract area index of 70:30 peat:FG and 70:30 peat:PTS. The bract area index for poinsettia ‘Charon Red’ showed no differences between substrate types. The 70:30 peat:PTS mix also had the highest pH of all the substrate treatments. The dry weights had no significant differences for either cultivar of either species. Overall, either wood fiber substrate showed that it can produce significantly similar if not better plants compared to plants produced in traditional substrates. This makes wood fiber a viable option as a horticultural substrate.
Literature Cited


Table 3.1 Physical properties of six different substrates. Two ratios, 85:15 and 70:30 with Canadian sourced sphagnum peat moss as the larger portion combined with 15 or 30% medium grade expanded perlite, ForestGold, or hammermilled Pine Tree Substrate.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Component</th>
<th>TP</th>
<th>CC</th>
<th>AS</th>
<th>DB</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15</td>
<td>Peat:perlite</td>
<td>82.8</td>
<td>64.3</td>
<td>18.5</td>
<td>0.09</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:perlite</td>
<td>81.9</td>
<td>69.8</td>
<td>12.1</td>
<td>0.11</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:PTS</td>
<td>88.2</td>
<td>71.2</td>
<td>17.0</td>
<td>0.10</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:PTS</td>
<td>84.7</td>
<td>70.5</td>
<td>14.2</td>
<td>0.13</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:FG</td>
<td>87.1</td>
<td>69.8</td>
<td>17.4</td>
<td>0.10</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:FG</td>
<td>90.1</td>
<td>71.0</td>
<td>19.2</td>
<td>0.09</td>
</tr>
</tbody>
</table>

LSD  2.43  2.76  2.90  0.008

*Physical and hydrologic properties determined using the methods of Fonteno and Harden (2010).

*TP = total porosity; total percentage of pore volume (TP = CC + AS).

*CC = container capacity; maximum water content after free (gravitational) drainage.

*AS = air space; total percentage of pore space not filled with water at CC.

*BD = bulk density; substrate dry weight/total sample volume.

*Means separation down column for individual properties using Tukey’s HSD with α = 0.05, means followed by the same letter are not significantly different (n=3).

*PTS = Pine tree substrate

*FG = ForestGold

*LSD = Fisher’s Least Significant Difference
Table 3.2 Bract area index of poinsettias grown in 6in standard containers with six different substrate mixes. Two ratios, 85:15 and 70:30 with Canadian sourced sphagnum peat moss as the larger portion combined with 15 or 30% medium grade expanded perlite, ForestGold wood fiber, and hammermilled Pine Tree Substrate.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>‘Astro Red’</th>
<th>‘Charon Red’</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15 peat:perlite</td>
<td>64.7 a_y</td>
<td>72.9 a_y</td>
</tr>
<tr>
<td>70:30 peat:perlite</td>
<td>52.3 c</td>
<td>71.4 a</td>
</tr>
<tr>
<td>85:15 peat:PTS</td>
<td>59.4 b</td>
<td>73.8 a</td>
</tr>
<tr>
<td>70:30 peat:PTS</td>
<td>61.4 ab</td>
<td>71.8 a</td>
</tr>
<tr>
<td>85:15 peat: FG</td>
<td>49.8 c</td>
<td>74.4 a</td>
</tr>
<tr>
<td>70:30 peat: FG</td>
<td>64.3 ab</td>
<td>75.3 a</td>
</tr>
<tr>
<td>LSD_v</td>
<td>5.37</td>
<td>7.10</td>
</tr>
</tbody>
</table>

_A Bract Area Index calculate with BAI = (width * length * π)/4_ (Lopez & Camerato, 2011)

_y Means separation down column for individual properties using Tukey’s HSD with α = 0.05. Means followed by the same letter are not significantly different (n=4)

 PTS = Pine Tree Substrate
 FG = ForestGold
 LSD = Fisher’s Least Significant Difference
Table 3.3 Poinsettias ‘Astro Red’ and ‘Charon Red’ were grown in mini-horhizotrons and root growth was measured (cm) over six weeks. The two were combined to analyze the effect of six different substrate treatments. Two ratios, 85:15 and 70:30 with Canadian sphagnum peat moss as the larger portion combined with 15 or 30% medium grade perlite, ForestGold wood fiber, and hammermilled Pine Tree Substrate (PTS).

<table>
<thead>
<tr>
<th>Substrate Ratio</th>
<th>Component</th>
<th>Poinsettia</th>
<th>Total Root Length (log10(cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15 Peat:perlite</td>
<td>Week 1</td>
<td>1.3 ab</td>
<td>1.5 ab</td>
</tr>
<tr>
<td>70:30 Peat:perlite</td>
<td>Week 2</td>
<td>1.3 ab</td>
<td>1.5 ab</td>
</tr>
<tr>
<td>85:15 Peat:PTS</td>
<td>Week 3</td>
<td>1.6 ab</td>
<td>1.8 a</td>
</tr>
<tr>
<td>70:30 Peat:PTS</td>
<td>Week 4</td>
<td>1.7 a</td>
<td>2.0 a</td>
</tr>
<tr>
<td>85:15 Peat:FG</td>
<td>Week 5</td>
<td>1.5 ab</td>
<td>1.9 a</td>
</tr>
<tr>
<td>70:30 Peat:FG</td>
<td>Week 6</td>
<td>1.0 b</td>
<td>1.2 b</td>
</tr>
</tbody>
</table>

\( \text{Root growth was measured each week after roots appeared on glass, the 5 longest roots were measured with a ruler and those 5 reps were totaled over each panel (6 panels per box) for a total of 30 reps into a total root length per mini-horhizotron root box with 3 reps of mini-horhizotrons per substrate.} \)

\( \text{Means separation down column for individual properties using Tukey’s HSD with } \alpha = 0.05. \) Means followed by the same letter are not significantly different (n=3)

\( x \text{PTS = Pine Tree Substrate} \)

\( w \text{FG = ForestGold} \)

ForestGold wood fiber, and hammermilled Pine Tree Substrate (PTS).
Table 3.4 Chrysanthemums ‘Gigi Yellow’ and ‘Kathleen Dark’ were grown in mini-horhizotrons and root growth was measured (cm) over six weeks. The two were combined to analyze the effect of six different substrate treatments. Two ratios, 85:15 and 70:30 with Canadian sphagnum peat moss as the larger portion combined with 15 or 30% medium grade perlite, ForestGold wood fiber (FG), and hammermilled Pine Tree Substrate (PTS).

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Component</th>
<th>Chrysanthemum Total Root Length (log10(cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Week 1</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:perlite</td>
<td>2.7 a</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:perlite</td>
<td>2.6 a</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:PTS_x</td>
<td>2.7 a</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:PTS</td>
<td>2.6 a</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:FG_w</td>
<td>2.5 a</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:FG</td>
<td>2.4 a</td>
</tr>
</tbody>
</table>

*R Root growth was measured each week after roots appeared on glass, the 5 longest roots were measured with a ruler and those 5 reps were totaled over each panel (6 panels per box) for a total of 30 reps into a total root length per mini-horhizotron root box with 3 reps of mini-horhizotrons per substrate.

¥ Means separation down column for individual properties using Tukey’s HSD with α=0.05. Means followed by the same letter are not significantly different (n=3)

PTS = Pine Tree Substrate

FG = ForestGold
Table 3.5 Chemical properties (pH) for Poinsettias ‘Astro Red’ and ‘Charon Red’ over nine weeks

<table>
<thead>
<tr>
<th>Substrate</th>
<th>pH for ‘Astro Red’ over time</th>
<th>Substrate</th>
<th>pH for ‘Charon Red’ over time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>Component</td>
<td>Week 1</td>
<td>Week 2</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:perlite</td>
<td>5.5 a</td>
<td>5.3 b</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:perlite</td>
<td>5.7 a</td>
<td>5.3 b</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:PTS x</td>
<td>4.9 b</td>
<td>4.8 c</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:PTS</td>
<td>5.6 a</td>
<td>5.8 a</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:FG w</td>
<td>5.0 b</td>
<td>4.9 c</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:FG</td>
<td>5.2 b</td>
<td>5.2 b</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:perlite</td>
<td>5.4 ab</td>
<td>5.0 bc</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:perlite</td>
<td>5.6 a</td>
<td>5.1 bc</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:PTS x</td>
<td>5.1 b</td>
<td>4.8 c</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:PTS</td>
<td>5.7 a</td>
<td>5.6 a</td>
</tr>
<tr>
<td>85:15</td>
<td>Peat:FG w</td>
<td>5.2 b</td>
<td>4.8 c</td>
</tr>
<tr>
<td>70:30</td>
<td>Peat:FG</td>
<td>5.3 b</td>
<td>5.1 b</td>
</tr>
</tbody>
</table>

Chemical properties of pH and EC are obtained with the pour through method (Wright, R.D. 1986). Means separated within column by Tukey’s HSD at $P \leq 0.05$. Means followed by the same letter are not significantly different (n=3).

PTS = Pine Tree Substrate  
FG = ForestGold
Table 3.6 Electrical conductivity (EC) for Poinsettias ‘Astro Red’ and ‘Charon Red’ over nine weeks

<table>
<thead>
<tr>
<th>Substrate Ratio</th>
<th>Component</th>
<th>EC for ‘Astro Red’ over time&lt;sub&gt;z&lt;/sub&gt;</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
<th>Week 8</th>
<th>Week 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15 Peat:perlite</td>
<td>1.3 ab&lt;sub&gt;y&lt;/sub&gt;</td>
<td>1.4 a</td>
<td>1.0 b</td>
<td>1.3 b</td>
<td>1.4 ab</td>
<td>1.2 ab</td>
<td>1.0 a</td>
<td>1.2 ab</td>
<td>2.1a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70:30 Peat:perlite</td>
<td>1.3 ab</td>
<td>1.4 a</td>
<td>1.7 a</td>
<td>1.6 ab</td>
<td>1.2 b</td>
<td>1.2 ab</td>
<td>0.8 a</td>
<td>1.0 b</td>
<td>2.2 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85:15 Peat:PTSx</td>
<td>1.4 ab</td>
<td>1.3 a</td>
<td>2.0 a</td>
<td>1.8 a</td>
<td>1.5 ab</td>
<td>1.2 ab</td>
<td>0.8 a</td>
<td>1.2 ab</td>
<td>2.1 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70:30 Peat:PTS</td>
<td>0.9 b</td>
<td>1.0 a</td>
<td>1.7 a</td>
<td>1.5 ab</td>
<td>1.4 b</td>
<td>0.9 b</td>
<td>0.7 a</td>
<td>1.1ab</td>
<td>2.2 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85:15 Peat:FGw</td>
<td>1.4 a</td>
<td>1.4 a</td>
<td>1.3 b</td>
<td>1.4 ab</td>
<td>1.8 a</td>
<td>1.1 ab</td>
<td>0.7 a</td>
<td>1.4 a</td>
<td>2.2 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70:30 Peat:FG</td>
<td>1.3 ab</td>
<td>1.2 a</td>
<td>1.2 b</td>
<td>1.2 b</td>
<td>1.7 a</td>
<td>1.6 a</td>
<td>0.9 a</td>
<td>1.2 ab</td>
<td>2.3 a</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substrate Ratio</th>
<th>Component</th>
<th>EC for ‘Charon Red’ over time&lt;sub&gt;z&lt;/sub&gt;</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Week 5</th>
<th>Week 6</th>
<th>Week 7</th>
<th>Week 8</th>
<th>Week 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15 Peat:perlite</td>
<td>1.3 a&lt;sub&gt;y&lt;/sub&gt;</td>
<td>1.4 ab</td>
<td>1.6 a</td>
<td>1.2 a</td>
<td>1.0 a</td>
<td>1.0 a</td>
<td>0.5 a</td>
<td>0.5 b</td>
<td>1.8 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70:30 Peat:perlite</td>
<td>1.3 a</td>
<td>1.4 a</td>
<td>1.5 a</td>
<td>1.4 a</td>
<td>1.0 a</td>
<td>1.1 a</td>
<td>0.6 a</td>
<td>0.6 b</td>
<td>1.6 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85:15 Peat:PTSx</td>
<td>1.1 a</td>
<td>1.4 ab</td>
<td>1.3 a</td>
<td>1.4 a</td>
<td>0.9 a</td>
<td>0.8 ab</td>
<td>0.4 a</td>
<td>0.4 b</td>
<td>1.6 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70:30 Peat:PTS</td>
<td>1.0 a</td>
<td>1.0 b</td>
<td>1.7 a</td>
<td>1.0 a</td>
<td>0.9 a</td>
<td>0.7 ab</td>
<td>0.4 a</td>
<td>0.5 b</td>
<td>1.9 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85:15 Peat:FGw</td>
<td>1.2 a</td>
<td>1.3 ab</td>
<td>1.7 a</td>
<td>1.4 a</td>
<td>1.3 a</td>
<td>0.9 a</td>
<td>0.6 a</td>
<td>1.0 a</td>
<td>1.8 a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70:30 Peat:FG</td>
<td>1.3 a</td>
<td>1.2 ab</td>
<td>1.5 a</td>
<td>1.4 a</td>
<td>1.1 a</td>
<td>0.5 b</td>
<td>0.5 a</td>
<td>0.5 b</td>
<td>1.8 a</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>z</sup> Chemical properties of pH and EC are obtain with the pour through method (Wright, R.D. 1986).

<sup>y</sup> Means separated within column by Tukey’s HSD at $P \leq 0.05$. Means followed by the same letter are not significantly different (n=3).

<sup>x</sup> PTS = Pine Tree Substrate

<sup>w</sup> FG = ForestGold
Table 3.7 Chemical properties, pH and electrical conductivity (EC) for Chrysanthemums ‘Gigi yellow’ and ‘Kathleen dark’ over 9 weeks (Starting = week 1, Final = week 9).

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Gigi Yellow</th>
<th>Kathleen Dark</th>
<th>Gigi Yellow</th>
<th>Kathleen Dark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Starting pH</td>
<td>Starting EC</td>
<td>Final pH</td>
<td>Final EC</td>
</tr>
<tr>
<td>85:15 peat:perlite</td>
<td>5.5 bc</td>
<td>3.2 a</td>
<td>5.0 ab</td>
<td>4.9 b</td>
</tr>
<tr>
<td>70:30 peat:perlite</td>
<td>5.9 ab</td>
<td>2.3 a</td>
<td>5.3 ab</td>
<td>5.4 a</td>
</tr>
<tr>
<td>85:15 peat:PTS</td>
<td>5.7 abc</td>
<td>3.4 a</td>
<td>5.2 ab</td>
<td>5.2 ab</td>
</tr>
<tr>
<td>70:30 peat:PTS</td>
<td>5.7 abc</td>
<td>2.6 a</td>
<td>5.1 ab</td>
<td>5.3 ab</td>
</tr>
<tr>
<td>85:15 peat: FG</td>
<td>5.6 bc</td>
<td>2.6 a</td>
<td>5.3 ab</td>
<td>5.1 ab</td>
</tr>
<tr>
<td>70:30 peat: FG</td>
<td>5.7 abc</td>
<td>2.4 a</td>
<td>5.2 ab</td>
<td>5.3 ab</td>
</tr>
</tbody>
</table>

Chemical properties of pH and EC are obtained with the pour through method (Wright, 1986).

Means separated within column by Tukey’s HSD at P ≤ 0.05. Means followed by the same letter are not significantly different (n=3).

PTS = Pine Tree Substrate

FG = ForestGold
Table 3.8 Shoot dry weights of Poinsettia “Charon Red” and “Astro Red” after 6 weeks of roots growth in the mini-horhizotrons.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Astro Red</th>
<th>Charon Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15 peat:perlite</td>
<td>8.0 a(y)</td>
<td>4.4 a(y)</td>
</tr>
<tr>
<td>70:30 peat:perlite</td>
<td>7.2 a</td>
<td>4.8 a</td>
</tr>
<tr>
<td>85:15 peat:PTS</td>
<td>7.9 a</td>
<td>4.7 a</td>
</tr>
<tr>
<td>70:30 peat:PTS</td>
<td>5.7 a</td>
<td>3.9 a</td>
</tr>
<tr>
<td>85:15 peat: FG</td>
<td>8.0 a</td>
<td>5.1 a</td>
</tr>
<tr>
<td>70:30 peat: FG</td>
<td>6.2 a</td>
<td>4.7 a</td>
</tr>
</tbody>
</table>

\(z\) Shoots were dried in a forced air drier at 70\(^\circ\)C for 48 hrs.
\(y\) Means separated by substrate treatment with Tukey’s HSD at \(P \leq 0.05\). Means followed by the same letter are not significantly different (n=3).
\(x\) PTS = Pine Tree Substrate
\(w\) FG = ForestGold
Table 3.9 Shoot dry weights of Chrysanthemums ‘Gigi yellow’ and ‘Kathleen dark’ after reaching anthesis, roughly 12 weeks after transplanting in 0.95L green plastic containers.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Gigi Yellow</th>
<th>Kathleen Dark</th>
</tr>
</thead>
<tbody>
<tr>
<td>85:15 peat:perlite</td>
<td>4.2 a(^y)</td>
<td>4.8 a</td>
</tr>
<tr>
<td>70:30 peat:perlite</td>
<td>2.8 a</td>
<td>4.7 a</td>
</tr>
<tr>
<td>85:15 peat:PTS(^x)</td>
<td>4.4 a</td>
<td>5.7 a</td>
</tr>
<tr>
<td>70:30 peat:PTS</td>
<td>3.4 a</td>
<td>5.2 a</td>
</tr>
<tr>
<td>85:15 peat: FG(^w)</td>
<td>2.3 a</td>
<td>5.9 a</td>
</tr>
<tr>
<td>70:30 peat: FG</td>
<td>4.7 a</td>
<td>5.4 a</td>
</tr>
</tbody>
</table>

\(^z\) Shoots dried in a forced air drier at 70°C for 48 hrs.
\(^y\) Means separated within column by Tukey’s HSD at \(P \leq 0.05\). Means followed by the same letter are not significantly different (n=4).
\(^x\) PTS = Pine Tree Substrate
\(^w\) FG = ForestGold
Figure 3.1 Six weeks of observed root growth in the mini-horhizotron comparison of two cultivars of poinsettias, ‘Astro Red’ represented by the blue line and ‘Charon Red’ represented by the orange line for 6 weeks of early root growth. (* = significant difference between the cultivars)
Figure 3.2 Six weeks of recorded root growth including poinsettias (‘Astro’ and ‘Charon’ Red combined together) in mini-horhizotron root boxes filled with 6 different substrates. Two ratios, 85:15 and 70:30 with Canadian sphagnum peat moss as the larger portion combined with 15 or 30% medium grade perlite (Per), ForestGold wood fiber (FG), and hammermilled Pine Tree Substrate (PTS) (*= significant differences between substrates as seen in Table 3.3).
Figure 3.3 Four weeks of observed root growth in the mini-horizotron comparison of two cultivars of Chrysanthemums, ‘Gigi Yellow’ represented by the blue line and ‘Kathleen Dark’ represented by the orange line. (* = significant difference between the cultivars)
Figure 3.4 Four weeks of recorded root growth including two cultivars of Chrysanthemums (‘Gigi Yellow’ and ‘Kathleen Dark’ combined) in mini-horhizotron root boxes filled with 6 different substrates. Two ratios, 85:15 and 70:30 with Canadian sphagnum peat moss as the larger portion combined with 15 or 30% medium grade perlite, ForestGold wood fiber (FG), and hammermilled Pine Tree Substrate (PTS) (*= significant differences between substrates as seen in Table 3.4).
Figure 3.5 pH of each substrate for poinsettias ‘Astro Red’ and ‘Charon Red’ over nine weeks of growth. Chemical properties of pH and EC are obtained with the pour through method (Wright, 1986).
Figure 3.6 Electrical conductivity (EC) of each substrate for poinsettias ‘Astro Red’ and ‘Charon Red’ over nine weeks of growth. Chemical properties of pH and EC are obtained with the pour through method (Wright, 1986).
APPENDICES
Appendix A. Photographs of the Poinsettia root growth project Fall 2018 in Chapter 3. (Figure A); The 5 longest were identified according to panels which were split in half at the curve of arm for a total of 6 panels. (Figure B); The mini-horhizotron’s were randomized on one side of the bench while the 4 reps of 6in pots for bract measurements and pour-through monitoring were randomized on the other. (Figure C); Once the five longest roots were identified they were measured by this flexible blue ruler.
Appendix B. Poinsettias in 0.95L green plastic standard containers with substrates as follows: 70:30 ratio of Canadian sphagnum peat moss as the larger portion combined (Figure A) 30% medium grade perlite, (Figure B) hammermilled Pine Tree Substrate, and (Figure C) ForestGold wood fiber. (Chapter 3)
Appendix C. Poinsettias after removal from mini-horizotron and brief root washing, the substrate treatment on the right is 70:30 Peat:Perlite and on the left is 70:30 Peat:Pine Tree Substrate (PTS). (Chapter 3)
Appendix D. Chrysanthemums in the mini-horhizotrons in the Fall of 2019. (Figure A) the mini-horhizotrons side panels were removed for filling with substrate and randomized on a bench once the rooted cutting was transplanted into the middle. (Figure B) Root growth two weeks after transplanting. (Figure C & D) Root growth four weeks after transplanting. (Chapter 3)
Appendix E. Chrysanthemums ‘Kathleen Dark’ in the mini-horzotrons in Fall semester of 2019; root growth five weeks after transplanting. (Figure A) 85:15 peat:perlite, (Figure B) 70:30 peat:perlite, (Figure C) 85:15 peat:PTS, (Figure D) 70:30 peat:PTS, (Figure E) 85:15 peat:FG, (Figure D)70:30 peat:FG. (Chapter 3).
Appendix F. Chrysanthemums ‘Gigi Yellow’ in the mini-horizotrons in the Fall of 2019; root growth five weeks after transplanting. (Figure A) 85:15 peat:perlite, (Figure B) 70:30 peat:perlite, (Figure C) 85:15 peat:PTS, (Figure D) 70:30 peat:PTS, (Figure E) 85:15 peat:FG, (Figure F) 70:30 peat:FG. (Chapter 3)
Appendix G. Materials used for substrates in Chapter 3; (Figure A) the NCSU PTS material was produced at the horticulture field lab with a hammermill and pine tree mulch from Parker Bark in Rose Hill, NC. (Figure B) ForestGold (a disk refined material produced Pindstrup, Denmark). (Figure C) Sphagnum peat moss sourced from Canada (Premier Pro Gro peat moss). (Figure D) Krumble Perlite from Carolina Perlite Company (Gold Hill, NC, U.S.A).
Appendix H. Traditional substrate materials; Perlite from Carolina Perlite Company (Gold Hill, NC, U.S.A.) Premier Pro-Gro Sphagnum peat moss sourced from Canada (Can Peat), and Sphagnum peat moss sources from Klassmann, Germany (Euro Peat). Characterized in Chapter 2.
APPENDIX I

A: GreenFibre Screw Extruded Wood
B: ForestGold Disk Refined Wood
C: NCSU hammermilled PTS
Appendix I. Chapter 2 Substrate materials in 3 inch cores. (Figure A) Screw-extruded Green Fibre from Klassmann, Germany (Figure B) Disk refined Forest Gold from Pindstrup, Denmark (Figure C) Hammermilled Pine Tree Substrate (PTS) from NC, U.S.A, (Figure D) European sourced peat (Euro Peat) from Klassmann, Germany, (Figure E) Perlite from Carolina Perlite Company (NC, U.S.A), (Figure F) Sphagnum peat moss sourced from Quebec Canada (Can Peat).
Appendix J. Wood Substrates; Forest Gold disk refined wood from Pindstrup, Denmark. Green Fibre screw extruded wood from Klassman, Germany, and hammermilled PTS from NC, U.S.A. Characterized in Chapter 2.