Chemical, Physical, and Biological Factors Influencing Nutrient Availability and Plant Growth in a Pine Tree Substrate

by

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(ABSTRACT)

Pine tree substrate (PTS) produced from freshly harvested loblolly pine (*Pinus taeda* L.) trees has potential for replacing or reducing the use of aged pine bark (PB) and peat moss as container substrates for horticulture crop production. The objective of this work was to determine the factors influencing nutrient availability in PTS compared to PB or peat substrates. Chapter two reports data on the response of japanese holly and azalea to fertilizer rate when grown in PTS and PB. This study demonstrated that an additional 2.4 $kg \cdot m^{-3}$ of Osmocote Plus (15N-3.9P-10K) controlled release fertilizer is required for both species when grown in PTS compared to PB. Data are reported in chapter three on the effects of fertilizer rate, substrate particle size, and peat amendment on growth and floral quality, and on post-production time-to-wilting of poinsettias. Data from this work show that PTS requires an additional 100 $mg \cdot L^{-1}$ N to grow poinsettias comparable to plants grown in peat unless the particle size of PTS was decreased or 25% peat was added, in which case no additional fertilizer was needed. Results also indicated that PTS shrinkage was similar to that of peat, and that post-production time-to-wilting in PTS plants was similar as plants grown in peat. Data in chapter four compares nitrogen (N) immobilization rates, substrate carbon dioxide (CO_2) efflux levels, and nutrient

leaching in peat, PB, and PTS over time. Data from these studies indicated that more N immobilization occurs in PTS than in PB or peat and that the substrate CO_2 efflux levels (estimate of microbial activity) corresponds to N immobilization in all substrates. Nutrient availability, changes in physical and chemical properties, substrate shrinkage, and microbial activity in PTS compared to PB during long-term nursery production are reported in chapter five. Results showed that substrate nutrient levels remain lower in PTS and that pH levels of PTS decrease considerably over two growing seasons compared to PB. Results also indicate that PTS does decompose over time in containers, but substrate shrinkage of PTS is similar to that of PL and PB during crop production.

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Ten years ago I began my academic journey never knowing what the future would hold or what direction my life would take. The only thing I had were high hopes and big dreams of a bright and exciting future filled with all those great opportunities in life that Dad always told me about. Little did I know then that over ten years later I would be where I am today. As I reflect on my time here at Virginia Tech, I have several thoughts that I will attempt to summarize in the paragraphs below as an overview of my exciting and challenging graduate experience and a mention of those who helped make it possible.

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*Unless otherwise noted in the figure captions, all figures are property of the author.

CHAPTER I

INTRODUCTION

The nursery and greenhouse industries have experienced tremendous growth over the last four decades. The USDA (Floriculture and Nursery Crops Yearbook, 2007) reported that the nursery and greenhouse industries have increased economically by $52 million from 2005 to total $17 billion in gross receipts in 2006. The greenhouse and nursery industries have undergone many changes and innovations during the last several decades to more efficiently and properly manage irrigation, fertility, substrate use, integrated pest management, etc (Bilderback, 2001; Yeager et al., 2007). Of these, research and development of new substrates to replace conventionally used peat moss and pine bark (PB) substrates has increased in recent years. In addition to developing and utilizing new substrates, much work has focused on managing fertility and irrigation programs of these substrates to maximize plant performance and minimize nutrient loss due to environmental concerns (Gouin and Link, 1973; Warren and Bilderback, 2004).

Growing in containers offers many advantages to the grower such as year-round marketing and the potential to produce many plants in a given area. However, container production also requires daily attention and precise control of many critical production factors (Bilderback, 1982). One of the most important factors is the medium or container substrate in which the plants are grown, since the development and maintenance of an extensive functional root system is essential to the growth of a healthy plant. A variety of terms are applied to the materials in which the roots of crops grow. They include growing media, soilless media, medium, potting or container mixes, potting composts and substrates. Many of these terms are imprecise or can be confusing and will often be

used interchangeably. The term "substrate" avoids much of the confusion of other terms and is descriptive of the entire composition.

Container-grown plants are subjected to the unique environment of growing in a limited volume of root medium from which water and nutrients must be absorbed. Uniformity in the substrate from one container to another or from one crop or season to the next is essential if a grower is to standardize fertilizer or water application. The need to develop new substrates and fertility management programs for the horticulture industry is an issue that is being addressed by researchers around the world.

LITERATURE REVIEW

Container Substrates in Horticulture

A container substrate is the material or combination of materials used to grow most greenhouse and nursery crops. The purpose of a container substrate is to physically support plants and to supply adequate oxygen, water, and nutrients for proper plant functions (Handreck and Black, 2005; Reinikainen, 1993). Several factors influence how to choose substrates for horticultural crop production beginning with the type/species of plants to be grown. Depending upon the production system substrates should be able to sustain plant growth for short-term or long-term crops with minimal shrinkage or degradation (Martin, et al., 1978; Reinikainen, 1993). Substrates should also be free from undesirable components such as pathogens, weed seeds, and foreign materials such as heavy metals, glass, and metal.

Soilless substrates began receiving notable attention in the 1970's to replace the use of field soil as a container substrate component (Aaron, 1982; DeWerth, 1971;

Gartner et al., 1971; Hoitink and Poole, 1979; Solbraa, 1974). In the last 35 years container production of most all horticultural crops has depended essentially on quality soilless substrates derived from both organic and inorganic constituents. Early reports of materials that were used to replace field soil include peat moss, barks (hardwood and softwood), wood shavings, wood chips, rice hulls, and numerous composted organic residues (Bollen, 1969; Bollen and Lu, 1961; Bunt, 1988; Cappaert et al., 1973; Gartner et al., 1973a; Hoitink and Poole, 1980; Molitor, 1983; Verdonck et al, 1983).

Physical and Chemical Properties of Container Substrates

The success of a horticultural substrate is mainly based on the behavior of the plants grown in them; high quality substrates with the proper physical and chemical properties can result in high yields and excellent plant quality (Chen et al., 1988; Verdonck and Gabriels, 1988). When plants are grown in containers, their roots are restricted to a small volume, consequently the demands made on the substrate for water, air, nutrients, and support are much more intense than those made by field-grown plants which have an infinitely greater volume of soil in which to facilitate root growth (Bunt, 1988). Interactions between individual substrate properties, irrigation water applied, the environment the substrate is subjected to, and the cultural practices they undergo, influence substrate structure (settling, decomposing, etc.) through time and in turn, plant performance.

Recommendations for desirable physical properties have been determined for horticultural substrates to give growers an idea of materials that could be used as components for their substrate blends. In addition, the suggested physical and chemical properties of substrates are outlined in The Best Management Practices (BMP) Guide for

Producing Container-Grown Plants (Yeager et al., 2007). This reference suggests the following ranges for desired physical properties for container substrates after irrigation and drainage (% volume basis): air space 10 to 30%, water holding capacity 45 to 65%, total porosity 50 to 80%, and bulk density 0.19 to 0.70 g/cm^3.

Numerous methods are used to determine physical properties of horticulture substrates. A common procedure for determining substrate physical properties is the North Carolina State University Porometer (Fonteno et al., 1995). Chemical properties can be determined from leachate extracted from substrates by using one of several popular methods including saturation extraction (Warncke, 1986), bulk solution displacement (Nelson and Faber, 1986), and the pour-through nutrient extraction procedure (Wright, 1986).

Bark Substrates

A by-product of the lumbermill and papermill industries, tree bark accumulated in large quantities prior to the 1970's and 1980's. To avoid unsightly piles, sawmills often incinerated the bark, or dumped it into rivers (Gartner et al., 1973b). Using treebark as a container substrate provided a rational solution to the waste bark disposal problem without polluting land, air, or water resources (Jervis and Regan, 1973; Svenson, 1986). Since then growers in the western and southeastern regions of the United States have found fir, redwood, or pine bark to be excellent sources of organic substrate components for the production of ornamental plants in containers, while loblolly pine bark is the favored component in the southeast U.S. (Pokorny, 1979). Hardwood tree bark has also

been shown to be a suitable substrate component for growers in the northern and midwestern regions (Gartner et al., 1971; Hoitink, 1980; Hoitink and Poole, 1979).

Pine bark is removed from harvested trees (Fig. 1.1) and sent to bark suppliers or private growers for aging/composting. Pine bark is aged in windrows for as little as 5 weeks or composted in windrows for up to 6 months. Aged PB (Fig. 1.2) is the preferred substrate for growers even though research has shown that fresh PB can be used as a substrate for successful crop production (Cobb and Keever, 1984; Harrelson et al., 2004). Recently, supplies of PB in many southeastern states have been erratic and increasing in price due to several factors. As the price of fuel and electricity increases, demand for PB (and other wood by-products) for use as fuel has increased (Griffith, 2007; Lu et al, 2006; Tilt et al., 1987), thereby reducing the amount of PB available for use as a growing substrate. Secondly, the demand for PB as a packaged and bulk landscape mulch has increased dramatically over the past decade. Since mulch commands a higher price to home owners, and costs less to produce (less hammer milling, screening, no aging, etc.), suppliers prefer to sell PB as mulch rather than as a less-profitable substrate to growers. Finally, the amount of PB being produced by sawmills (timber industry) fluctuates according to demand for lumber by the building industry and the need for pulpwood. As the demand for lumber rises or falls, the number of trees being harvested and debarked increases or decreases accordingly (Lu et al, 2006).

Peat moss

Sphagnum peat moss (Fig. 1.3) used in the U.S. comes from Canada and is usually transported throughout the U.S. in large 64 ft^3 bales (Fig. 1.4). Canadian

sphagnum peat moss is derived from the slow decomposition of sphagnum moss, which accumulates in Canada's bogs or peat lands (Fig. 1.5). To harvest peat, harvesters clear bogs of vegetation and then dig shallow ditches to lower the water table. When the peat dries, the equipment (Fig. 1.6) necessary to harvest the peat can operate on the field (Keys, 2001). This process requires a lot of heavy equipment and labor, which in turn means higher prices for the material.

The level of peatland exploitation is considered nonsustainable by wetland ecologists (Robertson, 1993), but considered sustainable by the peat industry (Robertson, 1993), even though they recognize that alternatives to peat must be developed to meet environmental and legal concerns pertaining to peatland exploitation (Pryce, 1991). The mining of peat (destruction of non-renewable peat bogs) has raised concern among environmental, scientific, private, and governmental agencies (Barkham, 1993; Carlile, 2004; Clark, 2008; Robertson, 1993) and have led to policy changes and governmental regulations on peat use in several European countries. Peat supplies/production can also be limited by wet weather conditions that restrict harvest (Hidalgo and Harkess, 2002) during certain times of the year. These concerns, coupled with increasing fuel (transportation) costs, have led to increased cost of peat substrates and therefore resulted in a greater interest in less expensive and readily available substitutes.

Coconut Coir

Coir dust is the remaining waste product when long fibers are extracted from coconut husk (*Cocos nucifera* L.). The coir constitutes the short fibers and mesocarp pith of coconuts (Ma and Nichols, 2004; Fig. 1.7). Coir originates primarily from Sir Lanka,

India, Philippines, Indonesia, Mexico, Costa Rica, and Guyana (Evans and Stamps, 1996) and is shipped to the U.S. in large bulk bales (Fig. 1.8). Coir dust has many desirable substrate characteristics such as high water holding capacity; excellent drainage; absence of weeds and pathogens; physically resilient; slow decomposition; acceptable pH, CEC, and EC; easily wettable, and a renewable resource with no known ecological drawbacks (Abad, et al., 2005; Cresswell, 1992; Lennartsson, 1997; Martinez et al., 1997; Pill and Ridley, 1998; Verdonck et al., 1983). Due to these favorable characteristics, coir has been extensively used as an environmentally safe substitute for natural peat in container substrates.

Researchers have evaluated the potential use of coir as a container substrate (or substrate component) with successful results growing annual bedding plants (Awang and Ismail, 1997; Evans and Stamps, 1996; Handreck, 1993c), herbaceous perennials (Pill and Ridley, 1998), foliage plants (Stamps and Evans, 1999), vegetables (Cresswell, 1992), and woody plants (Hernandez-Apaolaza et al., 2005). With the success and stability of coir as an organic container substrate it has become a commercially popular material that is now being used around the world as a peat substitute for container-grown crops (Abad et al., 2005; Handreck, 1993c; Noguera et al., 1997). Coir remains a heavily used alternative to peat moss as a substrate but due to the distances it has to be shipped, transportation costs are also becoming a factor in its economical use as a substrate.

Compost-based Materials

Although composting has been practiced for thousands of years, it was not until the 20th century that controlled scientific studies were published illustrating the benefits of compost use in crop production. The two main horticultural uses of composts are as

soil amendments and as components in container substrates (Raviv, 2005). Raviv (2005) lists three main reasons for the increased use of composts as a component in horticultural container substrates: 1) in many cases, nonedible crops, such as ornamentals, forest and garden trees, shrubs, etc., can serve as a safe outlet for composts that may be considered as undesirable for use in food crop production; 2) various composts perform as well as peat moss when used in container substrates and their cost is considerably lower; 3) mature composts may suppress many soil borne diseases. Research has been conducted through the years to confirm and further investigate the potential for marketing and successfully incorporating these organic materials into current horticulture production systems (Bugbee, 2002; Calkins et al., 1997; Chong et al., 2004; Hernandez-Apaolaza et al., 2005; Jackson et al, 2005; Raviv, 1998).

However, some materials used for composting are proving to be unsuitable because of their high degree of variability, limited availability, and their likelihood of containing undesirable materials such as a glass, metal fragments, and heavy metals to name a few. Other materials are not produced in volumes large enough to impact the commercial market (Evans and Stamps, 1996). Several materials that have been evaluated through the years for their potential for use as a container substrate are shown in Table 1.1.

Table 1.1. Organic materials researched as potential container substrate alternatives.

Materials	Reference
Municipal waste	Bugbee, 2002; Gouin, 1985; Hicklenton et al., 2001; Klock, 1997; Lopez et al., 1998; Marcotrigiano et al., 1985; Wilson and Stoffella, 2003;
Poultry waste	Bilderback and Fonteno, 1993; Evans, 2004; Tyler et al., 1993; Zoes et al., 2001
Pig, horse, and cattle waste	Atiyeh et al., 2002; Ball et al., 2000; Cull, 1981; Freeman and Cawthon, 1999; Inbar et al., 1986; Marfa et al., 2002
Green waste	Benito et al., 2005; Beeson, 1996; Burger et al., 1997; Guerin et al., 2001; Hartz et al., 1996; Prasad and Maher, 2001
Cork waste	Aguado et al., 1993; Carmona et al., 2003a; Carmona et al., 2003b
Tung husks (*Aleurites fordii* Hemsl.)	Gruszynski and Kampf, 2004
Pecan and almond shells	Urrestarazu et al., 2005; Wang and Pokorny, 1989
Rice hulls	Dueitt and Newman, 1994; Evans and Gachukia, 2004; Evans and Gachukia, 2008; Gachukia and Evans, 2008; Laiche and Nash, 1990; Marianthi, 2006
Peanut hulls	Bilderback et al., 1982; Fernandes et al., 2007; Reed, 1996
Carob (*Ceratonia siliqua* L.)	Reis et al., 1995; Rishani and Rice, 1988
Olive-mill waste	Papafotiou et al., 2004; Papafotiou et al., 2005
Mushroom media waste	Chong et al., 1994; Wever et al., 2005
Grape marc	Baran et al., 2001; Chen et al., 1988; Inbar et al., 1986; Reis et al., 1998; Reis et al., 2001
Apple pomace	Chong, 1992; Worrall and Yang, 1992
Palm press fibre	Thambirajah and Kuthubutheen, 1989
Bagasse (sugarcane/sorghum waste)	Handreck and Black, 2005; Sanchez et al., 2004; Stoffella and Graetz, 2000; Trochoulias et al., 1990
Cotton gin trash	Handreck and Black, 2005; Jackson et al., 2005a and 2005b; Lopez et al., 1998; Owings, 1994
Newspaper & waste paper	Craig and Cole, 2000; Glenn et al., 2000
Coal bottom ash	Butler and Bearce, 1995; Woodard et al., 1993
Aquatic plant waste	Lumis, 1980; Orquin et al., 2001
Earthworm castings (vermicompost)	Atiyeh et al., 2000; Atiyeh et al., 2001; Atiyeh et al., 2002; Hildago et al., 2002a and 2002b; Hildalgo et al., 2005
Pulp-mill waste	Tripepi et al., 1996
Agro-industrial wastes	Bragg, 1998; Garcia-Gomez et al., 2002; Inbar et al., 1988

Wood-based Substrates and Substrate Components

Wood residues constitute a significant source of soilless container substrates. These materials are generally by-products of the lumber and sawmill industries but their quantities depends on regional and sometimes seasonal availability. Nitrogen depletion by soil microorganisms, and shrinkage during the decomposition process, is one of the primary problems associated with these materials. However, supplemental applications of N to the growing media can make most wood residues valuable amendments. The lack of substrate consistency and insufficient quantities of these waste materials is a problem for long-term and sustained use as a major substrate, especially for large production operations. In response, researchers have begun testing wood-based substrates that are specifically produced for use as container substrates instead of utilizing wood waste and other by-product materials. Much work has been recently published on wood substrates to demonstrate these substrates can be alternatives to current materials. Table 1.2 lists some of the plant species used as sources of wood for substrate production.

Table 1.2. Several examples of tree species used in the production of wood- or sawdust-based substrates that have been evaluated as container substrates or substrate components.

Source	Reference
Hardwood species	
elm (*Ulmus* sp.)	Kenna and Whitcomb, 1985; McCool, 1949
chinese tung tree (*Aleurites fordii* Hemsl.)	Gruszynski and Kampf, 2004
eucalyptus sp. (*Eucalyptus* sp.)	Beardsell et al., 1979; Worrall, 1978
gorse (*Ulex* sp.)	Iglesias et al., 2008
locust (*Robinia pseudoacacia* L.)	McCool, 1949
oak sp. (*Quercus* sp.)	Kenna and Whitcomb, 1985; Rau et al., 2006
paper tree (*Melaleuca quinquenervia* Cav.)	Ingram and Johnson, 1983; Poole and Conover, 1985
red maple (*Acer rubrum* L.)	Rau et al., 2006
sycamore (*Platanus occidentalis* L.)	Rau et al., 2006
tree fern (*Dicksonia* sp.)	Prasad and Fietje, 1989; Salvador, 2008
willow (*Salix* sp.)	Gariglio et al., 2004
Softwood species	
balsam (*Abies grandis* D. Don)	Newton, 1953
cedar (*Thuja plicata* D. Don)	Newton, 1953
fir (*Pseudotsuga* sp.)	Cotter, 1974; Newton, 1953; Kullmann, et al., 2003
hemlock (*Tsuga heterophylla* Raf.)	Newton, 1953
larch (*Larix* sp.)	McCool, 1949
loblolly pine (*Pinus taeda* L.)	Fain et al., 2008 ; Wright and Browder, 2005
longleaf pine (*Pinus palustris* Mill.)	Fain et al., 2008
spruce (*Picea* sp.)	Gumy, 2001; McCool, 1949; Kullmann et al., 2003
scots pine (*Pinus sylvestris* L.)	Kullmann et al., 2003
slash pine (*Pinus elliottii* Engelm.)	Fain et al., 2008
white pine (*Pinus strobes* L.)	Rau et al., 2006
white spruce (*Picea glauca* Moench.)	Dorais et al., 2005
yellow pine (*Pinus echinata* Mill.)	McCool, 1949

European Research with Wood-based Substrates

Research in Europe has been conducted for over two decades on the development of horticultural substrates composed of wood (Gumy, 2001; Raviv and Lieth, 2008). There are considerable quality differences between the various types of wood fibre substrates available on the commercial market (Gumy, 2001). Substrate manufacturers would ideally like to have products whose physical and chemical properties are as similar

as possible to those of peat. It is possible however, that even with different properties, growers can use wood fiber substrates if they are willing to adapt their management and cultural practices to accommodate the new substrate mixes. The only wood fibre products that will be successful are those that are readily available, of consistent quality, competitively priced, and for which an efficient production system has been developed.

Hortifibre®

Systematic development of wood fibre products in Europe for horticultural purposes was initiated in France at the end of the 1980s by Elf Aquitaine, the inventor of the first commercial wood substrate called Hortifibre® (Schilling, 1999). Hortifibre® is produced from a patented process of wood fibre separation where mechanical and thermal pressure are applied to wood chips, cutting it into shavings which are then treated with steam to drive off (volatilize) toxins found in fresh wood (Lemaire et al., 1989). The species of pine used to produce Hortifibre® are *Pinus pinaster* and *Pinus sylvestris*. This process allows for the production of coarse or fine fibres so that the final product can have the particle size desired.

Fibralur®

Researchers at the Public University of Navarre (Pamplona, Spain) who, jointly with the Aralur company in Ziordia (Navarre, Spain), have developed a wood substrate that is patented and currently marketed in Europe (mainly Spain). The product is called "Fibralur®" and is made from pine wood shavings which have been defibered by means of an industrial process. The resulting material has proved to be successful in growing

mushrooms and other hydroponic crops, nursery crops, and to a lesser extent, with vegetable and forest nurseries (Aralur, 2008; Muro et al., 2005). The same machinery used for defibering wood to make paper is used to make Fibralur®. Wood fibre for papermaking goes through two or three defibering processes while Fibralur® substrate is the result of a single defibration resulting in thicker and longer wood fibers. During this defibration process the bark of the pine is subjected to a washing in water at a temperature of 90-115 ºC, the resulting cellulose being practically pure, free of phytotoxic products and ready to be used in the growing of agricultural crops (Aralur, 2008).

Toresa®

The most produced and available wood substrate currently in Europe is called Toresa®. Toresa® was developed and patented (European Patent No. 91 905 064. 1-2313 / 0 472 684) by Prof. Franz Penningsfeld and Gerhard Baumann in Germany (Gumy, 2001; Schilling, 1999). There are four different formulations/brands of Toresa® (Toresa Spezial, Toresa Standard, Toresa Holzfaser, and Toresa Eco) that are produced and marketed within Europe, with the main differences between the products being the addition (impregnation) of fertilizers or differences in the source and type of wood used to make the wood fibre. Toresa® is primarily produced in Germany, The Netherlands, Austria, and Switzerland with 90 – 95% of the wood used for production coming from spruce (*Picea abies*; Schilling, 1999). The remaining wood (5 – 10%) is derived from other conifer species, hardwood species, and some wood waste (Fraxinus, Populus, Salix, Fagus; Gumy, 2001). In 1999 it was estimated that 200,000 m^3 of Toresa® would be

produced and distributed in the EU (Schilling, 1999). The untreated wood used to make Toresa® is processed by two "thermo screw presses" that actually tear the wood chips, creating a soft wood fiber (personal observation at a Toresa® processing facility in Hamburg Germany at an Intertoresa AG, Inc. facility). The screws shred the wood chips under fractional pressure, heat and steam, and simultaneously have the capability to impregnate the wood fibre with additives (color, fertilizers, etc.; Gumy, 2001). It is recommended that 20-40% (up to 70%) of a container substrate can be replaced with this wood fibre with no negative impact on plant growth or without adjusting management strategies (fertilization, irrigation, etc.) of the substrate (Schilling, 1999).

A more complete list of the commercial wood substrates that have been developed and commercialized in Europe during the last two decades are in Table 1.3.

Table 1.3. Wood substrates developed and commercialized in Europe.

Substrate	Authors & Year
Toresa®	Gumy, 2001; Penningsfeld 1992
Culti-Fibre®	Gumy, 2001; Sramek and Dubsky, 2002
Pietal®	Gumy, 2001; Prasad and Maher, 2004
Torbo®	Gumy, 2001; Schmilewski, 2008
Torbella®	Gumy, 2001; Schmilewski, 2008
Bio-Culta®	Gumy, 2001; Schmilewski, 2008
HortiFibre®	Gumy, 2001; Beniot and Ceustermans, 1994
Fibralur®	Muro et al., 2005
Fibrosana®	Gruda et al., 2008
Ekofibre®	Clark and Basham, 2002; Wever et al., 2004

Sawdusts as Container Substrates or Substrate Components

Plant production in substrates which contain large portions of sawdust has required new strategies in N management as plants grown in such substrates have a tendency to become N deficient due to N immobilization (Handreck, 1991; Hoitink and

Poole, 1980; Worral, 1985). Like hardwood bark, plant growth is severely restricted in uncomposted sawdust (Allison and Murphy, 1962; Allison, 1965). This effect is mainly one of a depletion of available N but walnut and incense cedar sawdust is known to have direct phytotoxic effects (Allison and Murphy, 1962). Sawdust has characteristics that make it desirable for use in a growing mix. It has a bulk density slightly less than sphagnum peat moss, has similar water retention but greater air space after drainage than pine bark (Bilderback, 1982). Large amounts of N must be added to compensate for N depletion of sawdust. It is estimated that 2 to 3% N by weight is required to compost sawdust, thus 100 pounds (45 kg) of sawdust would require 2 to 3 pounds (0.91 - 1.36 kg) actual N. Great risk of very high soluble salt levels would occur if this much N was added while growing a nursery crop. Also hardwood sawdusts decay more rapidly than PB sawdust and require about 1% by weight more N to accomplish decomposition (Worrall, 1985). Old sawdust has a lower N requirement than fresh sawdust but full decomposition cannot occur without the addition of N.

Richards (1981) outlines the problems of growing plants in pure *Pinus radiata* sawdust including the difficulty in providing sufficient N to overcome N immobilization while avoiding osmotic stress from the salinity of the high concentration of nutrients applied. Thomas et al. (1980) found that seedling plants grown in peat/sand media were consistently superior to those grown in a similar mix but containing one third *P. radiata* sawdust. A range of fertilizer types and N levels did not significantly improve growth in the sawdust medium. Plants growing in the sawdust-based mix generally showed greater leaf chlorosis indicative of N deficiency. Sharman and Bodman (1991) grew a range of woody ornamentals in media containing 50% composted Eucalyptus sawdust, other

organic materials, and only 10 to 15% mineral materials. They applied controlled-release fertilizers at a range of rates and reported satisfactory growth particularly where leafy plants were grown at high N rates. Non-composted sawdust from douglas fir (*Pseudotsuga menziesii* Mirb.) and western hemlock (*Tsuga heterophylla* Raf.) have also been used to grow a wide range of herbaceous and woody container crops in Canada where sawdust is plentiful (Maas and Adamson, 1972).

Other Research with Wood-based Materials

Ground melaleuca trees (*Melaleuca quinquenervia* Cav.) were shown to be an acceptable substitute for bark or sedge peat when used to grow a number of woody and herbaceous plants (Conover and Poole, 1983a; Conover and Poole, 1983b; Ingram and Johnson, 1983; Poole and Conover, 1985). No phytotoxicity problems were evident in these studies as long as the proportion of melaleuca did not exceed 50% of the substrate volume.

Ground stem core of kenaf (*Hibiscus cannabinus* L.), a light weight biomass crop grown in several Gulf Coast States including Louisiana, Mississippi, and Texas has been used successfully as a replacement for pine bark in production media for greenhouse and tropical nursery crops (Goyne and Arnold, 1996; Howell et al., 1993; Wang, 1994). Lang (1997) and Webber et al. (1999) reported results with a substrate composed of noncomposted ground kenaf (*Hibiscus cannabinus* L.) plants to produce poinsettia and periwinkle (*Vinca minor* L.) with equal size and quality to plants grown in peat-based substrates. Tsakonas et al. (2005) used processed whole-stem kenaf and sand as a substrate to produce lettuce (*Lactuca sativa* L.) and pepper (*Capsicum annum* L.) plants.

Seeds were sown directly into the kenaf substrate and a peat-based substrate with germination and total plant growth data recorded over 100 days. They found that plant growth for both species was inhibited by kenaf even when used as only a 10% component of a peat substrate. Growth differences in their study were eliminated by soaking the kenaf substrate in an NH_4NO_3 solution prior to use, indicating that N was the limiting factor to plant growth. Laiche and Newman (1994) evaluated composted and noncomposted kenaf substrate in the production of holly (*Ilex crenata* Thunb. 'Cherokee') and found that composted kenaf produced larger and better quality plants. They also concluded that plants grown in composted kenaf substrate had equal growth to plants grown in the PB control. Composted kenaf produced larger plants than noncomposted kenaf, and the recommendation was made that kenaf needs to be composted prior to its use a substrate.

Kenna and Whitcomb (1985) demonstrated that *Pyracantha* x 'Mojave' and *Liquidambar formosana* Hance. grew as well in a substrate of woodchips:peat:sand (3:1:1 v/v/v) as in a substrate composed of bark:peat:sand (3:1:1 v/v/v). Wood chips for their study were produced by grinding entire trees including leaves, twigs, bark and wood of post oak (*Quercus stellata* Wangh.) and Siberian elm (*Ulmus pumila* L.). Wood shavings of fir (*Pseudotsuga menziesii* Mirb.) and redwood (*Sequoia sempervirens* D. Don) trees (derived from hardwood and softwood tree species (Criley and Watanabe, 1974) have been investigated for the production of carnations (*Dianthus caryophyllus* L.) (Stark and Lukaszuk, 1991), chrysanthemums (*Chrysanthemum morifolium* Ramat.) (Scott and Bearce, 1972; Still et al., 1972), and other potted foliage plants (Worrall, 1981) with results compared to peat-based substrates.

Pine Tree Substrates

Laiche and Nash (1986) produced a pine tree substrate (PTS) derived from PB with a considerable percentage of pine wood and a second PTS derived from whole pine trees (needles, twigs, bark, and wood). They reported that plant growth (*Rhododendron indica* L. 'President Clay', *Ligustrum sinense* Lour. 'Variegata', and *Ilex crenata* Thunb. 'Compacta') was highest in 100% PB compared to the two PTSs and that additional work was needed before pine wood could be used as a container substrate.

Wright and Browder (2005) demonstrated that japanese holly (*Ilex crenata* Thunb. 'Chesapeake'), azalea (*Rhododendron obtusum* Planck. 'Karen'), and marigold (*Tagetes erecta* Big. 'Inca Gold') could be grown in a noncomposted PTS (100% wood) produced from debarked loblolly pine trees. Nutrient analysis of the PTS substrate solution indicated that nutrient levels and pH were acceptable for plant culture, although extra fertilizer was added to PTS to maintain comparable electrical conductivity (EC) levels between the two substrates. Wright et al., 2006 also evaluated the growth of numerous woody nursery species (27 genera) in a PTS produced from ground pine logs (including the bark; approximately 90% wood and 10% bark) compared to PB. Results from this work concluded that plant dry weights were generally higher in PB than PTS, but differences in growth between PB and PTS were less when plants were supplied with higher fertilizer rates (21 g vs. 15 g Osmocote Plus 15N-3.9P-10K; O.M. Scott Horticulture Products, Maryville, OH). Growth differences in these studies were attributed to lower nutrient levels in the PTS due to either leaching or microbial immobilization of applied nutrients.

Based on this work a U.S. patent (Chipped wood as a substrate for plant growth; patent number 7165358) has been granted to Virginia Tech. Since then, PTS produced from freshly harvested delimbed loblolly pine trees that are between 12 and 15-years-old has also been used to successfully grow a wide variety of herbaceous annuals and perennials and greenhouse crops including poinsettias and chrysanthemums (Jackson et al., 2007; Jackson and Wright, 2008; Jackson et al., 2008b; Wright et al., 2008a; Wright et al. 2008c). Pines of that age are normally harvested as part of a thinning/management operation (Fig. 1.9) and the timber is often used for paper production or energy uses. The logs with bark still intact (Fig. 1.10) were chipped in an industrial tree chipper (Fig. 1.11) to produce pine chips (2.5 cm x 2.5 cm x 0.5 cm; Fig. 1.12). The pine chips are then passed through a hammer mill to obtain a desired particle size (Fig. 1.13). Once produced, PTS is a clean material free from foreign debris, soil, rocks, weed seeds or pathogens and can be immediately used to fill containers for plant production (Fig. 1.14). Conceivably, a tree can be harvested, chipped, ground, and filled in containers for use as a substrate all in the same day. Pine tree substrate has also been produced (hammered) with 25% PB to increase water retention and CEC (Fig. 1.15) which also gives the PTS a more "soil-like" look that most growers and retail consumers are accustomed to seeing in their potting substrates.

Fain et al. (2008b) manufactured a PTS (referred to as *WholeTree*) by chipping and grinding freshly harvested 8- to 10-year-old pine trees (*Pinus taeda, P. elliottii, and P. palustris*) including the wood, bark, limbs, and needles. They reported that vinca (*Catharanthus roseus* L.) grown in PTS were smaller than plants grown in 100% PB, but that growth index and visual quality of the plants were similar for both substrates.

Further work by Boyer et al. (2008) showed that growth of ageratum (*Ageratum houstonianum* Mill. 'Blue Hawaii') and salvia (*Salvia* x *superba* Stapf. 'Vista Purple') was comparable to 100% PB when grown in a substrate derived from a tree by-product (limbs, needles, bark, cones, etc.) known as clean chip residual that remains after pine trees are harvested for pulp wood. Clean chip residual has also been used as a successful substrate component in the production of wood shrubs and perennials (Boyer et al., 2007; Boyer, 2008).

In most studies additional fertilizer is required for PTS compared to commercial peat or PB substrates. Research has concluded that it takes an additional 100 $mg \cdot L^{-1}$ N from a 20N-4.4P-16.6K Peat-Lite Special water soluble fertilizer to produce comparable growth of bedding plants and chrysanthemums in PTS compared to peat substrates (Wright et al., 2008a and 2008c). However, the addition of peat moss or aged PB to PTS has been shown to improve plant growth, especially at lower fertilizer rates (Fain et al., 2008a, 2008c; Jackson et al., 2008a). This is likely because peat and PB increase the retention of nutrients available for plant uptake by increasing the cation exchange capacity (CEC) of the PTS. For woody plants it has been shown that an additional 4 lbs per cu. yd (2.4 $kg \cdot m^{-3}$) of Osmocote Plus (15N-3.9P-10K) controlled release fertilizer is required (depending on species, PTS particle size, irrigation regime, etc.) for optimal plant growth in PTS compared to PB (Jackson et al., 2008a; Wright et al., 2006).

Research on PTS has also shown that no lime additions are required for the variety of species tested due to the inherently high pH (around 6.0) of freshly harvested and ground pine wood (Saunders et al., 2005; Wright et al., 2008a). However, when peat moss and PB are added to PTS, lime is required in proportion to the ratio of peat and PB

added to PTS. For woody nursery plants a large number of genera have been grown without lime additions with comparable growth to those grown in PB which requires lime depending upon the species grown (Wright et al., 2006). Also, an addition of sulfur is required for PTS compared to peat moss and PB for the growth of marigold. Sulfur can be supplied as elemental sulfur, Micromax, $FeSO_4$, $MgSO_4$, or $CaSO_4$ at the rate of 1.5 lbs per cu. yd. of any one of the above materials (Wright and Jackson, 2008).

Loblolly pine is native to the southeastern U.S. (Fig. 1.16) and can be grown in areas far outside its native range putting it in close proximity to nursery and greenhouse operations across the southern U.S. (Fig. 1.17). Pine tree substrate can be produced in these areas, minimizing transportation costs to growers. It should also be mentioned that the use of wood materials (including loblolly pine trees) are being developed as fuel sources (i.e. wood pellets). Competition for loblolly pine trees for fuel wood should be considered as it relates to the cost of pine chips and ultimately the production cost of PTS as it is developed and utilized commercially in the future. One way to offset potential competition for pine wood is to establish pine plantations specifically for PTS production by individual growers or by a consortium of growers in areas throughout the southeast to guarantee sufficient wood sources in the future.

Nitrogen Immobilization in Wood-based Substrates

In wood substrates, microorganism activity is higher than peat or PB substrates due to the higher C/N ratio of wood (Gruda, 2005). The microorganisms need mineral N for the synthesis of their protein components and will immobilize available N from the soil/substrate solution, decreasing the amount of N that is available for plant uptake

(Gumy, 2001). Nitrogen immobilization in wood substrates can cause substantial nutritional problems for cultivated plants and thus became one of the most important factors causing possible yield losses (Gruda and Schnitzler, 1997; Gruda and Schnitzler 1999; Gruda et al., 2000). In addition to N, it has also been reported that phosphorus and sulfur can be immobilized by microorganisms during the decomposition of wood materials (Bodman and Sharman, 1993; Handreck, 1996; Sharman and Bodman, 1991).

Optimal plant growth is ensured only if the sufficient N is available for both, microorganisms and plants (Handreck, 1992a; Handreck, 1992b). Several methods and cultural strategies have been developed and utilized to reduce N immobilization in wood substrates and improve fertilizer management strategies during crop production: 1) Composting wood materials has been shown to eliminate or significantly reduce the potential for N immobilization to occur during crop production by lowering the C:N ratio and allowing the initial breakdown which requires high levels of N for microorganisms (Aldin, 1989; Bollen and Glennie, 1961; Gutser et al., 1983; McKenzie, 1958; Prasad, 1997; Worrall, 1985); 2) or the use of a nutrient impregnation process such as the one used in the production of Toresa®, a commercial wood fibre substrate in Europe, which mechanically grinds wood chips together with an accurately specified quantity of nutrient compounds in machines called retruders (Gumy, 2001; personal observation (Brian Jackson and Robert Wright) at an Intertoresa AG manufacturing facility in Hamburg, Germany, March 13, 2007). The nutrients are forced into the wood fibers by high pressure and heat during the production of Toresa (Baumann and Penningsfeld, 1991; Penningsfeld, 1992; Schilling, 1999). Gruda et al. (2000) concluded that N impregnation in wood fibre substrates was sufficient to provide enough N for the initial microbial

immobilization occurring during the first days of crop production; 3) or a technique call the Fersolin process impregnates wood material with sulfuric acid in the presence of hot gases 2000 °F (933 °C) resulting in a decrease in decomposable cellulose which results in lower microbial activity and need for N (Bollen and Glennie, 1961); 4) A process for treating wood materials by pyrolysis (a form of incineration that chemically decomposes organic materials by heat in the absence of oxygen) has been evaluated as a method to breakdown unstable and toxic wood components into more stable and non-toxic components that are resistant to microbial decay which retards microbial N demand (Bollen and Glennie, 1961). The methods described above are often expensive, time consuming, and non-practical for many substrate companies and growers, and 5) The application of additional fertilizer during crop production is an easy method for supplying the N concentrations needed to satisfy the microbial immobilization and the plant needs and this is the most widely used and preferred method of countering N immobilization (Gruda et al., 2000; Gruda, 2005; Jackson and Wright, 2008; Jackson et al., 2008a; Wright et al., 2008a).

Gruda et al. (2000) studied N immobilization in peat and wood fiber substrates (WFS) with and without N impregnation. Three levels of N fertilizer were tested and N immobilization was calculated on the basis of N balance including N uptake by plants and residual mineral N in the substrates. A strong net N immobilization appeared in non-impregnated WFSs, particularly under the higher N fertilization rates. On average for all three N levels, immobilization was calculated at more than 175 $mg \cdot L^{-1}$ N per L substrate in an experiment without plants and 200 $mg \cdot L^{-1}$ N in an experiment with plants. The quantity of immobilized N was over 6% higher in the experiment with plants than in the

experiment without plants. The calculated N immobilization varied between 102 - 282 $mg \cdot L^{-1}$ N in pots with non-impregnated wood fiber without plants. Similar results are supported by other works (Grantzau, 1991; Meinken and Fischer, 1997; Penningsfeld, 1992).

The impregnated wood fiber substrates studied by Gruda et al. (2000) had a similar C/N ratio to those for peat 54-63:1. The net N immobilization in impregnated WFS was approximately equal for peat with a mean of approximately 100 mg. In these experiments it was observed that the more N supplied, the higher the N immobilization was in a substrate. Meinken and Fischer (1997) showed in their investigations with marigold, that with an increase of N added to the substrate from 350 to 650 $mg \cdot L^{-1}$ N, N immobilization increased from 65 to 127 $mg \cdot L^{-1}$ N, respectively. These results were similar to those reported by Scharpf (2002) who also observed an increase in N immobilization with increasing rates N application. Zagal and Persson (1994) proposed that microorganisms in substrates will convert more N, if more N is applied, thus higher microbial populations are present in substrates with higher levels of N application. Other researchers reported the influence of plant root exudations, which can cause a fast reproduction of microorganisms and thus a higher N immobilization (Meinken and Fischer, 1997; Zagal et al., 1993).

The most frequently used and accepted method for determining N immobilization in soilless substrates is the nitrogen drawdown index (NDI) procedure developed by Handreck (1992a, 1992b). The NDI procedure involves saturating "charging" a substrate with a KNO_3 fertilizer solution containing 75 $mg \cdot L^{-1}$ N and then incubating the substrate at 22 ˚C for 4 days. Substrate solution nitrate (NO_3-N) levels are determined

immediately following saturation on day 0 and then again after day 4 (the incubation period). Nitrogen drawdown index is then calculated by the following formula (NO_3 measured on day 4 / NO_3 measured on day 0 x 100). The resulting index is a value between 1.0 and 0.0 with a value of 1.0 representing no N loss during the 4 day incubation and an index value of 0.0 indicating complete N loss after 4 days. Substrates composed of large amounts of wood materials (high C:N ratio) will immobilize all, or nearly all, of the N during the 4 day incubation when using 75 $mg \cdot L^{-1}$ N, making it impossible to determine the amount needed by the substrate. Handreck (1992b) has recommended that the N concentration in the saturating solution be 150 mg N L^{-1} when substrates with a high demand for N are being tested, or that the incubation time be decreased in order to obtain measurable amounts of N remaining in the substrate after incubation. Similarly, Sharman and Whitehouse (1993) suggest that saturating solutions with concentrations of 150, 200, or 300 mg N L^{-1} can be used in N immobilization tests on materials with high C:N ratios, such as PTS, that are expected to have high rates of immobilization occurring.

Factors Influencing Nitrogen Immobilization and Wood Decomposition

pH. Liming substrates to increase pH is a common nursery and greenhouse management practice that may influence N immobilization. Ogden and Mills (1988) and Niemiera and Wright (1986) reported that liming pine bark to increase pH from 3.5 to 5.5 produced a significant decrease in NO_3-N recovered in leachates. Increased microbial activity (and nutrient immobilization) at higher pH was proposed to account for the difference. McKenzie (1958) also reported that N immobilization in soil amended with sawdust increased significantly with a pH rise from 6.9 to 7.9. Contrary to these

findings, Sharman (1993) reported no change in N immobilization with changes in pH of a wood-based substrate. It is believed however that the range of pH levels (5.3 to 6.6) were not broad enough to influence microbial populations, therefore no change in N immobilization occurred.

Temperature. The influence of temperature on N availability is considered to have a major influence on microbial activity (Bagstam, 1978; Bagstam, 1979; Niemiera and Wright, 1987; Sharman, 1993; Walden and Wright, 1995). Increasing temperature over the range of 20 to 50 °C is reported to encourage microbial activity and accelerate cellulose decomposition (Cappaert et al., 1975). Sharman (1993) reported a significant increase in N immobilization in response to increasing temperature from 10 to 30 °C. Similar to these results, Bagstam (1978) reported higher microbial activity in spruce bark when incubation temperatures rose from 20 °C to 45 °C. The influence of temperature on N immobilization could explain the seasonal differences in N requirements of wood substrates during crop production as discussed by Sharman (1993). It is recommended that growers (users) of wood-based substrates incubate test samples at ambient production temperatures when assessing potential N immobilization so that accurate N requirements for the substrate can be determined under production conditions (Sharman, 1993).

Particle size. The rate of decomposition is positively correlated to the particle size of organic materials in soil (Allison and Murphy, 1963; Matus et al., 1997; Neal et al., 1965). Small particles result in greater overall surface area for a given volume of substrate/material, increasing the possibilities for microbial attack and activity (Fog,

1988; Thomas et al., 1998). In contrast, a large particle size will further delay the decomposition of recalcitrant plant components.

C:N ratio. Early texts on N immobilization tended to place a heavy emphasis on the C:N ratio. Bunt (1988) reported how two PBs with the same C:N ratio (about 300:1) and under similar conditions had very different C decomposition rates (i.e., 24% and 4%). However, Bunt (1988) also stated that N immobilization is more likely in materials with a high C:N ratio as they are more deficient in N. There are limitations with the C:N ratio as not all the C is available to microorganisms (Cheshire et al., 1999; Mtanbanengwe and Kirchmann, 1995).

Substrate CO_2 Efflux and Microbial Activity

The estimation of microbial populations in soils or soilless substrates may be accomplished by several methods, for example by counting a sub sample of the population (by either microscopy or plating on agar), by assaying some unique component of biomass such as ATP, or by measuring the metabolic activity of the population (Turner and Carlile, 1983). Measuring the metabolic activity of a microbial population (respiratory activity) involves monitoring CO_2 evolution or O_2 consumption. Techniques for monitoring CO_2 evolution from soil were pioneered by Waksman (1932) and are still widely used in studies of microbial activity in soils and soilless substrates (Gough and Seiler, 2004; Jackson et al., 2008a; Pronk, 1997; Söderstrom et al., 1983; Turner and Carlile, 1983). It has been shown that microbial activity (estimated by CO_2 efflux from soils) increases in response to N fertilization in N limiting soils (Zhang and Zak, 1988) and to P fertilization in P limiting soils (Gallardo and Schlesinger, 1994).

Microbial activity has also been reported to decrease in response to high rates of N fertilization of forest soils (Smolander et al., 1994; Thirukkumaran and Parkinson, 2000). Substrate respiration is influenced by a number of factors, including substrate quality (Fog, 1988), temperature (Davet, 2004), soil moisture (Bowden et al., 2004; Davet, 2004), root biomass (Davet, 2004; Helal and Sauerbeck, 1985), and microbial activity and biomass (Davet, 2004).

Laboratory incubation of root-free soil shows that heterotrophic respiration from the microbial community in fertilized plots is reduced compared to non-fertilized plots (Bowden et al., 2004). Compton et al. (2004) found that repeated N additions over time decreased microbial biomass and diversity, and Frey et al. (2004) observed that active fungal biomass was lower in fertilized plots than in control plots. Frey et al. (2004) also detected a significant reduction in the activity of the enzyme phenol oxidase, a lignin-degrading enzyme produced by white rot fungi with increased application of N to soils.

Shrinkage and Stability of Wood-based Substrates

The term shrinkage refers to decomposition and resulting loss of volume of a substrate in a container. According to Whitcomb (2006), three complications arise from media shrinkage. First, N is tied-up (immobilized) during decomposition. Second, the particle size, drainage, and aeration characteristics of the substrate change quickly, increasing the water holding capacity while decreasing the aeration. Third, reduced depth of the substrate in the container will further enhance poor drainage.

Prasad and O'Shea (1999) conducted incubation tests on several peat materials and on two commercial wood fibre substrates (Hortifibre® and Cultifibre®). Substrate

volume reduction was greatest (almost 50%) in the woodfibre materials compared to the peat. These results are consistent with other published by Fischer et al., (1993) who found reduction in a wood fibre substrate of 36-47% during a 15 month incubation period. Meinken and Fischer (1997) reported a 50% wood fibre substrate volume loss over a one year crop production experiment. The wood substrates used in these reports were composed of a mixture of various tree species; primarily spruce (*Picea abies* L.).

Lemaire et al. (1989) conducted an experiment with Hortifibre® and found that after 240 days of incubation without N there was 9% dry matter loss, and wood fibre samples with the addition of N experiences 12.5% dry matter loss signifying increased microbial breakdown with the addition of an N-source. Even with 12.5% dry matter loss, the biostability of Hortifibre® is considered to be acceptable for horticultural crop production (Lemaire et al., 1989; Lemaire, 1997).

Prasad and Maher (2004) evaluated the breakdown (shrinkage) of coconut coir and three wood fiber substrates (Hortifibre®, Toresa®, and Pietal®) and reported that breakdown (in the form of substrate shrinkage) was least in coir and higher in all the wood fibre substrates tested. The authors also reported that the incorporation of peat moss in the wood fibers significantly decreased the breakdown over 9 and 21 month incubation periods because of the stability of the peat and its resistance to further breakdown compared to the wood. It was also noted that the incorporation of lime increased the rate of breakdown in all the wood fibre substrates due to the increased substrate pH which apparently promoted increased microbial activity. These results were similar to other reports of increased breakdown of wood substrates when lime is incorporated (Aendekerk, 1997; Maher and Prasad, 2002).

The deterioration of peat-based substrates is low during storage or during plant production because of the high percentage of lignin found in peat, which is resistant to microbial attack. Thus, deterioration and/or absorption of added nutrients rarely occurs in peat media, even though these may be limed to pH levels of 5.5-6.0, a range eminently suitable for microbial development and activity (Carlile, 2004).

Summary

The use of wood-based materials as container substrates has been investigated for many years as alternatives to traditional PB and peat mixes. Many of the issues related to the use of wood as substrates have been discussed in this review with particular emphasis on N immobilization and fertility management during crop production. With the previous work as a reference, the work discussed in this dissertation is based on investigations of PTS to further understand its fertility requirements over time during crop production in containers. Issues of PTS that will be addressed in this work include specific fertilizer requirements for greenhouse and nursery crops, the degree and timing of N immobilization, the use of substrate CO_2 efflux as an estimate for microbial activity and N immobilization potential, the nutrient leaching potential, and changes in chemical and physical properties during plant production.

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Figure 1.1. Harvested loblolly pine trees being debarked at a processing facility located in Warsaw, VA. The debarked logs are used for pulpwood or saw timber and the removed bark is a by-product which can be used as a container substrate.

Figure 1.2. Aged pine bark stock piled on-site at a nursery.

Figure 1.3. Close-up view of unamended peatmoss. Peatmoss is most commonly used as a container substrate for greenhouse crop production.

Figure 1.4. Peatmoss is typically shipped from Canada in large compressed bales to growers or substrate companies here in the United States.

Figure 1.5. Canadian peat bogs in their natural state before peat extraction.

Figure 1.6. Once peat bogs are drained and cleared of vegetation, peat harvesting requires large equipment which extracts the peat by several methods including vacuuming.

Figure 1.7. Close-up view two grades (particle sizes) of coconut coir which is commonly used as a container substrate for greenhouse and nursery crop production.

Figure 1.8. Coconut coir is shipped in compressed bales to growers and substrate companies here in the United States from several countries where coconuts are produced including Sir Lanka, Indonesia, Mexico, and Costa Rica.

Figure 1.9. A managed plantation of loblolly pine (*Pinus taeda*) trees which are currently grown for pulpwood (paper industry) or for the saw timber industry, but can be grown specifically for producing pine tree substrate for the horticulture industry.

Figure 1.10. Harvested loblolly pine trees that have been delimbed and ready for further processing (in a hammer-mill) into pine tree substrate.

Figure 1.11. Industrial wood chipper used to chip pine logs into small wood chips that are then small enough to be ground in a hammer-mill for substrate production.

Figure 1.12. Loblolly pine wood chips ready for processing (grinding) in a hammer-mill to produce pine tree substrate.

Figure 1.13. Loblolly pine wood chips (top) are ground in a hammer-mill (middle) to reduce the size of the wood to a desired particle size (bottom) to produce pine tree substrate ready for potting and planting.

Figure 1.14. Pine tree substrate composed of 100% ground pine logs that is ready for potting and planting.

Figure 1.15. Pine tree substrate produced with the addition of 25% aged pine bark which improves the water and nutrient holding capacity of the substrate.

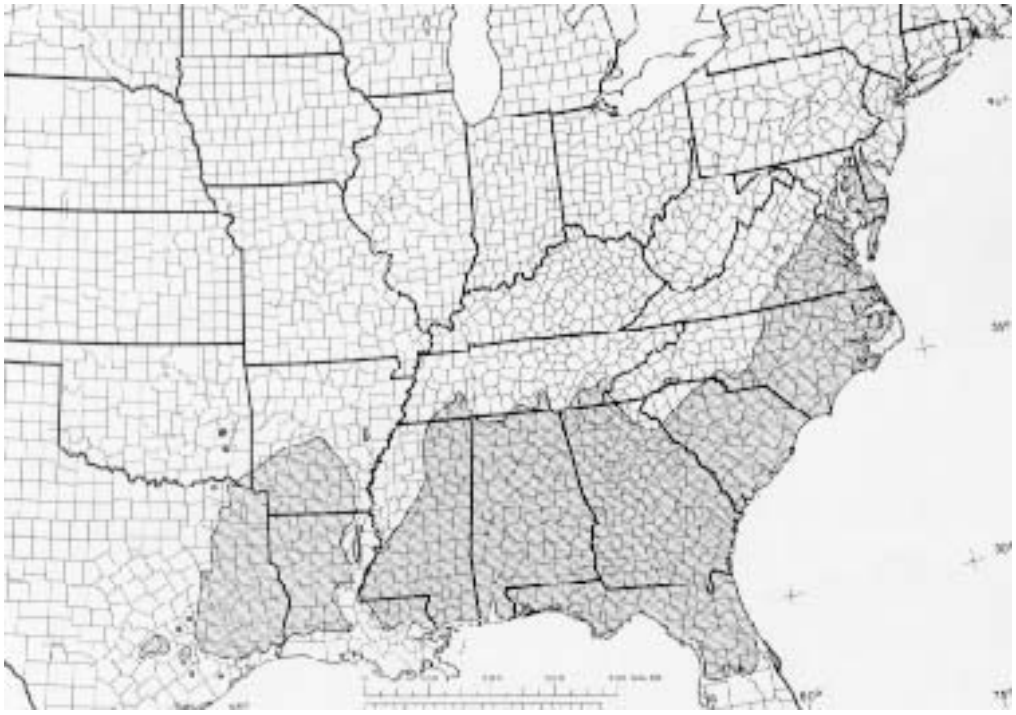

Figure 1.16. Native range of loblolly pine (*Pinus taeda* L.) trees in the United States, showing the broad area where these trees naturally occur and could be used for pine tree substrate production (USDA, 2008).

Figure 1.17. Loblolly pine trees can be grown in the shaded areas of the map which far expands the native range (Fig 1.16) covering a much larger portion of the United States where many nursery and greenhouse operations are located (Gilman and Watson, 1994).

CHAPTER II

Effect of Fertilizer Rate on Growth of Azalea and Holly in Pine Bark and Pine Tree Substrates

Abstract: Recent interest in the use of wood substrates in horticulture crop production has justified the need for determining fertilizer requirements in these substrates compared to traditional pine bark (PB) and peat moss substrates. The objective was to determine the response of japanese holly (*Ilex crenata* Thunb.'Compacta') and azalea (*Rhododendron obtusum* Planck. 'Delaware Valley') grown in a pine tree substrate (PTS) (trade name *WoodGro*™) or milled PB to fertilizer rate. Pine tree substrate is produced from freshly harvested loblolly pine trees (*Pinus taeda* L.) that are delimbed, chipped, and ground in a hammer mill to a desired particle size. Japanese holly plants were grown in 2.8-L containers in the fall of 2005 and again in the spring of 2007 with the addition of azalea. Plants grown in PTS or PB were fertilized by incorporating Osmocote Plus fertilizer (15N-3.9P-10K) at rates of 3.5, 5.9, 8.3 or 10.6 $kg \cdot m^{-3}$ for japanese holly and 1.2, 3.5, 5.9, or 8.3 $kg \cdot m^{-3}$ for azalea. After three months, shoot dry weights were determined for japanese holly and azalea. Japanese holly root dry weights were determined for both experiments, and substrate CO_2 efflux ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) was measured on the treatments at the end of the experiment using a LI-6400 soil CO_2 flux chamber. In 2005, japanese holly shoot dry weights of PTS-grown plants were comparable to plants grown in PB at the 8.3 $kg \cdot m^{-3}$ fertility rate, and shoot dry weights of PTS-grown plants were higher than PB at the 10.6 $kg \cdot m^{-3}$ rate. In 2007, japanese holly and azalea shoot dry weights of PTS-grown plants were comparable to PB plants at the 5.9 $kg \cdot m^{-3}$ fertilizer rate. Both japanese holly and azalea achieved shoot growth in PTS

comparable to shoot growth in PB with approximately 2.4 $kg \cdot m^{-3}$ additional fertilizer for PTS. Substrate CO_2 efflux rates were higher in PTS compared to PB indicating higher microbial activity, thereby increasing the potential for nutrient immobilization in PTS.

Introduction

The nursery and greenhouse industries have experienced tremendous growth over the last four decades. Brooker et al. (2000) reported that the nursery and greenhouse industries have increased economically from $661 million in 1960 to $12.11 billion in 1998. The nursery industry has undergone many changes and innovations during this time to more efficiently and properly manage irrigation, fertility, substrate use, integrated pest management, etc (Bilderback, 2001; Yeager et al., 2007). Of these, research and development of new substrates to replace conventionally used peat moss and PB substrates have increased in recent years. In addition to developing and utilizing new substrates, much work has focused on managing fertility and irrigation programs of these substrates to maximize plant performance and minimize nutrient loss due to environmental concerns (Gouin and Link, 1973; Warren and Bilderback, 2004). The need to develop new substrates and fertility management programs for the horticulture industry is an issue that is being addressed by researchers around the world.

Research in Europe has been conducted for over two decades on the development of alternative and renewable horticultural substrates composed of wood. The need for alternative substrates is in response to decreased peat use due to environmental regulations on the mining of peat bogs (Carlile, 2004; Riviere and Caron, 2001). Researchers have had success using wood substrates, and have developed several

commercialized products currently available to growers (Gumy, 2001; Penningsfeld, 1992).

Serious consideration is also being given to the development of alternative, organic container substrates here in the United States based on recent substrate shortages and increased substrate costs (Griffith, 2007; Lu et al., 2006). Ground melaleuca trees (*Melaleuca quinquenervia* Cav.) were shown to be an acceptable substitute for bark or sedge peat when used to grow a number of woody and herbaceous plants (Conover and Poole, 1983; Ingram and Johnson, 1983). No phytotoxicity problems were evident in these studies as long as the proportion of melaleuca did not exceed 50% of the substrate volume. Kenna and Whitcomb (1985) demonstrated that *Pyracantha* x 'Mojave' and *Liquidambar formosana* Hance. grew as well in a substrate of woodchips:peat:sand (3:1:1 v/v/v) as in a substrate composed of bark:peat:sand (3:1:1 v/v/v). Wood chips for their study were produced by grinding entire trees including leaves, twigs, bark and wood of post oak (*Quercus stellata* Wangh.) and Siberian elm (*Ulmus pumila* L.). Non-composted sawdust from douglas fir (*Pseudotsuga menziesii* Mirb.) and western hemlock (*Tsuga heterophylla* Raf.) have also been used to grow a wide range of herbaceous and woody container crops in Canada where sawdust is plentiful (Maas and Adamson, 1972).

Laiche and Nash (1986) produced a PTS derived from PB with a considerable percentage of pine wood and a second PTS derived from whole pine trees (needles, twigs, bark, and wood). They reported that plant growth (*Rhododendron indica* L. 'President Clay', *Ligustrum sinense* Lour. 'Variegata', and *Ilex crenata* Thunb. 'Compacta') was highest in 100% PB compared to the two PTS's and that additional work was needed before pine wood could be used as a container substrate. Two decades later, Wright and

Browder (2005) demonstrated that japanese holly (*Ilex crenata* Thunb. 'Chesapeake'), azalea (*Rhododendron obtusum* Planck. 'Karen'), and marigold (*Tagetes erecta* Big. 'Inca Gold') could be grown in a noncomposted PTS (100% wood) produced from debarked loblolly pine trees. Nutrient analysis of the PTS substrate solution indicated that nutrient levels and pH were acceptable for plant culture, although extra fertilizer was added to PTS to maintain comparable electrical conductivity (EC) levels between the two substrates. Wright et al., 2006 also evaluated the growth of numerous woody nursery species in a PTS produced from ground pine logs (including the bark) (approximately 90% wood and 10% bark) compared to PB. Results from this work concluded that plant dry weights were generally higher in PB than PTS, but differences in growth between PB and PTS were less when plants were supplied with higher fertilizer rates (21 g vs. 15 g Osmocote Plus 15N-3.9P-10K; O.M. Scott Horticulture Products, Maryville, OH). Growth differences in these studies were attributed to lower nutrient levels in the PTS due to either leaching or microbial immobilization of applied nutrients.

Fain et al. (2008) manufactured a pine tree substrate (referred to as *WholeTree*) by chipping and grinding freshly harvested 8 to 10 year-old pine trees including the wood, bark, limbs, and needles. They reported that vinca (*Catharanthus roseus* L.) grown in PTS were smaller than plants grown in 100% PB, but that growth index and visual quality of the plants were similar for both substrates. Further work by Boyer et al. (2006) showed that growth of ageratum (*Ageratum houstonianum* Mill. 'Blue Hawaii') and salvia (*Salvia* x *superba* Stapf. 'Vista Purple') was comparable to 100% PB when grown in a substrate derived from a tree by-product (limbs, needles, bark, cones, etc.) known as clean chip residual (CCR) that remains after pine trees are harvested for pulpwood.

Gruda and Schnitzler (1999) reported that growth of tomatoes in a 100% wood substrate was comparable to a peat substrate if the wood substrate was impregnated with nitrogen (N) during manufacturing or when extra N was added during cultivation. Wright et al. (2008) also showed that mums (*Chrysanthemum* x *grandiflora* Tzvelev. 'Baton Rouge') can be grown in PTS as well as in a commercial peat substrate when an additional 100 ppm N was given to PTS-grown plants. Based on these observations, additional fertilizer (primarily N) is needed for plant production when growing in a wood-based substrate. The goal of a fertility program is to maintain an optimal level of nutrients in the substrate throughout the growing season while limiting nutrient loss from the container. Due to an increased awareness of and attention to environmental contamination from nursery runoff sites, growers and researchers are working to precisely manage fertility of container substrates during production to minimize nutrient losses while continuing to maximize plant growth. Therefore, the purpose of this research was to study the effect of fertilizer rate on growth of japanese holly and azalea in PTS compared to PB to begin development of an efficient fertility management program for growing plants in PTS. A fertility management program will allow plant growth in PTS to be maximized at the lowest fertilizer rate possible while minimizing nutrient waste and loss.

Materials and Methods

2005 Study: On 17 Aug. 2005, japanese holly liners (10-cm tall in 64 cm^3 containers) were potted in 2.8-L plastic containers [17cm (h) x 17cm (d)] containing either PB or PTS. Pine tree substrate was produced from loblolly pine trees

(approximately 30-cm basal diameter) that were harvested at ground level and delimbed on 25 July 2005 in Warsaw VA. Trees were then chipped (including bark) with a Morbark Chipper (Winn, MI) operated by Wood Preservers Inc., (Warsaw, VA) on 26 July 2005. Wood chips (2.5-cm x 2.5-cm x 0.5 cm) were further ground in a hammer mill (Meadows Mills, Inc., North Wilkesboro, NC) on 27 July 2005 to pass through a 6.35 mm screen. Pine tree substrate was used fresh (uncomposted) and amended with 0.6 $kg \cdot m^{-3}$ calcium sulfate ($CaSO_4$) based on previous work by Saunders et al. (2005) that showed improved growth in herbaceous species when $CaSO_4$ was incorporated in PTS. No preplant amendments are required with PB for japanese holly production. Osmocote Plus (15N-3.9P-10K; O.M. Scott Horticulture Products, Marysville, OH) was preplant incorporated in PB and PTS at rates of 3.5, 5.9, 8.3, or 10.6 $kg \cdot m^{-3}$ (5.3, 8.9, 12.5, or 16 $g \cdot m^{-3}$ of N) respectively. Plants were grown on benches in a greenhouse in Blacksburg, VA and irrigated as needed with beaker applied water to achieve an approximate 30 % leaching fraction. Average day and night temperatures in the greenhouse were 26 ^{o}C and 22 ^{o}C, respectively. Substrate solution was extracted using the pour-through (PT) method (Wright, 1986) every four weeks and analyzed for pH and EC using a Hanna HI 9811 instrument (Hanna Instruments, Woonsocket, RI). Nutrient analysis was conducted on substrate solution taken on 7 Oct. 2005 and analyzed for nitrate (NO_3-N) with an Orion ion selective electrode (Thermo Electron, Beverly, MA) and phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were determined with a Spectro Ciros Vision ICP (Spectro Analytical Instrument, Muhwah, NJ). On 22 Nov. shoots were severed at the substrate surface and roots were washed, dried at 65 º C for 4 days, and weighed. Samples of the most recently matured leaves from four plants per

treatment were harvested and analyzed for N, P, and K (Quality Analytical Laboratories, Panama City, FL).

As a measure of microbial activity in PB and PTS, substrate CO_2 efflux levels were determined as an indicator of the potential for N immobilization to occur (Wang et al., 2003). Substrate CO_2 efflux (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) was determined at the end of the experiment (23 Nov. 2005) on three container replications of both substrates, at each fertilizer rate using a LI-6400 (LI-COR, Lincoln, NE) fitted with a soil CO_2 flux chamber designed to take nondestructive CO_2 measurements from the substrate filled containers. A 10.2-cm diameter x 5.1-cm high plastic collar was inserted 0.5 cm into the container substrate surface allowing the soil CO_2 flux chamber to be inserted and positioned securely above the substrate surface for CO_2 efflux measurements.

Physical properties including air space (AS), container capacity (CC), total porosity (TP), and bulk density (BD) were determined on three replicate samples of each substrate at the beginning of the experiment using the North Carolina State University (NCSU) Porometer method as described by Fonteno et al. (1995). Cation exchange capacity (CEC) was determined by A & L Eastern Laboratories (Richmond, VA) using the AOAC International Official Method (Thrope, 1973).

2007 Study: An experiment similar to the previous experiment was conducted from 1 Mar. to 25 May 2007. Pine tree substrate was produced from 12 year-old loblolly pine trees (approximately 25-cm in basal diameter) that were harvested at ground level and delimbed on 19 Feb. 2007 in Blackstone VA, and chipped with bark intact on 20 Feb. 2007 with a Bandit Chipper (Model 200, Bandit Industries, Inc. Remus, MI). Wood chips were then further ground in a hammer mill on 21 Feb. 2007 to pass through a 6.35

mm screen. Physical properties of both substrates were determined using the method described in the 2005 study. Osmocote Plus (15N-3.9P-10K) was incorporated in PB and PTS at rates of 3.5, 5.9, 8.3, or 10.6 $kg \cdot m^{-3}$ (5.3, 8.9, 12.5, or 16 $g \cdot m^{-3}$ of N), respectively. In addition to japanese holly, this experiment also included azalea. Since azaleas require lower fertilizer rates (compared to holly) for optimal growth (Yeager et al., 2007), this species was included in this study to provide growth data on a woody species with a relatively low nutrient requirement when grown in PB and PTS. Fertilizer rates for azalea were 1.2, 3.5, 5.9, and 8.3 $kg \cdot m^{-3}$ (1.8, 5.3, 8.9, or 12 $g \cdot m^{-3}$ of N), respectively. Both substrates were preplant amended similar to the 2005 study. Plants were grown on a gravel ground bed in a greenhouse in Blacksburg, VA and overhead irrigated at a rate of 4.5 cm/hr with a Basic Grower boom sprayer (McConkey Co., Sumer, WA) as needed to achieve an approximate 30 % leaching fraction. Species were grouped separately on the ground bed and irrigated independently during the entire experiment. Substrate solution was extracted using the PT method every two weeks and analyzed for pH and EC for both species. Nutrient analysis was conducted on substrate solution taken from each species on 30 Apr. 2007 in the same method as previously described for the 2005 study. On 25 May 2007 shoots of both species were severed at the substrate surface and the roots of japanese holly were washed, dried at 65 º C for 4 days, and weighed. Samples of the most recently matured leaves from five plants, per treatment, per species were harvested and analyzed for N, P, and K by Penn State Analytical Testing Laboratory, University Park, PA. Substrate CO_2 efflux was measured on three container replications of each treatment for japanese holly.

The experimental design was completely randomized with six single container replications per treatment in 2005 and five replications per treatment per species in 2007. All data in both studies were analyzed with the analysis of variance procedure using SAS (version 9.1 SAS Institute, Inc. Cary, NC) and subjected to regression analysis using SigmaPlot (version 9.01 SPSS, Inc., Chicago, IL) with the exception that substrate physical properties were subjected to analysis of variance within the GLM procedure, with treatment means separated by least significant difference analysis. Standard error bars are presented in Figures 2.1 through 2.3 with the linear and quadratic regression responses presented.

Results and Discussion

2005 study: There was a significant substrate x fertilizer rate interaction ($P \leq 0.001$) for shoot dry weight: at fertilizer rates of 3.5 and 5.9 $kg \cdot m^{-3}$, shoot dry weight was higher for PB than PTS; at 8.3 $kg \cdot m^{-3}$ dry weight was about equal for the two substrates; at 10.6 $kg \cdot m^{-3}$ dry weight was higher for PTS than PB (Fig. 2.1A). Root dry weights were not influenced by fertilizer rate ($P \leq 0.145$) but were higher in PB than PTS at the 3.5 and 5.9 $kg \cdot m^{-3}$ rates and equal in both substrates at the 8.3 and 10.6 $kg \cdot m^{-3}$ rates (Fig. 2.1B). There was a significant substrate x fertilizer rate interaction ($P \leq 0.002$) for substrate CO_2 efflux. Efflux levels were higher in PTS than in PB at each fertilizer rate with the magnitude of difference decreasing as fertilizer rate increased (Fig. 2.1C). At the lowest fertilizer rate (3.5 $kg \cdot m^{-3}$) substrate efflux levels in PTS were four times higher than in PB, but were nearly the same at the highest fertilizer rate (10.6 $kg \cdot m^{-3}$). In

contrast to PTS, substrate efflux levels slightly increased in the PB substrate as fertilizer rates increased, resulting in similar efflux levels at the highest fertilizer rate (Fig. 2.1C).

Substrate solution EC values increased with increasing fertilizer rate and at any particular fertilizer rate levels were higher in PB than in PTS (Table 2.1), showing that higher fertilizer rates were required for PTS compared to PB to achieve comparable substrate EC levels. Substrate solution pH was higher in PTS at each fertilizer rate compared to PB and decreased as fertilizer rate increased (Table 2.1). The pH of PB did not change with increasing fertilizer rates. There was a significant substrate and fertilizer rate response for all nutrient concentrations (except for K) in the substrate solution sampled on 7 Oct. 2005 (Table 2.2). Similar to the EC levels previously discussed, nitrate (NO_3-N) concentrations were higher in PB at each fertilizer rate compared to PTS. Solution concentrations of P, K, Ca, and Mg were also higher in PB compared to PTS (Table 2.2).

Leaf tissue nutrient concentrations were generally higher in PB-grown plants compared to PTS-grown plants at each fertilizer rate (Table 2.3). All nutrient levels generally increased as fertilizer rate increased for PB up to the 10.6 $kg \cdot m^{-3}$ rate, and nutrient levels increased in PTS plants up to the 8.3 $kg \cdot m^{-3}$ rate (Table 2.3). Tissue N levels in PB-grown plants were above the recommended sufficiency range of 1.80 to 2.80 % (Mills and Jones, 1996) at all fertilizer rates, and tissue N levels in PTS-grown plants were within the recommended range at the 5.9, 8.3, and 10.6 $kg \cdot m^{-3}$ fertilizer rates (Table 2.3).

Total porosity was similar for both PB and PTS and was within the recommended range outlined in *The Best Management Practices Guide for Producing Container-Grown*

Plants (BMP) for physical properties of container substrates (Yeager et al., 2007) (Table 2.4). Air space was significantly higher in PTS (38.2 %) than in PB, and was above the recommended BMP range. Container capacity was higher in PB (56.1 %) than in PTS (45.2 %), but both were within the BMP range (45-65%) for both substrates. Bulk density of PTS was similar to PB but was below minimum recommended value of 0.19 $g \cdot cm^{-3}$ (Table 2.4).

2007 study. As with the 2005 experiment, there was a significant substrate x fertilizer rate interaction ($P \leq 0.025$) for japanese holly shoot dry weight: at the fertilizer rate of 3.5 $kg \cdot m^{-3}$ shoot dry weight was higher for PB than PTS; at rates 5.9, 8.3, and 10.6 $kg \cdot m^{-3}$ dry weight was similar for PB and PTS plants (Fig. 2.2A). The data also indicate that maximum shoot dry weight for japanese holly in PB is at 3.5 $kg \cdot m^{-3}$ or less, and for PTS is between the 3.5 and 5.9 $kg \cdot m^{-3}$ rates (Fig. 2.2A).

There was a substrate x rate interaction for japanese holly root dry weights ($P \leq 0.017$). Root growth in both PTS and PB decreased as fertilizer rate increased (Fig. 2.2B) but in contrast to 2005, root growth was generally higher in PTS-grown plants than PB-grown plants. There was a significant substrate x fertilizer rate interaction ($P \leq 0.001$) for substrate CO_2 efflux. Similar to 2005 results, substrate CO_2 efflux levels were higher in PTS than in PB at each fertilizer rate with the magnitude of difference decreasing slightly as fertilizer rate increased (Fig. 2.2C). At all fertilizer rates (3.5, 5.9, 8.3, and 10.6 $kg \cdot m^{-3}$) substrate CO_2 efflux levels were twice as high in PTS as in PB (Fig. 2.2C). As with the 2005 experiment, substrate solution EC levels increased with increasing fertilizer rates in both substrates (Table 2.1). Also similar to 2005, substrate solution pH was higher in PTS than PB regardless of fertilizer rate, and pH decreased with increasing

fertilizer rate in PB and PTS (Table 2.1). Similar to the 2005 data, nitrate concentrations in the substrate solution were generally higher in PB compared to PTS and substrate solution concentrations of P, K, Ca, and Mg were in most cases higher in PB compared to PTS (Table 2.2). Similar to 2005, japanese holly leaf tissue nutrient levels generally increased in response to increasing fertilizer rate for PB and PTS-grown plants (Table 2.3). In contrast to 2005 data, leaf nutrient levels at the 8.3 and 10.6 $kg \cdot m^{-3}$ fertilizer rates for N and at the 5.9, 8.3, and 10.6 $kg \cdot m^{-3}$ rates for P (Table 2.3) were higher in PTS-grown plants compared to PB-grown plants. Tissue N levels were above the recommended sufficiency range (1.8 to 2.8 %) at all fertilizer rates for plants grown in both substrates except for the 3.5 $kg \cdot m^{-3}$ rate in PTS. Potassium levels were higher in PTS-grown plants at all fertilizer rates (Table 2.3). Physical property data of PTS and PB in 2007 were similar to 2005 data and therefore are not reported.

There was a significant substrate x fertilizer rate interaction ($P \leq 0.013$) for azalea shoot dry weight: at the fertilizer rates of 1.2 and 3.5 $kg \cdot m^{-3}$ shoot dry weight was higher for PB than PTS; at rates 5.9 and 8.3 $kg \cdot m^{-3}$ dry weights were similar for PB and PTS plants (Fig. 2.3) with maximum shoot dry weight occurring at 3.5 $kg \cdot m^{-3}$ for PB and at 5.9 $kg \cdot m^{-3}$ for PTS. Substrate solution EC levels for azalea increased with increasing fertilizer rate in both substrates, and were higher in PB than in PTS at all rates (Table 2.5). This once again shows that higher fertilizer rates are required in PTS compared to PB to achieve similar substrate EC levels. Similar to japanese holly, substrate solution pH was higher in PTS than PB regardless of fertilizer rate (Table 2.5). pH decreased in PB as fertilizer rate increased, in contrast to pH values of PTS that did not change with fertilizer rate (Table 2.5). Substrate solution nitrate concentrations increased with

increasing fertilizer rate in both substrates, and were lower in PTS compared to PB at each fertilizer rate (Table 2.5). Substrate solution P and K concentrations were generally higher in PB than PTS at each fertilizer rate (Table 2.5). Azalea N and K leaf tissue nutrient concentrations increased in response to increasing fertilizer rate in both PB-grown and PTS-grown plants (Table 2.5). Phosphorus concentrations were generally the same at all fertilizer rates in PB-grown plants while in PTS-grown plants P concentrations increased with fertilizer up to the 5.9 $kg \cdot m^{-3}$ rate. Tissue N concentrations were higher in PB than in PTS at all fertilizer rates. Tissue N concentrations were within the sufficiency range (2.0 to 3.0 %) (Mills and Jones, 1996) for PB plants at the 3.5, 5.9, and 8.3 $kg \cdot m^{-3}$ fertilizer rates, but only at the 5.9, and 8.3 $kg \cdot m^{-3}$ rates for PTS plants.

This study demonstrates that a higher rate of fertilizer is required for japanese holly and azalea to achieve shoot growth in PTS comparable to shoot growth in PB. Both japanese holly and azalea achieved shoot growth in PTS comparable to shoot growth in PB with approximately 2.4 $kg \cdot m^{-3}$ additional fertilizer for PTS. For example, shoot growth of japanese holly was similar at 5.9 $kg \cdot m^{-3}$ in PB and 8.3 $kg \cdot m^{-3}$ in PTS in 2005 (Fig. 2.1A) and shoot growth was similar at 3.5 $kg \cdot m^{-3}$ in PB and 5.9 $kg \cdot m^{-3}$ in PTS in 2007 (Fig. 2.2A). The different growth response in japanese holly to fertilizer rate in 2005 versus 2007 may be due in some way to the seasonal effects (light and temperature differences effecting irrigation need and frequency) between the fall (2005) and spring (2007) experiments. In addition, the placement of the 2007 study on graveled ground beds of the greenhouse instead of on bench tops (2005 study) may have resulted in less air circulation and decreased drying of the containers resulting in a lesser need for water. Lower irrigation rates and frequency in 2007 could have reduced the amount of nutrient

leaching from the substrates and resulted in higher substrate EC averages which occurred in 2007 compared to 2005 (Table 2.1). Niemiera and Leda (1993) showed N (NO_3-N and NH_4-N) leaching in a PB substrate increases with increasing leaching fraction (irrigation volume) resulting in lower substrate solution EC levels and lower concentrations of substrate solution N. In contrast, a lower leaching fraction (less irrigation volume) causes less nutrient leaching and results in higher substrate solution EC levels and N concentrations. Their results help to explain the higher EC levels reported in the 2007 study which received generally lower and less frequent irrigation applications. The higher EC levels in 2007 than in 2005 are likely the reason for higher tissue N concentrations at all fertilizer rates for plants grown in both PB and PTS in 2007 (Table 2.3). Higher tissue N concentrations at lower fertilizer rates in 2007 could explain the increased growth response in japanese holly at lower fertilizer rates compared to plants grown in 2005.

Maximum shoot growth of azalea occurred at the same fertilizer rates (3.5 $kg \cdot m^{-3}$ for PB and 5.9 $kg \cdot m^{-3}$ for PTS; Fig. 2.3) as japanese holly in 2007 which was unexpected since azalea is considered a woody plant with lower nutrient requirements compared to japanese holly. The substrate solution EC levels and nutrient concentrations for azalea plants grown in PB and PTS were generally lower (Table 2.5) at the same fertilizer rates (3.5, 5.9, and 8.3 $kg \cdot m^{-3}$) compared to levels seen in the substrate solution of japanese holly plants (Table 2.2) also in the experiment. The lower EC and substrate solution nutrient levels in azalea may be due to different growth rates between azalea and japanese holly, with azalea having more shoot growth than japanese holly (approximately 18 g for azalea and 11 g for japanese holly; Fig. 2.3) suggesting that azalea plants were utilizing

more nutrients from the substrate solution for growth (lowering the EC and nutrient levels) and requiring more frequent irrigations than japanese holly, leading to potentially more nutrient leaching. In contrast, the smaller holly plants required less irrigation and therefore conceivably had less nutrient leaching during this experiment causing the higher (and statistically similar) substrate solution EC levels between substrates (Table 2.1) and generally higher nutrient levels (Table 2.2) in both PB and PTS in 2007. Tissue N concentrations in azalea were not within the sufficiency range (2.0 to 3.0 %) until the 3.5 $kg \cdot m^{-3}$ fertilizer rate for PB plants (2.4 % tissue N) and at the 5.9 $kg \cdot m^{-3}$ fertilizer rate for PTS-grown plants (2.3 % tissue N) (Table 2.5). At these fertilizer rates maximum shoot growth occurred in each substrate.

Lower substrate solution EC for PTS compared to PB has been reported previously by Wright and Browder (2005) and Wright et al. (2006). The reason for this difference may be two-fold. First, PTS is more porous and has a significantly lower CEC compared to PB (Table 2.4) which could result in more nutrient leaching from PTS. The second may relate to higher rates of microbial N immobilization demonstrated with PTS. Substrate CO_2 efflux for PTS (Fig. 2.1C and 2.2C) was higher than in PB and likely related to the higher carbon: nitrogen ratio of PTS (550:1) compared to PB (50:1) (Bollen and Lu, 1957; Tisdale et al., 1993). Similar to our results (Fig. 4A and B), previous work has shown a reduction in substrate CO_2 efflux as fertilizer rate increased (Maas and Adamson, 1972) possibly due to the increased salt concentration which apparently either modified the microflora in the substrate or reduced their activity (Allison, 1965). This study provides preliminary evidence that N immobilization could be a viable reason for the higher fertilizer requirement in PTS. Substrate solution pH was lower for PB than for

PTS reflective of inherently higher pH of PTS which may be due to the chemical nature of freshly ground wood. The pH levels for both substrates in these studies are acceptable for both japanese holly and azalea. There was no visual substrate shrinkage or decomposition in PTS during the three month experiment which is consistent with observations from other unpublished studies by these authors. Future studies to investigate the rate and impact of decomposition of PTS in containers during long term production will be reported. In addition to evaluating PTS decomposition in containers, different methods of PTS storage and the effect of storage on PTS over time will be investigated.

Conclusions

A higher fertilizer requirement for PTS compared to PB is of concern and must be considered when using PTS as a substrate for woody nursery crops. Fertilizer recommendations for growing woody crops in PTS will help growers maximize plant growth and minimize fertilizer use which can reduce both fertilizer costs and the potential for excess nutrient losses in to the nursery runoff system. Further work is needed to determine the extent of nutrient leaching in PTS as well as establish irrigation requirements during crop production with PTS. The addition of various proportions of PB, as well as other organic materials and composts, to PTS may increase the CEC and reduce nutrient leaching, as well as improving (decreasing) the carbon: nitrogen ratio of PTS (currently at 550:1) potentially reducing N immobilization and reducing the need for additional fertilizer for PTS. Manufacturing PTS to have more small particles (fines) could result in higher container capacity and less porosity to reduce irrigation (and

nutrient) leaching. The reason for lower substrate solution nutrient levels in PTS needs further investigation to more fully understand and manage fertility requirements when growing plants in PTS during short and long term production. Future studies plan to investigate the influence of a relatively high microbial activity in PTS (evident by increased substrate CO_2 levels) on substrate nutrient levels, the rate and significance of nitrogen immobilization, and on substrate decay over longer plant production cycles and in larger containers.

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Table 2.1. Average electrical conductivity (EC) levels and pH values of substrate solution for japanese holly grown in pine bark or pine tree substrates for three months when fertilized with four rates of Osmocote Plus15N-3.9P-10K.[z]

Treatment	2005 study (n = 3)		2007 study (n = 6)	
Osmocote ($kg \cdot m^{-3}$)	pH	EC ($dS \cdot m^{-1}$)[y]	pH	EC ($dS \cdot m^{-1}$)
Pine bark				
3.5	3.6	0.56	4.43	1.15
5.9	3.2	1.50	4.27	1.58
8.3	3.3	2.06	4.20	2.14
10.6	3.3	2.11	4.32	2.47
Significance[xw]	NS Q**	L*** Q***	L*** Q***	L*** Q***
Pine tree substrate[v]				
3.5	5.2	0.27	5.70	0.62
5.9	4.8	0.40	5.60	1.00
8.3	4.1	1.20	5.27	1.53
10.6	4.0	1.26	4.95	2.52
Significance	L*** Q**	L*** Q***	L*** Q***	L*** Q**
Substrate	0.0001	0.0001	0.0001	0.2152
Fertilizer rate	0.0004	0.0001	0.0001	0.0001
Substrate x fertilizer rate	0.0047	0.0789	0.0001	0.0001

[z]pH and electrical conductivity (EC) of substrate solution obtained by the pour-through method (Wright, 1986).
[y]1 $dS \cdot m^{-3}$ = 1 mmho/cm.
[x]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***), respectively.
[w]L = linear; Q = quadratic response for concentration at *, **, or ***.
[v]Pine tree substrate produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer milled to pass through a 6.35 mm screen.

Table 2.2. Substrate solution nutrient concentrations sampled on 7 Oct. 2005 and 20 Apr. 2007 for japanese holly grown in pine bark or pine tree substrate fertilized with four rates of Osmocote Plus 15N-3.9P-10K.[z]

	2005					2007				
Treatment	NO_3-N	P	K	Ca	Mg	NO_3-N	P	K	Ca	Mg
Osmocote ($kg \cdot m^{-3}$)	($mg \cdot L^{-1}$)[y]					($mg \cdot L^{-1}$)				
Pine bark										
3.5	24.3	11.3	89.0	30.5	13.8	52.0	10.2	85.3	62.4	12.5
5.9	90.5	23.5	161.5	75.5	28.8	75.4	29.6	171.0	65.2	27.7
8.3	125.5	35.3	203.8	99.0	38.5	115.9	37.5	188.0	54.4	33.2
10.6	128.5	42.3	205.5	87.0	35	129.0	68.1	288.9	74.4	45.2
Significance[xw]	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q**	L** Q*	NS NS	L* NS
Pine tree substrate[v]										
3.5	1.3	2.8	29.3	14.5	7.3	5.6	10.2	59.4	46.4	23
5.9	1.0	6.8	54.5	18.0	10.3	42.8	19.2	77.2	60.9	20.4
8.3	60.3	19.0	137.3	52.5	34.3	88.06	20.1	77	73.7	18.1
10.6	65.3	19.3	150.0	59.3	37.5	161.2	25.4	68.7	81.6	18.2
Significance	L*** Q**	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L** Q**	NS NS	NS NS	NS NS
Substrate	0.0001	0.0001	0.0001	0.0001	0.0175	0.1422	0.0029	0.0001	0.8812	0.0555
Fertilizer rate	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0006	0.0510	0.4324	0.2701
Substrate x fertilizer rate	0.0435	0.0440	0.2647	0.0158	0.0624	0.1384	0.0572	0.0807	0.6400	0.0709

[z]Substrate solution nutrient concentrations obtained by the pourthrough method (Wright, 1986).
[y]1 $mg \cdot L^{-1}$ = 1 ppm.
[x]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).
[w]L = linear; Q = quadratic response for concentration at *, **, or ***.
[v]Pine tree substrate produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer milled to pass through a 6.35 mm screen.

Table 2.3. Leaf tissue analysis taken on 22 Nov. 2005 and 25 May 2007 for japanese holly grown in pine bark or pine tree substrate and fertilized with four rates of Osmocote Plus 15N-3.9P-10K.

	2005			2007		
Treatment	N[z]	P[z]	K[z]	N	P	K
Osmocote ($kg \cdot m^{-3}$)	(%)			(%)		
Pine bark						
3.5	3.19	0.23	1.77	4.04	0.25	1.51
5.9	3.86	0.35	2.04	4.52	0.39	1.75
8.3	4.10	0.42	2.16	4.61	0.47	1.95
10.6	3.93	0.45	2.22	4.39	0.36	1.64
Significance[yx]	L* Q*	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
Pine tree substrate[w]						
3.5	1.19	0.17	1.36	2.51	0.13	1.61
5.9	2.87	0.25	1.99	3.96	0.44	1.97
8.3	2.96	0.34	2.28	4.81	0.73	2.25
10.6	2.68	0.31	2.10	5.01	0.75	2.83
Significance	NS Q*	L*** Q***	L** Q***	L* Q***	L* Q***	NS Q***
Substrate	0.0001	0.0001	0.0596	0.0002	0.0020	0.0001
Fertilizer rate	0.0022	0.0001	0.0001	0.0001	0.0001	0.0001
Substrate x fertilizer rate	0.3749	0.3213	0.0260	0.0001	0.0001	0.0001

[z]Tissue analysis performed on the most recently matured leaves per plant. N, nitrogen; P, phosphorus; K, potassium.

[y]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).

[x]L = linear; Q = quadratic response for concentration at *, **, or ***.

[w]Pine tree substrate produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer milled to pass through a 6.35 mm screen.

Table 2.4. Physical and chemical properties of unamended pine bark and pine tree substrates used in the production of japanese holly in 2005. Data were collected from three samples per substrate on 13 Sept. 2005 and represented as means.[z]

Substrates	Total porosity[y] (% vol)	Air space[x] (% vol)	Container capacity[w] (% vol)	Bulk density[v] ($g \cdot cm^{-3}$)	Cation exchange capacity[u] ($cmol \cdot L^{-1}$)
Pine bark	82.9 a[t]	26.9 b	56.1 a	0.20 a	17.9 a
Pine tree substrate[s]	83.6 a	38.2 a	45.2 b	0.15 a	2.1 b
BMP guidelines[r]	50-85	10-30	45-65	0.19-0.70	-

[z]Analysis performed using the North Carolina State University Porometer method (Fonteno et al., 1995).

[y]Total porosity is equal to container capacity + air space.

[x]Air space is the volume of water drained from the sample ÷ volume of the sample.

[w]Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.

[v]Bulk density after forced-air drying at 105 °C for 48 h; 1 $g \cdot cm^{-3}$ = 0.5780 $oz/inch^3$.

[u]Cation exchange capacity determined by A&L Eastern Agricultural Laboratories (Richmond, VA) using the AOAC International Official Method (Thrope, 1973).

[t]Means were separated within column between pine bark and pine tree substrate by least significance difference at $P \leq 0.05$.

[s]Pine tree substrate produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer milled to pass through a 6.35 mm screen.

[r]BMP = Best Management Practices recommended sufficiency ranges for physical properties of substrates used in general nursery production (Yeager et al., 2007).

Table 2.5. Leaf tissue analysis taken on 25 May 2007, average electrical conductivity (EC) levels and pH values over the experiment and substrate solution nutrients sampled on 20 Apr. 2007 for azalea grown in pine bark or pine tree substrate and fertilized with four rates of Osmocote Plus 15N-3.9P-10K.

	Leaf tissue[z]			Substrate solution[y]				
Treatment	N	P	K	pH	EC	NO_3-N	P	K
Osmocote ($kg \cdot m^{-3}$)	(%)				($dS \cdot m^{-1}$)[x]	($mg \cdot L^{-1}$)[x]		
Pine bark								
1.2	1.40	0.29	0.91	4.9	0.60	4.2	2.3	18.6
3.5	2.42	0.26	1.21	4.7	0.83	22.7	6.1	45.6
5.9	2.86	0.24	1.57	4.4	1.5	62.5	11.2	99.5
8.3	3.07	0.24	1.75	4.3	2.04	96.4	24.3	122.5
Significance[wv]	L*** Q***	NS Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L** Q**	L*** Q***
Pine tree substrate[u]								
1.2	0.95	0.21	0.63	5.5	0.41	3.2	1.0	18.7
3.5	1.52	0.54	1.49	5.5	0.60	10.4	4.7	24.5
5.9	2.33	0.55	1.89	5.6	0.71	43.5	17.2	44.8
8.3	2.95	0.37	2.07	5.4	1.6	75.6	20.7	57.2
Significance	L*** Q***	L** Q**	L*** Q***	NS Q***	L*** Q***	L*** Q***	L** Q**	L*** Q***
Substrate	0.0001	0.0001	0.0009	0.0001	0.0001	0.4762	0.0980	0.0001
Fertilizer rate	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Substrate x fertilizer rate	0.0001	0.0001	0.0001	0.0001	0.0029	0.0004	0.0885	0.0015

[z]Tissue analysis performed on the most recently matured leaves per plant. N, nitrogen; P, phosphorus; K, potassium.
[y]pH, electrical conductivity (EC), and substrate solution nutrient concentrations were obtained by the pour-through method
[x]1 $dS \cdot m^{-3}$ = 1 mmho/cm, 1 $mg \cdot L^{-1}$ = 1 ppm.
[w]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).
[v]L = linear; Q = quadratic response for concentration at *, **, or ***.
[u]Pine tree substrate produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer milled to pass through a 6.35 mm screen.

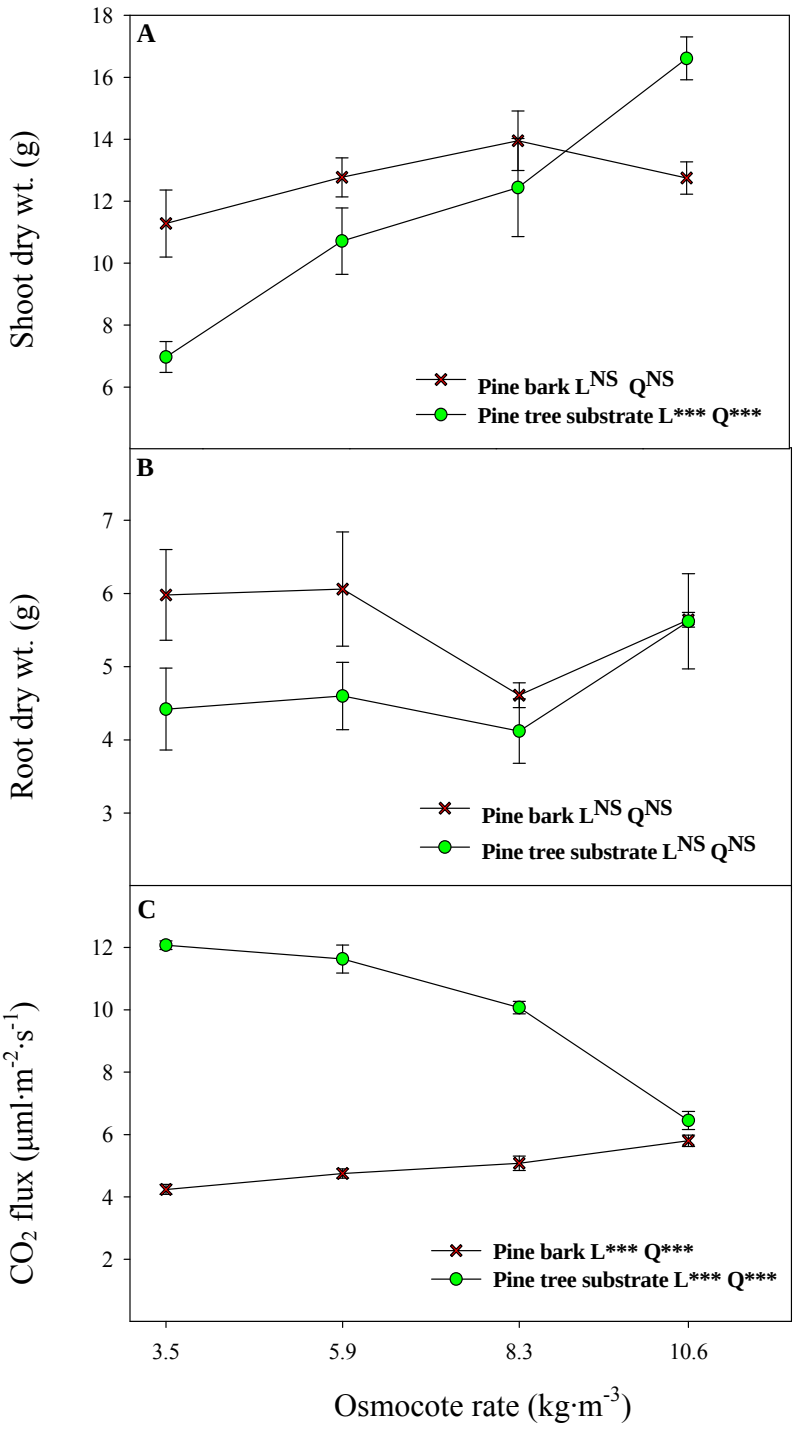

Figure 2.1. (A) (*2005 study*) Shoot dry weight (pine bark: y = 13.3930 (1 - 0.5364x), R^2 = 0.16 and pine tree substrate: y = 3.3072 + 0.6071x – 0.0066x^2, R^2 = 0.67); (B) root dry weight (pine bark: y = 8.1313 – 0.4120x + 0.0146x^2, R^2 = 0.12 and pine tree substrate: y = 7.3761 – 0.3766x + 0.0112x^2, R^2 = 0.23); (C) substrate CO_2 efflux rates (µmols $CO_2 \cdot m^{-2} \cdot s^{-1}$) (pine bark: y = 3.9333 + 0.0594x + 0.0108x^2 , R^2 = 0.54 and pine tree substrate: y = 9.3141 + 1.2809x – 0.1458x^2, R^2 = 0.87) of japanese holly grown from 17 Aug. 2005 to 22 Nov. 2005 in pine bark (x) or pine tree substrate (○) incorporated with four rates of Osmocote Plus 15N-3.9P-10K. Each point represents the means ± SE indicated by standard error bars (n = 5). L = linear; Q = quadratic responses, non-significant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***) respectively.

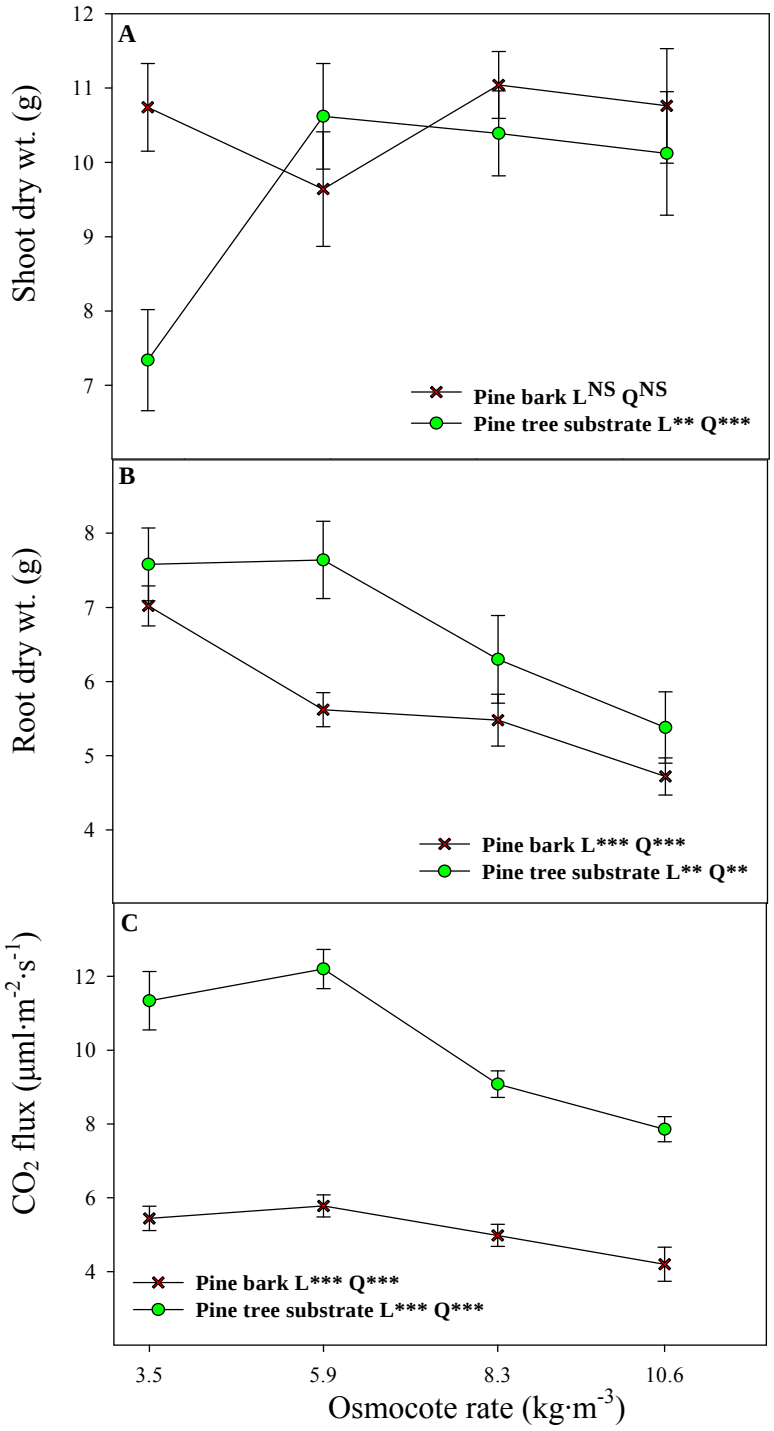

Figure 2.2. (A) (*2007 study*) Shoot dry weight (pine bark: $y = 11.7374 + 0.4768x - 0.0382x^2$, $R^2 = 0.04$ and pine tree substrate: $y = -369167.4 + 269177.8(1-0.0385x)$, $R^2 = 0.79$)); (B) root dry weight (pine bark: $y = 9.0014 - 0.6902x + 0.0279x^2$, $R^2 = 0.65$ and pine tree substrate: $y = 7.1347 - 0.3125x + 0.0459x^2$, $R^2 = 0.43$); (C) substrate CO_2 efflux rates (µmols $CO_2 \cdot m^{-2} \cdot s^{-1}$) (pine bark: $y = 4.8700 + 0.3601x + 0.0459x^2$, $R^2 = 0.62$ and pine tree substrate: $y = 10.0108 + 0.8013x + 0.0974x^2$, $R^2 = 0.62$) of japanese holly grown from 1 Mar. 2007 to 25 May 2007 in pine bark (x) or pine tree substrate (○) incorporated with four rates of Osmocote Plus 15N-3.9P-10K. Each point represents the means ± SE indicated by standard error bars (n = 5). L = linear; Q = quadratic responses, non-significant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***) respectively.

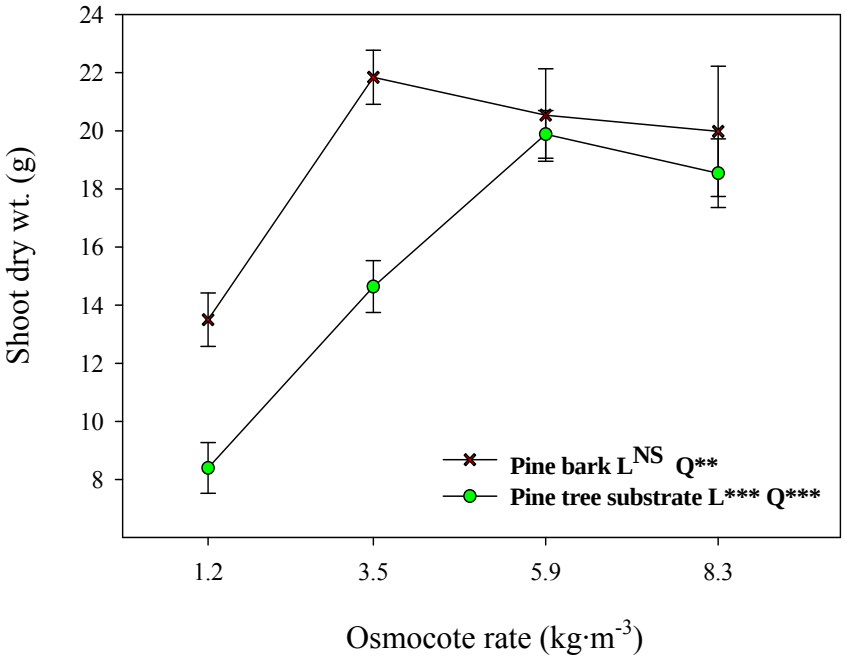

Figure 2.3. (*2007 study*) Shoot dry weight (pine bark: $y = 20.1497(1 - 0.5475x)$, $R^2 = 0.40$ and pine tree substrate: $y = 3.0218 + 2.7865x - 0.1184x^2$, $R^2 = 0.83$) of azalea grown from 1 Mar. 2007 to 25 May 2007 in pine bark (x) or pine tree substrate (○) incorporated with four rates of Osmocote Plus 15N-3.9P-10K. Each point represents the means ± SE indicated by standard error bars (n = 5). L = linear; Q = quadratic responses, non-significant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).

CHAPTER III

Pine Tree Substrate, Nitrogen Rate, Particle Size, and Peat Amendment Affects Poinsettia Growth and Substrate Physical Properties

Abstract: 'Prestige' poinsettias (*Euphorbia pulcherrima* Willd. Ex Klotzsch) were grown at different fertilizer rates in three pine tree substrates (PTS) made from loblolly pine trees (*Pinus taeda* L.) and a peat-based control. Pine tree substrates were produced from pine trees that were chipped, and hammer-milled to a desired particle size. Substrates used in this study included peat-lite (PL), PTS produced with a 2.38-mm screen (PTS1), PTS produced with a 4.76-mm screen (PTS2), and PTS produced with a 4.76-mm screen and amended with 25% peatmoss (v/v) (PTS3). Initial and final substrate physical properties and substrate shrinkage were determined to evaluate changes over the production period. Poinsettias were grown in 1.7-L containers in the fall of 2007 and fertilized at each irrigation with 100, 200, 300, or 400 $mg \cdot L^{-1}$ N. Shoot dry weight and growth index were higher in PL at 100 $mg \cdot L^{-1}$ N, but similar for all substrates at 300 $mg \cdot L^{-1}$ N. Bract length was generally the same or longer in all PTS-grown plants compared to plants grown in PL at each fertilizer rate. Post-production time-to-wilting was the same for poinsettias grown in PL, PTS1 and PTS3. Initial and final air space (AS) was higher in all PTSs compared to PL and container capacity (CC) of PTS1 was equal to PL initially and at the end of the experiment. The initial and final CC of PTS2 was lower than PL. The incorporation of 25% peat (PTS3) increased shoot dry weight and bract length at lower fertilizer rates compared to 4.76-mm PTS alone (PTS2). Substrate shrinkage was not different between PL and PTS1, but greater than shrinkage with the coarser PTS2. This study demonstrates that poinsettia can be

successfully grown in a PTS with small particles (2.38-mm screen) or a PTS with large particles (4.76-mm screen) when amended with 25% peatmoss which results in physical properties (CC and AS) similar to those of PL.

Introduction

Poinsettia is the number one selling potted plant produced and sold in the United States and the preferred substrates for their production are peat-based (Hidalgo and Harkess, 2002). Peat moss is also the preferred substrate for the production of most all other greenhouse crops. The production of greenhouse crops has increased over the past decade (2007 Floriculture and Nursery Crops Yearbook, 2007) thereby increasing the use and demand of peat. Although world peat reserves are significant, the question of limiting peat extraction to avoid the destruction of these fragile natural environments (non-renewable peat bogs) is of increasing concern among environmental, scientific, private, and governmental agencies in Europe (Carlile, 2004; Clark, 2008; Riviere et al. 2008; Robertson, 1993). In the United Kingdom for example, these concerns have prompted governmental regulations on the use of peat, and set target deadlines of 90% peat replacement by 2010 (Holmes, 2008). In response to the regulations, investigation of numerous peat alternatives in Europe has been conducted, but the acceptance and use of these materials has been gradual due to the continued low cost of peat (Schmilewski, 2008). There aren't regulations or governmental mandates to decrease the use of peat (mined and shipped from Canada) here in the U.S., but recent increases in fuel (transportation) costs, have led to the increasing cost of peat substrates and therefore have resulted in a greater interest in less expensive and locally available peat substitutes. Researchers are addressing the increasing cost of peat by investigating renewable

alternative substrates from other organic materials that can offer equal growth performance as that of peat but at a cheaper cost.

Wang and Blessington (1990) reported similar growth of poinsettia (number of branches and bracts, days to flower, and overall plant grade) in a substrate derived from composted cotton burrs compared to plants grown in a peat: pine bark substrate. Other works demonstrating the use of composted organic materials (Ku et al., 1998; Papafotiou et al., 2004) have been reported for poinsettia production.

Research has also been conducted on utilizing wood and plant-based substrates for greenhouse crop production. Lang (1997) and Webber et al. (1999) reported results with a substrate composed of noncomposted ground kenaf (*Hibiscus cannabinus* L.) plants to produce poinsettia and periwinkle (*Vinca minor* L.) with equal size and quality to plants grown in peat-based substrates. Wood shavings of fir (*Pseudotsuga menziesii* Mirb.) and redwood (*Sequoia sempervirens* D. Don) trees (Criley and Watanabe, 1974) and sawdust (derived from hardwood and softwood tree species) have been investigated for the production of carnations (*Dianthus caryophyllus* L.; Stark and Lukaszuk, 1991), chrysanthemums (*Chrysanthemum morifolium* Ramat.; Scott and Bearce, 1972; Still et al., 1972), and other potted foliage plants (Worrall, 1981) with results compared to peat-based substrates.

The problem with most of the aforementioned materials is the lack of uniformity that often exists with composts and wood waste materials like sawdust and wood shavings. The lack of substrate consistency and insufficient quantities of these waste materials is a problem for long-term and sustained use as a major substrate, especially for large production operations. In response, researchers have begun testing wood-based

substrates that are specifically produced for use as container substrates instead of utilizing wood waste and by-product materials. Research in Europe has been conducted for over two decades on the development of horticultural substrates composed of wood (Gumy, 2001; Nazim Gruda, pers. comm., 2007; Raviv and Lieth, 2008; Schilling, 1999). Gerber et al. (1999) demonstrated that geranium (*Pelargonium* x *hortorum* L.H. Bailey) could be grown in a 100% wood fiber substrate with similar growth to plants grown in peat if they were irrigated and fertilized more often than the plants grown in peat.

More recently, a PTS derived from delimbed loblolly pine trees, and referred to as *WoodGro*™ (WoodGro LLC., Blacksburg, VA) was developed. Successful production has been reported on numerous woody (Wright and Browder, 2005, Wright et al., 2006, Jackson et al., 2008) and herbaceous species (Wright et al., 2008). Fain et al. (2008) and Boyer et al. (2008) reported successful bedding plant growth in PTSs derived from loblolly pine trees (including limbs, bark, and needles) compared to plants grown in 100% pine bark (PB).

Nelson (2003) in describing the desirable properties of substrates for greenhouse crops noted the importance of organic matter stability and carbon (C): nitrogen (N) ratio. The high C:N ratio of wood substrates, resulting in the tie-up of N due to microbial immobilization, and wood substrate stability (decomposition) over time have been major concerns of researchers and growers. Researchers have shown, however, that reduced plant growth in wood substrates is generally only a problem when fertility levels (primarily N) are near the lower limits for optimal plant growth and development (Hicklenton, 1983). Wright et al. (2008) have shown that chrysanthemums can be successfully grown in a 100% PTS with an additional 100 ppm N compared to plants

grown in a commercial peat substrate. Other works by Still et al. (1972), Gruda and Schnitzler (1999), Wright et al. (2006), and Jackson et al. (2008) have shown that growth of plants produced in wood substrates is equal to plants produced in peat and PB substrates when higher fertilizer rates are supplied. Stability of wood substrates over time has been reported to range from 36% volume loss over 15 months (Fischer et al., 1993) to 50% volume loss over 51 weeks (Meinken and Fischer, 1997) during crop production. The wood substrates used in these reports were wood fiber (so named due to their manufacturing process and physical properties) and were derived from a mixture of various tree species; primarily spruce (*Picea abies* L.). Jackson and Wright (2008) and Jackson et al. (2008) report no significant visual substrate shrinkage or decomposition of PTS during greenhouse and nursery crop production and Fain et al. (2008) noted less shrinkage of a PTS than a peat substrate during a five week greenhouse trial. Changes brought about by shrinkage are undesirable because containers may need to be topped-off with substrate before distribution (sell). Furthermore, substrate shrinkage usually increases container capacity (CC) and decreases air space (AS) of substrates during production (Aendekerk, 2001).

In addition to substrate stability and C:N ratio, the successful production of poinsettia (and all greenhouse crops) requires having a substrate with other desirable physical and chemical properties that can promote and sustain healthy plant growth. Previous plant growth experiments with PTS have been conducted on various substrate screen sizes (with a range of physical properties) including 4.76-mm (Wright et al. 2008), and 6.35-mm (Fain et al., 2008; Jackson et al., 2008; Wright et al., 2006) with plant growth being similar to plants grown in peat or PB. Researchers have shown that PTS

can be constructed to produce a wide range of physical properties such as air space (AS) and water holding capacities (WHC) that are similar to commercial peat substrates (Saunders et al., 2006). To achieve this, PTS is hammer milled for a longer period of time to further reduce the particle size. The longer processing requires additional time, energy and labor thereby increasing the cost of PTS production. Incorporation of peat, PB, or other amendments may improve physical properties of larger PTS particle sizes to create a desired substrate for greenhouse crop production at a cheaper cost (less grinding time of PTS in a hammer mill). Browder et al. (2006) has shown that the incorporation of peat in PTS improves plant growth at lower fertility rates compared to 100% unamended PTS.

Research has not been reported on poinsettia production in PTS, or the evaluation of plant growth in different particle sizes of PTS under different fertility regimes. Results from a preliminary unpublished study in 2005 indicated that poinsettia can be grown in PTS with comparable growth to plants grown in PL if the fertilizer solution N concentration was increased from 200 $mg \cdot L^{-1}$ N to 300 $mg \cdot L^{-1}$ N. This experiment is a follow-up to the study mentioned above with the incorporation of particle size and peat amendment as additional parameters for evaluation. The affect of peat incorporation into PTS needs to be further investigated as a way to improve physical and chemical properties of PTS during crop production. Potential shrinkage of PTS during crop production and how it may affect substrate physical properties has not been reported. Determination of PTS stability over time under fertilized container conditions is critical since the change in physical properties during crop production can directly affect irrigation needs and plant growth. Based on these unanswered questions, the objectives

of this research were to determine the effect of 1) fertilizer rate; 2) substrate particle size and 3) peat amendment on growth and floral quality, and on post-production time-to-wilting of poinsettias.

Materials and Methods

The substrates used in this experiment were 1) PTS produced with a 2.38-mm screen (PTS1); 2) PTS produced with a 4.76-mm screen (PTS2); 3) PTS produced with a 4.76-mm screen and amended with 25% (v/v) peat moss (PTS3; Premier Tech, Quebec, Canada); and 4) a mix composed of 80% peat and 20% perlite (v/v; peat-lite – PL). The PTSs selected for this experiment were chosen based on their range of physical properties (Jackson and Wright, 2008). Pine tree substrate was produced from 12-year-old loblolly pine trees (approximately 25-cm in basal diameter) that were harvested at ground level, delimbed on 9 Apr. 2007 in Blackstone VA, and chipped with bark intact on 8 Aug. 2007 with a Bandit Chipper (Model 200, Bandit Industries, Inc. Remus, MI). Wood chips were then hammer-milled on 8 Aug. 2007 to pass through either a 2.38- or 4.76-mm screen. Peat-lite substrate was pre-plant amended with dolomitic lime at a rate of 3.6 $kg \cdot m^{-3}$ and calcium sulfate ($CaSO_4$) at a rate of 0.6 $kg \cdot m^{-3}$. Only PTS3 was incorporated with 1.8 $kg \cdot m^{-3}$ dolomitic lime due to the 25% peat moss amendment. Neither PTS1 or PTS2 were amended with lime due to the relatively inherent high pH (~6.0) of freshly ground pine wood (Wright et al., 2008), but all PTSs were amended with 0.6 $kg \cdot m^{-3}$ $CaSO_4$ as Saunders et al. (2005) reported improved growth of herbaceous species when $CaSO_4$ was incorporated.

On 16 Aug. 2007 single rooted cuttings of 'Prestige' poinsettia (Ecke Ranch, Yoder Brothers, Inc. Barberton, OH) were transplanted into 12-cm-tall x 15-cm-square

(1.7-L) plastic containers filled with the four substrates. To stimulate branching, the apical growing point was removed on 30 Aug. 2007 to leave approximately 6 nodes. Plants were fertilized at each irrigation with 250 mL (beaker applied) of 100, 200, 300, or 400 $mg \cdot L^{-1}$ N made from Peters 20N-4.4P-16.6K Peat-Lite Special (The Scotts Co., Marysville, OH) containing 12% nitrate (NO_3-N) and 8% ammonium (NH_4-N) until 2 Oct. 2007. From 2 Oct. until 10 Nov. 2007 plants were fertilized with the same N concentrations derived from Peters 15N-2.2P-20.75K Poinsettia Peat-Lite Special (The Scotts Co., Marysville, OH) containing 11% NO_3-N and, 4% NH_4-N respectively. Fertilizers were switched to lower the amount of NH_4-N and increase the amount of NO_3-N supplied to the crop as suggested by Ecke et al. (2004). Plants in all substrate treatments were irrigated and fertilized similarly. Plants were grown without growth regulators on raised benches in the Virginia Tech (Blacksburg, VA) Greenhouse Facility (glass-covered) with average day and night temperatures of 24 ^{o}C and 19 ^{o}C, respectively. Substrate solution was extracted using the pourthrough (PT) method (Wright, 1986) one day after potting (DAP) and then once per week for the first four weeks followed by every two weeks for the remainder of the experiment and analyzed for pH and EC using a Hanna HI 9811 instrument (Hanna Instruments, Woonsocket, RI). Substrate solution extracted on 14 Sept. 2007 (30 DAP) and 26 Oct. 2007 (72 DAP) were frozen and later analyzed for NO_3-N with an Orion ion selective electrode (Thermo Electron, Beverly, MA) on 17 Jan. 2008, and phosphorus (P), and potassium (K) concentrations on 31 Jan. 2008 with a Spectro Ciros Vision ICP (Spectro Analytical Instrument, Muhwah, NJ). On 28 Sept. 2007 (42 DAP) growth index of each plant was determined using the following formula: [(height + widest width + perpendicular width)

÷ 3]. On 15 Nov. 2007 (94 DAP) final growth measurements were taken including growth index (GI) and bract length (BL) of the five largest bracts on each of the two tallest stems (10 bracts total). On 15 Nov. 2007 plants (10 single plant replications) were severed at the substrate surface, forced-air dried for 5 d at 65 °C, and dry weights were recorded.

On 3 Dec. 2007 six uniform replications of poinsettias grown at the 300 $mg \cdot L^{-1}$ N fertilizer rate in each of the substrates were selected to assess the post-production time-to-wilting of poinsettia without irrigations in an indoor environment. Plants fertilized with 300 $mg \cdot L^{-1}$ N were chosen due to the similar plant growth across all substrates at that fertilizer rate. Plants were irrigated with 250 mL applications of water three times over eight hours to maintain moisture content near container capacity for all substrates. After drainage, plants were moved from the greenhouse to a laboratory (to simulate interior home conditions) and randomly spaced on tables. Plants were maintained at 16 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of irradiance from cool-white fluorescent lights for 10 h daily at 26 ± 1 °C. Plants were observed daily and monitored for wilting. When the first leaf on a plant began to droop, the day and time were recorded for that plant (Stage I). When all leaves on a plant wilted the day and time were again recorded (Stage II).

For substrate physical properties determination, 25-L samples of all substrates were collected on 14 Aug. 2007. These substrates were taken from the same batch used to pot the poinsettias and therefore amended similarly. Substrate samples were air-dried for two days then bagged and dry-stored for 14 weeks (the duration of the poinsettia experiment). Plastic containers [12-cm-tall x 15-cm-wide (1.7-L)] were filled with PL, PTS1, and PTS2 on 14 Aug. 2007 and placed fallow on a greenhouse bench. Six

replications of each substrate were fertilized with 300 $mg \cdot L^{-1}$ N made from Peters 20N-4.4P-16.6K Peat-Lite Special (The Scotts Co., Marysville, OH) containing 12% nitrate (NO_3-N) and 8% ammonium (NH_4-N) until 12 Nov. 2007 (96 DAP). Containers were irrigated once weekly with 500 mL of fertilizer solution. Substrate shrinkage (cm) was determined by measuring the difference in substrate height (from the top of the containers to the substrate surface) at 1 DAP following the first irrigation, and again at 96 DAP. At 96 DAP, two containers of each substrate were combined and prepared for physical property determination (n = 3).

Physical properties including AS, CC, total porosity (TP), and bulk density (BD) were determined on 10 Dec. 2007 on three replicate samples of each substrate from the initial dry-stored bagged samples and from the fallow samples fertilized in containers, using the North Carolina State University (NCSU) Porometer Method (Fonteno et al. 1995). Particle size distribution of 150 g oven-dried samples of PL, PTS1 and PTS2 were determined with 14 sieves (ranging from > 6.3-mm to < 0.06-mm) plus a bottom pan (Table 1). Sieves and pan were shaken for 10 min with a RX-29 Ro-Tap sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}; W.S. Tyler, Mentor, OH) and the particle fractions retained on each sieve and the amount that passed through the smallest sieve and retained by the sieve pan were weighed.

The experimental design was completely randomized with four substrates, four fertilizer rates, and eight replications per substrate for a total of 128 plants. Data were tested using the analysis of variance procedures of SAS (version 9.1 SAS Institute, Inc. Cary, NC). Data were also subjected to regression analysis using SigmaPlot (version 9.01 SPSS, Inc., Chicago, IL) with the exception that substrate physical properties were

subjected to analysis of variance within the GLM procedure, with treatment means separated by least significant difference analysis.

Results and Discussion

Particle size distribution. Peat-lite had the highest percentage of coarse particles (>2.0-mm; 23%) due primarily to the aggregates and clumps found in peat and also due to the perlite particles present in this substrate (Table 3.1). The PTS2 had the next highest percentage of coarse particles (1%), followed last by PTS1 (0.2%). Particle size distribution between 2.0- and 0.5-mm was 46% in PL, 59% in PTS1, and 70% in PTS2. Percentage of fine particles (<0.5-mm) was highest in PTS1 (41%) followed by PL with 31% and PTS2 with 29% (Table 3.1). By grinding wood with the 2.76-mm screen (PTS1) there was a 24% increase in the amount of fines produced compared to grinding with the 4.76-mm screen (PTS2; Table 3.1).

Physical properties: Initial. Total porosity was higher in all PTSs compared to PL, and were within, or higher than, the upper limit of the recommended range of (50-85%; Yeager et al., 2007; Table 3.2). Air space was high in all PTSs and within the recommended range (10-30%; Table 3.2). Peat-lite had the lowest percentage AS (15%) but was within the recommended range. Bulk density was equal for all PTSs and the PL value was similar to the PTS2 value. Container capacity values for PTS1 and PTS3 were equal to PL; PTS1 and PTS3 CC values were higher than the PTS2 value. This is likely due to the higher percentage of fine particles in PTS1 (Table 3.1) which are known to increase CC, and PTS3 is higher because of the water retention of the 25% peat component.

Physical properties: Final. (Final data were not determined for PTS3 due to sample contamination during storage). Total porosity increased in PL and PTS1 after 14 weeks but did not change in PTS2, and all substrate TP values were above the upper limit of the recommended range (50-85%; Table 3.2). Higher than recommended TP values (>85%) have been previously reported with several commercial wood substrates in Europe, including Cultifiber® (94%), Fibralur® (96%), Hortifiber® (94%), Pietal® (93%), and Toresa® (92-97%; Gumy, 2001; Raviv and Leith, 2008). Air space did not change for PTS2, but decreased in PL and PTS1. Air space for all substrates was within the recommended range (10-30%) after 14 weeks. Bulk density for all substrates was below the suggested levels (0.19-0.70) after 14 weeks. Container capacity values were equal in PL and PTS1 and were lowest in PTS2 (Table 3.2). All substrates increased CC after 14 weeks and were at or above the suggested range at the end of the experiment. Decreased AS and increased CC over time could be due to the settling "nesting" of the particles in a substrate when the finer particles fit between larger particles as described by Bilderback and Lorscheider (1995) or due to substrate decomposition. This increase in CC and decrease in AS has been shown by Bohne and Gunter (1997) and Prasad and Chualain (2005) in response to changes in particle sizes of a substrate. Over time for PTSs, the changes in physical characteristics were minor and with the exception of TP were substantially the same as those in PL showing that PTS can maintain desirable physical properties throughout a short-term crop production period.

Shrinkage after 14 weeks was lowest in PTS2 (7%) followed by PL (12%), and PTS1 (13%; Table 3.2). Less shrinkage with PTS2 is likely due to the larger particle size compared to PTS1 which agrees with observations by Wang (1994) who reported less

shrinkage of a coarse particle substrate derived from kenaf wood compared to a smaller particle kenaf substrate. Conversely, the increased shrinkage observed in PL and PTS1 is likely due to their high percentage of small particles (Table 3.1). Shrinkage is due to either breakdown (microbial decomposition) of the substrate or by substrate settling and compression caused by gravity and water movement through the substrate during irrigations (Fonteno et al, 1981; Meinken and Fischer, 1997). When particles of different sizes are mixed, shrinkage of the final volume occurs, as small particles fill the pores located between the large particles (Bures et al., 1993; Nash and Pokorny, 1990).

Effects on poinsettia growth, floral quality, and post-production time-to-wilting. Shoot dry weight increased in response to increasing fertilizer rate in each of the substrates (Table 3.3). There was a substrate x fertilizer rate response for shoot dry weight across substrates (Table 3.3). At the 100 $mg \cdot L^{-1}$ N rate shoot dry weight was higher in plants grown in PL than in all other substrates; shoot dry weight of plants grown in PTS1 and PTS3 were not different; and dry weight of plants grown in PTS2 was lowest (Table 3.3). At the 200 $mg \cdot L^{-1}$ N rate shoot dry weight was equal for PL, PTS1, and PTS3, with PTS2 being lowest. The 25% peat in PTS3 is likely responsible for the improved shoot dry weight at the 100 and 200 $mg \cdot L^{-1}$ N fertilizer rates compared to PTS2 due to improved physical (Table 3.2) and chemical properties of the coarser PTS. Shoot dry weight at the 300 $mg \cdot L^{-1}$ N rate was equal in all substrates. These growth results are the same as our preliminary study in 2005 and those reported by Wright et al. (2008), who showed that chrysanthemums require an additional 100 $mg \cdot L^{-1}$ N when grown in 4.76-mm PTS (PTS2) to achieve comparable growth to plants grown in a peat substrate. The 300 $mg \cdot L^{-1}$ N rate required for plants grown in PTS is within the recommended

fertilizer range (200-300 mg·L^{-1} N) suggested for poinsettia growth (Ecke et al., 2004). Shoot dry weight at the 400 mg·L^{-1} N rate was less for the PL-grown plants than plants grown in PTS1 and PTS3.

Decreased shoot dry weight of plants in PL at the 400 mg·L^{-1} N rate may be in response to the low substrate pH level (4.8) or the high EC value (3.7 dS·m^{-3}) that was observed at that fertilizer rate (Table 3.7; to be discussed later) and lower shoot dry weight for PTS2-grown plants is likely due to lower CC (Table 3.2). The increased microbial activity in PTS, reported by Jackson et al. (2008) and the resulting N immobilization in PTS (Jackson and Wright, 2007; Jackson and Wright 2008) is the likely reason for the additional fertilizer requirement in PTS for optimal plant growth. It is not believed that the absence of dolomitic lime in PTS1 and PTS2 (and therefore the additional Ca supplied by the lime to PL and PTS3) had any effect on plant growth in this experiment. Calcium concentrations in substrate solution were sufficient in all substrates at all fertilizer rates (data not shown) and therefore are negligible in the growth results. In addition, Saunders et al. (2005) and numerous unpublished studies by these authors have shown that increased Ca application to PTS (above the 0.6 kg·m^{-3} applied) does not increase plant growth in PTS.

Growth index at 42 DAP for PL-grown plants was not influenced by fertilizer rate but GI did increase in response to fertilizer for plants in all PTSs (Table 3.4). Similar to shoot dry weight, GI was higher in PL-grown plants than the PTSs at the 100 mg·L^{-1} N rate at 42 and 94 DAP, but as fertilizer rate increased, GI differences between substrates were few, with the possible exception of PTS3 at 94 DAP. It is not understood why GI of

PTS3-grown plants at 94 DAP did not equal the GI of PL-grown plants at the 200 and 300 $mg \cdot L^{-1}$ N rates like was shown at 42 DAP and for shoot dry weight.

Bract length increased as fertilizer rate increased for all substrates (Table 35). Bract length was determined because bract size is an indicator of high quality, visually appealing poinsettias. In general, with the exception of some minor discrepancies, BL was lowest in PTS2-grown plants and highest for PL, PTS1, and PTS3-grown plants. The reason for increased BL in PL, PTS1, and PTS3 is likely, (as with shoot dry weight), due to higher CC, thus higher water and nutrient retention compared to PTS2 (Table 3.2).

Post-production time-to-wilting (Stage I and Stage II) occurred first in PTS2-grown plants with no differences in the drying/wilting time among plants grown in PL, PTS1, or PTS3 (Table 3.6). The earliness of the PTS2-grown plants to wilt is most likely due to the lower CC of that substrate compared to the others (Table 3.2). The presence of 25% peat in the PTS3 substrate plus the smaller particle fines of PTS1 (Table 3.1) improved the water holding capacity compared to PTS2 and made it equal to the CC of PL (Table 3.2) and thereby lengthened the time to wilting for plants in that substrate. Thus, PTS does not require greater post-production maintenance (irrigations) than traditional PL substrates if CC is comparable.

Substrate chemical and nutrient status. Substrate solution EC, NO_3-N, P, and K increased and pH decreased as fertilizer rate increased (Table 3.7). Substrate solution pH was higher in all PTSs at each fertilizer rate compared with PL and decreased as fertilizer rate increased (Table 3.7). Substrate solution EC values increased with increasing fertilizer rate and at any particular fertilizer rate levels were higher in PL than the three PTSs (Table 3.7), showing that higher fertilizer rates were required for all PTSs

compared with PL to achieve comparable substrate EC levels. Lower substrate solution EC and higher pH in PTS compared to PL has been reported previously by Wright et al. (2008).

There was a substrate x fertilizer rate response for P and K in the substrate solution, but not for NO_3-N. Nitrate concentrations increased as fertilizer rates increased in all substrates and were generally higher in PL at each fertilizer rate than in the PTSs. Similar to the EC levels and NO_3-N concentrations previously discussed, P concentrations were higher in PL (except at the 100 $mg \cdot L^{-1}$ N rate) at each fertilizer rate compared to the three PTSs (Table 3.7). Conversely, substrate solution K concentrations were higher at each fertilizer rate in all PTSs than in PL which has been previously reported by Wright et al. (2008) during the production of chrysanthemums. Substrate solution sampled on 26 Oct. showed similar responses and trends to these reported for 14 Sept. and therefore are not shown.

Lower NO_3-N concentrations in substrate solution of PTS is likely a result of microbial immobilization of NO_3-N as reported by Jackson and Wright (2008). The reason for lower substrate solution P concentrations in all PTSs may be two-fold. First, it has been shown that microbial immobilization of P occurs in wood-based substrates (Handreck, 1996), reducing the amount of soluble P in solution. Secondly, it has been reported that P retention is higher in wood-based substrates (resulting in less water extractable P) compared to peat due to exchange sites on the internal surfaces of the wood particles (Brown and Pokorny, 1977). Higher substrate solution K in all PTSs is likely due to higher concentrations of K present in fresh (noncomposted) wood compared

to K concentrations found in peat which has been observed by these authors (unpublished results) and also reported by Prasad (1980).

Conclusions

Results from this experiment indicate that 100% PTS can be a successful greenhouse substrate with similar plant growth and shrinkage as a traditional peat substrate if additional fertilizer is supplied or if substrate physical properties are adjusted to be similar to those of peat. We also observed the apparent benefits that the addition of peat moss can have to a coarse PTS to improve plant growth and post-production self life due to improved physical properties.

Since PTS is produced from freshly harvested trees, it, unlike many compost based substrates, is a clean material free from undesirable components such as glass, metal, weed seeds, pathogens, and heavy metals. The ability to grind PTS to various particle sizes to achieve desired physical properties (AS and CC) excludes the need for additional amendments (perlite, vermiculite, PB, etc.) that are required for commercial peat substrates. The low BD of PTS could be important for shipping considerations of these substrates, since weight increases shipping costs.

Loblolly pine is native to the southeastern U.S. and can be found in close proximity to nursery and greenhouse operations. Pine tree substrate can be produced in these areas, minimizing transportation costs to growers. It should also be mentioned that the use of wood materials (including loblolly pine trees) are being developed as fuel sources (i.e. wood pellets) as alternative energy sources. Competition for loblolly pine trees for fuel wood should be considered as it relates to the cost of pine chips and

ultimately the production cost of PTS as it is developed and utilized commercially in the future. One way to offset potential competition for pine wood is to establish pine plantations specifically for PTS production by individual growers or by a consortium of growers in areas throughout the southeast to guarantee sufficient wood sources in the future.

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Table 3.1. Particle size distribution of peat-lite (PL) and pine tree substrates (PTS) produced with 2.36 and 4.76-mm hammer mill screens.[z]

	Particle size distribution (% of dry wt)						
	PL[y]		PTS1[x]		PTS2[x]		
Particle size (mm)	Mean	SD[w]	Mean	SD	Mean	SD	Particle Size Range[v]
>2.0	23.18	1.01	0.16	0.07	0.96	0.93	Coarse
1.0-2.0	20.89	0.10	15.29	2.53	36.98	2.11	
0.5-1.0	25.29	0.85	43.47	1.79	33.09	1.97	Medium
0.25-0.5	17.38	0.34	25.89	1.08	19.16	1.60	
0.125-0.25	10.29	0.54	12.64	0.84	8.69	0.68	
0.63-0.125	2.69	0.50	1.76	0.25	0.96	0.04	Fine
<0.063	0.36	0.08	0.80	0.13	0.22	0.10	

[z]Values are means of three air-dried substrate samples.
[y]PL composed of 80% peat moss / 20% perlite (v/v).
[x]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm screen (PTS1) or 4.76-mm screen (PTS2).
[w]Standard deviation of means.
[v]Particle size range: coarse ≥ 2.0-mm; medium < 2.0-mm to ≥ 0.5-mm; fine < 0.5-mm.

Table 3.2. Initial and final (after 14 weeks in containers fertilized weekly with 300 mg·L^{-1} N) physical properties of peat-lite (PL) and pine tree substrates (PTS). Peat-lite and the PTSs were used in the production of 'Prestige' poinsettias from16 Aug. 2007 to 15 Nov. 2007.[z]

	Total porosity[y] (% vol)			Air space[x] (% vol)			Bulk density[w] (g·cm^{-3})			Container capacity[v] (% vol)			Substrate shrinkage[u] (%)
Substrate	Initial	Final	LSD	Initial	Final	LSD	Initial	Final	LSD	Initial	Final	LSD	
PL[t]	80.6b[s]	85.9b	3.5[r]	15.0c	13.0c	1.9	0.16a	0.18a	0.02	65.6a	72.9a	4.8	11.9a
PTS1[q]	86.7a	90.0a	2.4	22.1b	18.0b	1.5	0.14b	0.15b	0.01	64.6a	72.0a	3.0	12.7a
PTS2[q]	84.9a	89.4a	4.7	30.2a	24.7a	7.9	0.15ab	0.16b	0.01	54.6b	64.9b	4.8	6.8b
PTS3[qp]	86.5a	-	-	21.4b	-	-	0.14b	-	-	65.9a	-	-	-
Range[o]	50-85		-	10-30		-	0.19-0.70		-	45-65		-	-

[z]Data were collected from three samples per substrate and represented as means. Analysis performed using the North Carolina State University Porometer method (Fonteno et al., 1995).
[y]Total porosity is equal to container capacity + air space.
[x]Air space is the volume of water drained from the sample ÷ volume of the sample.
[w]Bulk density after forced-air drying at 105 °C for 48 h.
[v]Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.
[u]Shrinkage = substrate height in container at 1 day after potting (DAP) - substrate height at 96 DAP.
[t]PL composed of 80% peat moss / 20% perlite (v/v).
[s]Means separated within columns (initial and final) by Duncan's multiple range test, $P \leq 0.05$.
[r]Means were separated within rows between initial and final substrate properties by least significance difference (LSD) at $P \leq 0.05$.
[q]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm (PTS1) or 4.76-mm (PTS2) screens. PTS3 was produced with a 4.76-mm screen and amended with 25% peat moss (v/v).
[p]Only initial physical properties were determined on this substrate.
[o]Suggested range for container substrates = Best Management Practices recommended sufficiency ranges for physical properties of substrates used in general container production (Yeager et al., 2007).

Table 3.3. Shoot dry weight (g) of 'Prestige' poinsettias grown from 16 Aug. 2007 to 15 Nov. 2007 (94 DAP) in either peat-lite (PL) or pine tree substrates (PTS) and fertilized with four rates of a 15N-2.2P-20.75K soluble fertilizer.

Fertilizer rate ($mg \cdot L^{-1}$)[z]	Shoot dry wt (g)			
	Substrate			
	PL[y]	PTS1[x]	PTS2[x]	PTS3[x]
100	20.6a[w]	15.9b	11.0c	14.1b
200	35.8a	36.6a	27.9b	32.2ab
300	48.2a	49.0a	43.3a	47.7a
400	37.3b	42.1ab	40.0b	49.1a
Significance[v]	L***	L***	L***	L***
	Q***	Q***	Q***	Q***
P-vales:[u] Substrate (S) = 0.0065; Fertilizer (F) = ≤0.0001; S*F = 0.0453				

[z]$1 mg \cdot L^{-1}$ = 1 ppm.
[y]PL composed of 80% peat moss / 20% perlite (v/v).
[x]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm (PTS1) or 4.76-mm (PTS2) screens. PTS3 was produced with a 4.76-mm screen and amended with 25% peat moss (v/v).
[w]Means separated within row by Duncan's multiple range test, $P \leq 0.05$.
[v]L = linear; Q = quadratic response for concentration at *, **, or ***
[u]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).

Table 3.4. Growth index[z] of 'Prestige' poinsettias at 42 days after planting (DAP) and 94 DAP grown in either peat-lite (PL) or pine tree substrates (PTS) and fertilized with four rates of a 15N-2.2P-20.75K soluble fertilizer.

Fertilizer rate ($mg \cdot L^{-1}$)[w]	Growth index			
	Substrate			
	PL[y]	PTS1[x]	PTS2[x]	PTS3[x]
			42 DAP	
100	28.5a[v]	22.2b	17.7c	20.2b
200	27.9ab	28.4a	25.8b	27.4ab
300	29.3a	29.6a	28.9a	29.7a
400	26.3b	27.4ab	27.0ab	30.1a
Significance[u]	L^{NS}	L**	L***	L***
	Q^{NS}	Q***	Q***	Q***
P-vales:[t] Substrate (S) = 0.0432; Fertilizer (F) = <0.0001; S*F = 0.0022				
Fertilizer rate ($mg \cdot L^{-1}$)			94 DAP	
100	41.2a	37.8b	33.5c	31.1c
200	49.0a	46.1b	44.0b	40.4c
300	50.7a	49.7a	48.0a	45.0b
400	46.8a	45.8a	47.2a	46.0a
Significance	L*	L***	L***	L***
	Q***	Q***	Q***	Q***
P-vales: Substrate (S) = ≤0.0001 ; Fertilizer (F) = ≤0.0001; S*F = 0.0006				

[z]Growth index [(height + widest width + perpendicular width)÷3].
[y]PL composed of 80% peat moss / 20% perlite (v/v).
[x]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm (PTS1) or 4.76-mm (PTS2) screens. PTS3 was produced with a 4.76-mm screen and amended with 25% peat moss (v/v).
[w]1 $mg \cdot L^{-1}$ = 1 ppm.
[v]Means separated within row by Duncan's multiple range test, $P \leq 0.05$.
[u]L = linear; Q = quadratic response for concentration at *, **, or ***
[t]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).

Table 3.5. Bract length (cm) of 'Prestige' poinsettias grown from 16 Aug. 2007 to 15 Nov. 2007 (94 DAP) in either peat-lite (PL) or pine tree substrates (PTS) and fertilized with four rates of a 15N-2.2P-20.75K soluble fertilizer.

Fertilizer rate ($mg \cdot L^{-1}$)[x]	Bract length (cm)			
	Substrate			
	PL[z]	PTS1[y]	PTS2[y]	PTS3[y]
100	12.1a[w]	12.1a	11.1b	12.6a
200	13.7b	13.4b	13.3b	15.0a
300	14.9b	15.5a	14.3c	15.9a
400	14.0b	15.3a	13.9b	15.2a
Significance[v]	L***	L***	L***	L***
	Q***	Q***	Q***	Q***
P-vales:[u] Substrate (S) = ≤0.0001; Fertilizer (F) = ≤0.0001; S*F = 0.0016				

[z]PL composed of 80% peat moss / 20% perlite (v/v).
[y]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm (PTS1) or 4.76-mm (PTS2) screens. PTS3 was produced with a 4.76-mm screen and amended with 25% peat moss (v/v).
[x]1 $mg \cdot L^{-1}$ = 1 ppm.
[w]Means separated within row by Duncan's multiple range test, $P \leq 0.05$.
[v]L = linear; Q = quadratic response for concentration at *, **, or ***
[u]Nonsignificant (NS) or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***).

Table 3.6. Post production days required for two stages of wilting of poinsettias grown in peat-lite (PL) and three pine tree substrates (PTS) at a 300 $mg \cdot L^{-1}$ N fertilizer rate.[z]

Wilting stage	Day to wilting			
	Substrate			
	PL[y]	PTS1[x]	PTS2[x]	PTS3[x]
Stage I[v]	7.9a[w]	7.9a	5.6b	8.5a
Stage II[u]	11.0a	10.5a	8.4b	10.8a

[z]Plants were stored in an indoor environment (temperature of 26 °C, respectively). Data collected on 6 plants in each substrate.
[y]PL composed of 80% peat moss / 20% perlite (v/v).
[x]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm (PTS1) or 4.76-mm (PTS2) screens. PTS3 was produced with a 4.76-mm screen and amended with 25% peat moss (v/v).
[w]Means separated within row by Duncan's multiple range test, $P \leq 0.05$.
[v]Stage I was recoded when wilting first began (leaf droop).
[u]Stage II was recorded when all leaves were completely wilted against the stem.

Table 3.7. pH, electrical conductivity (EC), and substrate nutrient concentrations collected on 14 Sept. 2007 from 'Prestige' poinsettia grown in either peat-lite (PL) or pine tree substrates (PTS) and fertilized with four rates of a 15N-2.2P-20.75K soluble fertilizer.[z]

Fertilizer rate ($mg \cdot L^{-1}$)[y]	pH	EC ($dS \cdot m^{-1}$)[x]	NO_3-N	P	K
			($mg \cdot L^{-1}$)		
PL[w]					
100	5.36	0.69	40.0	12.7	32.4
200	5.24	1.85	129.0	38.0	125.0
300	5.02	2.88	243.6	76.9	234.5
400	4.86	3.72	285.2	150.8	417.2
Significance[uv]	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
PTS1[t]					
100	6.58	0.53	24.0	13.3	55.1
200	6.36	1.14	79.0	31.1	163.9
300	5.82	2.55	184.4	60.8	342.2
400	5.66	3.58	271.8	135.7	590.8
Significance	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
PTS2[t]					
100	6.66	0.53	21.0	13.7	72.8
200	6.42	0.96	61.0	31.3	148.5
300	5.66	1.95	140.2	57.9	262.6
400	5.34	2.99	302.4	108.0	436.3
Significance	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
PTS3[t]					
100	6.50	0.64	31.0	12.5	65.5
200	6.26	1.19	116.6	32.2	142.6
300	5.80	2.42	227.6	50.9	272.2
400	5.54	3.52	318.6	113.9	474.8
Significance	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
Substrate (S)	<.0001	<.0001	0.0004	<.0001	<.0001
Fertilizer (F)	<.0001	<.0001	<.0001	<.0001	<.0001
S*F	<.0001	0.0045	0.0831	<.0001	<.0001

[z]pH and EC of substrate solution determined on pourthrough extracts (Wright, 1986).
[y]1 $mg \cdot L^{-1}$ = 1 ppm.
[x]1$dS \cdot m^{-3}$ = 1mmho/cm.
[w]PL composed of 80% peat moss / 20% perlite (v/v).
[v]Nonsignificant or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***), respectively.
[u]L= linear; Q= quadratic response for concentration at *, **, or ***.
[t]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 2.38-mm (PTS1) or 4.76-mm (PTS2) screens. PTS3 was produced with a 4.76-mm screen and amended with 25% peat (v/v).

CHAPTER IV

Comparison of Fertilizer Nitrogen Availability, Immobilization, and Leaching in Pine Tree Substrate, Peat-Lite, and Pine Bark

Abstract: The objective of this study was to compare nitrogen (N) immobilization and nutrient leaching rates in peat-lite (PL), aged pine bark (PB), and a pine tree substrate (PTS) over time under greenhouse conditions. Pine tree substrate was produced from loblolly pine logs (*Pinus taeda* L.) that were chipped, and hammer-milled to a desired particle size. Substrates used in this study were PL, PB, and PTS ground through a 2.38-mm hammer-mill screen. A short-term (28 days) N immobilization study was conducted on substrates fertilized with 150 or 300 $mg \cdot L^{-1}$ NO_3-N. Substrates were incubated for four days after fertilizing and NO_3-N levels were determined initially and at the end of the incubation. A second medium-term study (10 week) was also conducted to evaluate the amount of N immobilized in each substrate when fertilized with 100, 200, 300, or 400 $mg \cdot L^{-1}$ N. In addition to determining the amounts of N immobilized, substrate CO_2 efflux ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) was also measured as an assessment of microbial activity, which can be an indication of N immobilization. A leaching study on all three substrates was also conducted to determine the amount of N, phosphorus (P), and potassium (K) leached over 14 weeks under greenhouse conditions. Nitrogen immobilization was highest in PTS, followed by PB and PL. Nitrogen immobilization increased as fertilizer rate increased to 200 $mg \cdot L^{-1}$ N in PL and 300 $mg \cdot L^{-1}$ N for PB and PTS, followed by a reduction or no further increase in immobilization when fertilizer rates increased beyond these rates. Nitrogen immobilization was generally highest in all substrates two weeks after potting, after which immobilization tended to decrease over the course of several

weeks, with less of a decrease for PTS compared to PL and PB. Substrate CO_2 efflux levels were highest in PTS followed by PB and PL at each measurement in both the short- and medium-term studies. Patterns of substrate CO_2 efflux levels (estimate of microbial populations) between substrates, at both fertilizer rates, and over time were somewhat mirrored by N immobilization during the studies. Nitrate leaching was lower in PTS than in PB or PL through 14 weeks, P leaching was generally similar across all substrates with a few minor exceptions, and more K leached from PTS and PB than from PL through 12 weeks, after which no differences in K leaching occurred.

Introduction

In recent years several peat and bark alternative substrates have been developed and researched in the United States and throughout the world. The interest in new substrates is in response to the increasing cost and environmental issues surrounding the use of peat moss and the cost and availability of pine bark (PB) substrates. Many of the substrates investigated are wood-based or plant debris-based materials that have been processed for use as a container substrate and include Chinese tung tree (*Aleurites fordi* Hemsl.; Gruszynski and Kämpf, 2004), paper bark tree (*Melaleuca quinquenervia* Cav.; Poole and Conover, 1985), forest gorse (*Ulex europaeus* L.; Iglesias et al., 2008), tree fern (*Dicksonia squarosa* Swartz.; Prasad and Fietje, 1989), and miscanthus (*Miscanthus sinensis* Anderss.; Carthaigh et al., 1997) to name a few. Evaluation of these and other wood/plant-based substrates has proven successful in the production of vegetables (Pudelski and Pirog, 1984; Schnitzler et al., 2004), foliage plants (Roeber and Leinfelder, 1997), bedding plants (Boyer et al., 2008; Wright and Browder, 2005; Wright et al., 2008b), poinsettias and mums (Jackson et al., 2008b; Wright et al., 2008a), and woody

shrubs and trees (Jackson et al., 2008a; Wright et al., 2006). Much attention is now focused on pine tree substrates (PTS) that are produced by grinding loblolly pine trees to a size acceptable for use a container substrate (Boyer, 2008; Fain et al, 2008a; Jackson et al., 2007; Wright and Browder, 2005).

In contrast to peat and composted PB, plant production in substrates composed of wood, or large portions of wood, have a tendency to become nitrogen (N) deficient as a result of high rates of N immobilization (Handreck, 1991; Handreck, 1993b; McKenzie, 1958). Wood contains large amounts of useable/degradable carbon (C) compounds, but only a small amount of nutrients to offer for decomposing microorganisms, resulting in a draw upon nutrient sources (primarily N) from the surrounding environment (Gumy, 2001). The N extraction from the soil/substrate solution by microorganisms lowers available nutrient supplies to plants, which in turn leads to plant nutrient deficiencies if additional N is not added to correct the problem (Bodman and Sharman, 1993; Handreck, 1993b). Successfully producing crops in wood substrates will require new strategies in N management so that the collective amounts of N required by microorganisms and the by plants will be supplied in sufficient quantities (Lunt and Clark, 1959; Worrall, 1985).

Several methods and cultural strategies have been developed and utilized to reduce N immobilization in wood substrates and improve fertilizer management strategies during crop production: 1) Composting wood materials has been shown to eliminate or significantly reduce the potential for N immobilization to occur during crop production by lowering the C:N ratio and allowing the initial breakdown which requires high levels of N by microorganisms (Gutser et al., 1983; Prasad, 1997); 2) A nutrient impregnation process used in the production of Toresa®, a commercial wood fibre substrate in Europe, mechanically grinds wood chips together with an accurately

specified quantity of nutrient compounds in machines called retruders [Gumy, 2001; personal observation (Brian Jackson and Robert Wright) at an Intertoresa AG manufacturing facility in Hamburg, Germany, March 13, 2007). The nutrients are forced into the wood fibers by high mechanical pressure and heat generated during the production of Toresa® (Schilling, 1999). Gruda et al. (2000) concluded that N impregnation in wood fiber substrates was sufficient to provide enough N for the initial microbial immobilization occurring during the first days of crop production; 3) A technique call the Fersolin process impregnates wood material with sulfuric acid in the presence of hot gases (933 °C) resulting in a decrease in decomposable cellulose which results in lower microbial activity and need for N (Bollen and Glennie, 1961); and 4) A process for treating wood materials by pyrolysis (a form of incineration that chemically decomposes organic materials by heat in the absence of oxygen) has been evaluated as a method to breakdown unstable and toxic wood components into more stable and non-toxic components that are resistant to microbial decay which retards microbial N demand (Bollen and Glennie, 1961). The methods described above (1-4) are often expensive, time consuming, and non-practical for many substrate companies and growers. As a more practical approach, a common method for supplying nutrients to counter-act microbial N immobilization from a substrate is by the application of additional fertilizer during crop production. This is the most commonly used and preferred method of countering the effects of N immobilization on plant growth (Gruda et al., 2000; Gruda, 2005; Wright et al., 2008a).

The most frequently used and accepted method for determining N immobilization in soilless substrates is the nitrogen drawdown index (NDI) procedure developed by Handreck (1992a, 1992b). The NDI procedure involves saturating or “charging” a

substrate with a KNO_3 fertilizer solution containing 75 $mg \cdot L^{-1}$ N and then incubating the substrate at 22 ˚C for 4 days. Substrate solution nitrate (NO_3-N) levels are determined immediately following saturation on day 0 and then again after day 4 (the incubation period). Nitrogen drawdown index is then calculated by the following formula (NO_3-N measured on day 4 / NO_3-N measured on day 0 x 100). The resulting index is a value between 1.0 and 0.0 with a value of 1.0 representing no N loss during the 4 day incubation and an index value of 0.0 indicating complete N loss after 4 days. Substrates composed of large amounts of wood materials (high C:N ratio) will immobilize all, or nearly all, of the N during the 4 day incubation when using 75 $mg \cdot L^{-1}$ N, making it impossible to determine maximum amount used by microorganisms. Handreck (1992b) has recommended that the N concentration in the saturating solution be 150 mg L^{-1} N when substrates with a high demand for N are being tested, or that the incubation time be decreased to obtain measurable amounts of N remaining in the substrate after incubation. Similarly, Sharman and Whitehouse (1993) suggest that saturating solutions with concentrations of 150, 200, or 300 mg L^{-1} N be used in N immobilization tests on materials with high C:N ratios, such as PTS.

Nitrogen immobilization in soils and organic materials results from microbial assimilation of ammonium nitrogen (NH_4-N) and NO_3-N into proteins, nucleic acids and other organic complexes contained within microbial cells (Davet, 2004). Carbon dioxide (CO_2) release represents the final stage of oxidation of organic substrates and is the older and still more commonly used method for estimation of microbial biomass (Wang et al., 2003). Since root respiration is also a source of CO_2 in the soil, it is important to take into account the sources of CO_2 evolution. Soil CO_2 efflux is influenced by a number of factors, including soil/substrate quality and organic matter content, temperature, soil

moisture, root biomass, and microbial activity and biomass (Davet, 2004; Fog, 1988; Wang et al., 2003).

The estimation of microbial populations in soils or soilless substrates may be accomplished by several methods, for example by counting the population (by either microscopy or plating on agar), chloroform fumigation procedure for biomass determination, or by assaying some unique component of biomass such as ATP, extracellular dehydrogenase, or by measuring the metabolic activity of the population (Carlile and Dickinson, 2004; Needelman et al., 2001; Turner and Carlile, 1983; Vance et al., 1987). Measuring the metabolic activity of a microbial population (respiratory activity) involves monitoring CO_2 evolution or O_2 consumption. Techniques for monitoring CO_2 evolution from soil were pioneered by Waksman (1932) and are still widely used in studies of microbial activity in soils and soilless substrates (Gough and Seiler, 2004; Jackson et al., 2008a; Pronk, 1997; Söderstrom et al., 1983; Turner and Carlile, 1983). Microbial activity (estimated by CO_2 efflux from soils) increases in response to N fertilization in N limiting soils (Zhang and Zak, 1988) and to P fertilization in P limiting soils (Gallardo and Schlesinger, 1994). Microbial activity has also been reported to decrease in response to high rates of N fertilization of forest soils (Smolander et al., 1994; Thirukkumaran and Parkinson, 2000). Less work has been completed on soilless substrates compared to field or forest soils using CO_2 efflux to monitor/estimate microbial activity.

In addition to N immobilization, nutrient leaching in PTS has been proposed as a possible reason for the lower EC and nutrient levels observed in PTS compared to PL or PB during plant production (Wright and Browder, 2005; Wright et al., 2008a). Nutrient leaching from horticulture crop production areas is a major concern for growers and

environmental agencies, particularly NO_3-N and ortho-phosphate anions. Nitrate levels >10 ppm in drinking water are considered unsafe for humans (Environmental Protection Agency, 2006), and elevated P levels from container leaching/runoff are often associated with increasing algal blooms and eutrophication of lakes and ponds (Hart et al., 2004). Even though P is considered rather immobile in many soils, it is more readily leached from soilless container media (Broschat, 1995; Yeager and Wright, 1982). Nitrate is readily leached from both mineral soils and soilless container substrates (Bugbee and Elliott, 1998). Limited information is available on nutrient leaching from wood substrates, and no information is available on nutrient leaching in PTS during crop production. This is an important issue in light of the higher fertilizer requirements reported for PTS (Jackson et al, 2008a; Jackson and Wright, 2008; Wright et al, 2008a) which increases the potential for nutrient leaching.

Most nursery and greenhouse producers base their fertility management on previous growing experiences with PL and PB substrates. These fertility practices may not be applicable when growing crops in PTS in light of the higher fertilizer requirements, limited understanding of N immobilization timing and rate, and its unknown leaching potential. Determining the extent and timing of N immobilization and nutrient leaching in PTS therefore needs to be determined for more accurate nutrient management (application timing and rates) strategies when producing plants in this substrate. The objective of these studies was to compare N immobilization, substrate CO_2 efflux, and nutrient leaching rates in PL, PB, and PTS over time under greenhouse conditions.

Materials and Methods

Short-term (4 week) N immobilization. Pine tree substrate used in this study was produced from loblolly pine trees (approximately 25-cm basal diameter) that were harvested at ground level and delimbed on 25 April 2006 in Warsaw VA. Trees were then chipped (including bark) with a Morbark Chipper (Winn, MI) operated by Wood Preservers Inc., (Warsaw, VA) on 26 April 2006. Wood chips (2.5-cm x 2.5-cm x 0.5-cm) were further ground in a hammer-mill (Meadows Mills, Inc., North Wilkesboro, NC) on 27 April 2006 to pass through a 2.38-mm screen. Pine tree substrate was used fresh (uncomposted) and amended with 0.6 $kg \cdot m^{-3}$ calcium sulfate ($CaSO_4$) as Saunders et al. (2005) reported improved growth of herbaceous species when $CaSO_4$ was incorporated. Samples of PTS were tested for pH prior to potting and not amended with lime due to the relatively high pH (~6.0) observed which has been previously reported in freshly ground pine wood (Wright et al., 2008a). Other substrates used in this study were an aged PB and a mix composed of 80% peat (Premier Tech, Quebec, Canada) and 20% perlite (v/v; peat-lite – PL). Pine bark and PL were pre-plant amended with dolomitic lime at a rate of 3.6 $kg \cdot m^{-3}$ and $CaSO_4$ at the rate of 0.6 $kg \cdot m^{-3}$. Substrates were prepared on 1 May 2006 and moistened to 50% moisture content (typical potting moisture content) to facilitate lime reactions (in the peat and PB) and provide adequate moisture for microbial activity in all substrates. Substrates were stored in closed containers for eight days (following wetting) prior to the initiation of the experiment as suggested by Handreck (1992a).

On 8 May 2006 12-cm-tall x 15-cm-square (1.7-L) plastic containers were filled with the three substrates and placed on raised benches in the Virginia Tech (Blacksburg, VA) Greenhouse Facility (glass-covered) with average day and night temperatures of 24 ^{o}C and 19 ^{o}C, respectively. Containers were irrigated with 500-mL of nutrient solution (beaker-applied) at the rates of 0, 150, or 300 $mg \cdot L^{-1}$ N as potassium nitrate (KNO_3;

Handreck, 1992a) which consequently supplied 420 mg·L^{-1} K at the 150 mg·L^{-1} N rate and 840 mg·L^{-1} K at the 300 mg·L^{-1} N rate. Phosphorus was also supplied at 45 mg·L^{-1} P as phosphoric acid (H_3PO_4) in light of published studies reporting the requirement (and immobilization) of P by microbial populations in soils and wood substrates (Gallardo and Schlesinger, 1994; Handreck, 1996). The 0 mg·L^{-1} N rate was added as a control to observe the effect of fertilizer on substrate CO_2 efflux compared to a non-fertilized treatment. Fertilizer treatments were applied to substrates on day 0 (day of potting) and every seven days thereafter for 28 days for a total of five applications. Following fertilizer applications (every seven days), three replications of each treatment were removed from the greenhouse and analyzed for N immobilization using the NDI incubation and extraction procedure as described above. Substrate solutions extracted before and after incubation at each sampling date were frozen and later analyzed for NO_3-N with an Orion ion selective electrode (Thermo Electron, Beverly, MA) on 17 Aug 2006. Substrate solution N levels were determined on day 0 (initial) and on day 4 (final) and the amount of N immobilized was calculated by determining the difference between day 4 and day 0. Total N loss (mg N per L of substrate) was then calculated for the total 4 day incubation. Nitrogen immobilization data from the 0 mg·L^{-1} N rate in all substrates was excluded from data analysis as a result of no N immobilization occurring at that rate. Between fertilizer/irrigation applications, containers were kept uncovered on open greenhouse benches and substrate moisture was determined by weighing representative containers of each substrate and applying tap water to readjust substrate moisture to 70% of their water holding capacities (determined prior to the initiation of this experiment).

Substrate CO_2 efflux levels were determined on all substrates and at all fertilizer rates as an estimate of microbial activity and potential N immobilization (Wang et al.,

2003). Substrate CO_2 efflux (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$) was determined each week on three container replications of each substrates, at each fertilizer rate using a LiCor 6250 (LI-COR, Lincoln, NE) infrared gas analyzer (IRGA) equipped with a closed chamber constructed from a polyvinyl chloride (PVC) pipe end cap designed to take nondestructive CO_2 measurements from the substrate filled containers. The chamber was placed on the substrate surface and pressed firmly to the surface of the substrate before CO_2 efflux measurements were taken. A gas sampling and return air port (constructed from 0.6-cm plastic tubing) from the chamber allowed air to be circulated from the chamber to the IRGA. Soil CO_2 efflux rates were determined by measuring change in CO_2 concentration (ΔC) over a 30-s period. The LiCor 6250 was recalibrated before each sampling date and the system zeroed between treatment replications. Substrate efflux was measured at approximately the same time of day for each sampling date.

The experimental design was completely randomized with three substrates, three fertilizer rates, and 15 replications per substrate for a total of 135 containers. Nitrogen immobilization data were tested using the analysis of variance procedures of SAS (version 9.1 SAS Institute, Inc. Cary, NC) with treatment means separated by Duncan's Multiple Range test ($\alpha = 0.05$). Substrate CO_2 efflux data were tested using the analysis of variance procedures of SAS and data were also subjected to regression analysis using SigmaPlot (version 9.01 SPSS, Inc., Chicago, IL).

Medium-term (10 week) immobilization. Pine tree substrate used in this study, as well as the leaching experiment (described next) was produced from loblolly pine trees that were harvested at ground level and delimbed on 15 July 2007 in Blackstone VA. Trees were then chipped (including bark) with a Bandit Chipper (Model 200, Bandit Industries, Inc. Remus, MI) on 17 July 2007. Wood chips were further ground in a

hammer-mill on 18 July 2007 to pass through a 2.38-mm screen. Other substrates used in this study included aged PB and PL. All substrates were amended similarly as described in the short-term experiment above.

On 21 Aug 2007 12-cm-tall x 15-cm-square (1.7-L) plastic containers were filled with the three substrates and placed on raised benches in the Virginia Tech (Blacksburg, VA) Greenhouse Facility (glass-covered) with average day and night temperatures of 24 ^{o}C and 19 ^{o}C, respectively. Fertilizer solutions were beaker-applied (500-mL) every two weeks (14 d) to the substrates at the rates of 100, 200, 300, or 400 mg·L^{-1} N as KNO_3 which consequently supplied 280 mg·L^{-1} K for each 100 mg·L^{-1} N rate increase. Phosphorus was also supplied at 45 mg·L^{-1} as H_3PO_4. After fertilizer application and drainage for 1 h, three single container replications of each treatment were removed from the greenhouse and analyzed for N immobilization using the NDI incubation and extraction procedure (as described in the short-term experiment) on week 0 (day of potting) and again every 14 days for 10 weeks for a total of six sampling dates. Substrate solutions extracted before and after incubation at each sampling date were frozen and later analyzed for NO_3-N with an Orion ion selective electrode on 22 Jan 2008. Nitrogen immobilization data were calculated in this study as described above in the short-term experiment. Between fertilizer/irrigation applications, containers were kept uncovered on open greenhouse benches and substrate moisture was maintained at 70% in all substrates as described above in the short-term experiment. Substrate CO_2 efflux was determined every two weeks (alternate weeks of fertilizer applications) on three container replications of each substrates, at each fertilizer rate using a LiCor 6250 as previously described above.

The experimental design was completely randomized with three substrates, four fertilizer rates and 24 replications per substrate for a total of 288 containers. Data were tested using the analysis of variance procedures of SAS (version 9.1 SAS Institute, Inc. Cary, NC). Data were also subjected to regression analysis using SigmaPlot (version 9.01 SPSS, Inc., Chicago, IL).

Nutrient leaching. Pine tree substrate, PL, and PB used in this experiment were prepared as described above in the medium-term experiment and amended similarly. On 21 Aug 2007 12-cm-tall x 15-cm-square (1.7-L) plastic containers were filled (by vol) with the three substrates. Fertilizer solutions were beaker-applied (500-mL) every two weeks (14 d) to the substrates at the rates of 100 or 300 $mg \cdot L^{-1}$ N prepared from KNO_3 which consequently supplied 280 $mg \cdot L^{-1}$ K at the 100 $mg \cdot L^{-1}$ N rate and 560 $mg \cdot L^{-1}$ K at the 300 $mg \cdot L^{-1}$ N rate. Phosphorus was supplied at 45 $mg \cdot L^{-1}$P as H_3PO_4. Fertilizer applications were made to all substrates every other week through the conclusion of the study (14 weeks).

Leaching of NO_3-N, P, and K was monitored on six replicates of each treatment. Leachate collection devices were made by cutting 15-cm circular holes in the lids of 4.5-L plastic buckets. Lids were then securely fitted on buckets and fallow substrate filled containers were inserted halfway through the lids into the buckets. Buckets (with containers inserted) were then and placed on raised benches in the Virginia Tech (Blacksburg, VA) Greenhouse Facility (glass-covered) with average day and night temperatures of 24 ^{o}C and 19 ^{o}C, respectively. This system allowed only the leachate passing through the fallow containers to be collected after irrigations. After applying fertilizer solutions, containers were allowed to completely drain (1 h) before containers were removed from buckets for leachate collection. Leachate volume was determined

and an aliquot was taken and subsequently frozen and later analyzed for NO_3-N with an Orion ion selective electrode on 17 Jan. 2008, and P and K concentrations were analyzed on 31 Jan. 2008 with a Spectro Ciros Vision ICP (Spectro Analytical Instrument, Muhwah, NJ). Between fertilizer/irrigation applications, containers were kept uncovered on open benches in a greenhouse and substrate moisture was maintained at 70% as described in the medium-term experiment above.

The experimental design was completely randomized with three substrates, two fertilizer rates and six replications per substrate for a total of 36 containers. Data were tested using the analysis of variance procedures of SAS (version 9.1 SAS Institute, Inc. Cary, NC).

Results and Discussion

Short-term (4 week) N immobilization. At each measuring date and at both fertilizer rates, the amount of N immobilization was highest in PTS compared to PB and PL, and the amount of immobilization in PB was higher at all dates and fertilizer rates compared to PL (Table 4.1). At the 150 mg·L^{-1} and 300 mg·L^{-1} N rate, the amount of N immobilization increased in PL through day 14, and in PB and PTS through day 21 (Table 4.1). This indicates that immobilization occurs in the first days after potting in all substrates, which justifies the starter charge fertilizer that is typically added to commercial substrate mixes. The quick release starter charge fertilizer supplies N to the substrate upon planting which can offset the N immobilized by microbes. Immobilized N was equal at both fertilizer rates in PL and also in PB at all five measuring dates in this study while PTS had a higher amount of N immobilization at the 300 mg·L^{-1} N rate through day 21 compared to the 150 mg·L^{-1} N rate (Table 4.1). Immobilization amounts

were higher at day 28 (end of experiment) at both fertilizer rates and in all substrates compared to day 0 indicating continued N immobilization over the course of 28 days during plant production (Table 4.1).

Substrate solution NO_3-N levels in response to N immobilization were lower in PB and PTS compared to PL after incubation for 4 days at both fertilizer rates at days 0 and 7, with levels in PTS being the lowest of all the substrates (Table 4.2). The levels of NO_3-N recovered in PTS at the low fertilizer rate were very low at the first two measurements (<1.0 $mg \cdot L^{-1}$ N), but increased by the last measurement date (9.3 $mg \cdot L^{-1}$ N; Table 4.2). Through days 14, 21, and 28 the NO_3-N levels after incubation in PTS remain lower at both fertilizer rates than PB and PL (Table 4.2). The lower substrate solution NO_3-N levels in PTS (resulting from more N immobilization) compared to PB have also been reported even when plant growth was similar (Jackson et al., 2008a) and in PL (Jackson et al., 2008b; Wright et al., 2008a). The reason for higher initial (day 0) substrate solution N levels at all measuring dates in PB and PL compared to PTS at the 300 $mg \cdot L^{-1}$ N rate can be explained by the already existing N in the substrates from previous fertilizer applications that remained in the substrate as a result of the lower amount of N immobilization occurring in those substrates each week (Table 4.1).

Short-term fast growing crops (e.g. bedding plants) grown in PL or PB are commonly fertilized at rates between 100 and 200 $mg \cdot L^{-1}$ N which is unacceptable for plants growing in PTS (Jackson and Wright, 2008). Based on the increased N immobilization in PTS compared to PB and PL at both fertilizer rates (Table 4.1) and as a result the higher NO_3-N levels remaining in substrate solution in PB and PL after four days compared to PTS (Table 4.2), it is clear why decreased plant growth is usually observed in PTS at relatively low (100-200 $mg \cdot L^{-1}$ N) fertilizer rates. Similar to these

results, Sharman and Whitehouse (1993) observed less available N in substrate solution at low fertilizer rates (75 and 150 mg·L^{-1} N) in wood-based substrates, but at higher fertilizer rates (300 mg·L^{-1} N) N levels in substrate solution were higher and closer to levels in peat. Work by Browder et al. (2006) showed that when PTS was amended with 40% peatmoss (v/v), plant growth was similar to plants grown in 100% peat at 200 mg·L^{-1} N. Additionally, Fain et al. (2008b) reported improved plant growth at lower fertilizer starter charge rates when their PTS was amended with 20-50% peatmoss (v/v). These previous studies suggest that the presence of peat (having less N immobilization) allowed more N to remain in substrate solution for plant use.

Substrate CO_2 efflux increased as fertilizer rates increased in all substrates and at all measurement dates over 28 days and was highest in PTS and lowest in PL with PB being intermediate (Table 4.3) which is similar to results reported by Jackson and Wright (2007) . There was a substrate x fertilizer rate interaction for substrate CO_2 efflux at each measurement date, with PTS having a more pronounced CO_2 efflux increase as fertilizer rate increased compared to PB or PL (Table 4.3). Higher substrate CO_2 efflux in PTS indicates a higher level of microbial activity, which is supported by the aforementioned higher amount of N immobilized in PTS compared to PB and PL (Table 4.1). Substrate CO_2 efflux levels generally increased in all substrates at both fertilizer rates and then decreased by the end of the experiment (Table 4.1).

Medium-term (10 week) N immobilization. Nitrogen immobilization increased as fertilizer rate increased from 100 mg·L^{-1} N to 300 mg·L^{-1} N in PL at the first two measuring dates, but beginning at week 4 through week 10 immobilization decreased at the 300 and 400 mg·L^{-1} N rate (Table 4.4). Immobilization of N in PB increased from100 mg·L^{-1} N to 200 mg·L^{-1} N at all dates and decreased at the 400 mg·L^{-1} N (Table

4.4). Immobilization of N in PTS increased as fertilizer rate increased from 100 mg·L^{-1} N to 300 mg·L^{-1} N at all dates, and was less at the 400 mg·L^{-1} N at all dates. Pine tree substrate had higher amounts of N immobilization at each fertilizer rate and at each week followed by PB and PL (Table 4.4). There was a substrate x fertilizer rate interaction for each measuring date with higher increases in N immobilization for PTS in response to fertilizer rate at each date compared to PB and PL (Table 4.4).

Nitrogen immobilization at low fertilizer rates observed in this study as well as in commercial substrates during early crop production, is associated with the undecomposed carbonaceous materials (wood fragments, bark, etc) found in substrates that are being broken down by microbes (Bunt, 1988). The decrease in immobilization at the high fertilizer rates (300 and 400 mg·L^{-1} N depending on the substrate) may be in response to high salt levels which may be toxic to microbes (Maas and Adamson, 1972) thereby limiting or decreasing their populations.

Substrate solution NO_3-N levels after incubation were lowest in PTS compared to PB or PL at each measuring date (Table 4.5). Nitrate levels generally increased over time with each measuring date in all substrates at all fertilizer rates (Table 4.5). Similar to the data discussed in the short-term study (Table 4.2) the NO_3-N levels in PTS after incubation remain low (<25 mg·L^{-1} N) compared to PB and PL, through week 4 at the 100 and 200 mg·L^{-1} N fertilizer rates, but NO_3-N levels in solution were above 90 mg·L^{-1} at the 300 mg·L^{-1} N fertilizer rate at week 4 (28 days). Solution NO_3-N levels in PTS at the 300 mg·L^{-1} N were closer to the levels reported for PB and PL at the 200 mg·L^{-1} N during several of the dates (weeks 0, 2, 4, 6; Table 4.5) which supports the reason for an additional 100 mg·L^{-1} N required for comparable plant growth in PTS compared to PB or PL (Wright et al., 2008a, 2008b).

Substrate CO_2 efflux rates generally increased as fertilizer rates increased in all substrates up to the 300 mg·L^{-1} N fertilizer rate (Table 4.6) as in the previous experiment (Table 4.3). There was a substrate x fertilizer rate interaction for substrate CO_2 efflux at each measurement date (except week 10), with PTS having a more pronounced CO_2 efflux increase as fertilizer rate increased compared to PB or PL. At the 400 mg·L^{-1} N rate substrate efflux levels decreased indicating a reduction in microbial activity in all substrates which also supports the results of the previous experiment. This decrease in substrate CO_2 efflux corresponds to the decrease in N immobilization that was evident in all substrates at the highest (400 mg·L^{-1} N) fertilizer rate (Table 4.4). Lower CO_2 substrate efflux rates have also been reported at relatively high fertilizer rates by Jackson et al. (2008a) and Maas and Adamson (1972).

Nutrient leaching. The amount of N leached in all substrates generally increased as fertilizer rate increased from 100 to 300 mg·L^{-1} N in every week (Table 4.7). At both fertilizer rates more N leached from PB than from PTS each week through the duration of the 14 week experiment (Table 4.7). More N leached in PL than in PTS at each fertilizer rate beginning in week 5 and continuing through the end of the study. Pine bark and PL had the same amounts of N leached at the low fertilizer rate beginning in week 4 and every week thereafter (Table 4.7). Despite PB having higher amounts of N immobilization than PL (Table 4.4), similar N leaching could be in response to the higher saturated hydraulic conductivity of PB compared to PL as observed in unpublished studies of these authors (Brian Jackson and Robert Wright). The lower amounts of N leached from PTS than from PB or PL during most weeks of the study can reasonably be attributed to higher N immobilization rates in PTS compared to PB or PL (Tables 4.1 and 4.4). The amount of N leaching from PB and PL increased through the experiment more

so than from PTS likely as a result of accumulated N in those substrates from previous fertilizations (a result of less N immobilization).

The amount of P leached in all substrates increased as fertilizer concentration applied increased from 100 to 300 $mg \cdot L^{-1}$ N in all 14 weeks of this study (Table 4.8). All substrates generally leached equal amounts of P at the low fertilizer rate throughout the study with only two exceptions (Table 4.8). At the higher fertilizer rate PB leached more P than PL or PTS through week 2, equal amounts to PL and PTS through week 8, and then less than PL and PTS from week 10 through 14 (Table 4.8).

In general, higher amounts of K were leached from PB and PTS than from PL in the first 6 weeks at the low fertilizer rate, and by week 14 there were no differences in mg of K leached in all substrates (Table 4.9). At the high fertilizer rate higher amounts of K were leached from PB and PTS than from PL through week 10. Higher amounts of K leaching is expected in PB and PTS based on the numerous reports of higher K concentrations in substrate solution of PB and PTS, and other wood substrates compared to PL (Jackson et al., 2008a; Prasad, 1980; Wright et al., 2008).

Conclusions

These studies demonstrate that there are higher amounts of N immobilized in PTS compared to PB or PL up to10 weeks. Pine bark also was shown to immobilize more N than PL over the course of all studies. Results also suggest that immobilization amounts are highest 2 weeks after potting (under production conditions) and then generally decrease (but remain rather high) through the next several weeks. Substrate solution NO_3-N levels increase over time in PTS similar to PB and PL which could be important during longer-term crop (e.g. chrysanthemum or poinsettias) production since more NO_3-

N would be in substrate solution when the plants are larger and have higher nutrient requirements. The lower levels of N leaching in PTS compared to PB or PL is important in face of environmental pressures to reduce nutrient (particularly NO_3) leaching from agricultural/horticultural operations. The most important point is that higher levels of N applications to PTS doesn't result in higher N pollution through leaching as a result of the high amounts of N immobilization that retains the N in the substrate. The substrate CO_2 efflux data showed a similar trend with the N immobilization amounts (increased or decreased as N immobilization amounts increased or decreased) which supports the use of this method as an indicator of microbial activity in substrates and the potential for N immobilization.

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Table 4.1. Nitrate nitrogen (NO_3-N) immobilized (mg) in peat-lite, pine bark, and pine tree substrate at five sampling dates over 28 days (short-term experiment) in containers fertilized with two rates of N from potassium nitrate (KNO_3).

Substrates	NO_3-N immobilized[z]				
Nitrogen rate ($mg \cdot L^{-1}$)[y]	Day 0	Day 7	Day 14	Day 21	Day 28
Peat-lite[x]					
150	2.4 d[w]	3.0 d	3.2 d	3.0 d	2.9 c
300	2.2 d	2.5 d	2.8 d	2.8 d	2.4 c
Pine bark					
150	6.1 c	7.3 c	7.5 c	9.3 c	6.2 b
300	5.6 c	7.0 c	7.9 c	8.6 c	6.4 b
Pine tree substrate[v]					
150	9.8 b	11.3 b	13.2 b	14.4 b	15.0 a
300	11.4 a	16.2 a	18.1 a	20.0 a	16.1 a
Substrate (S)	0.0001	0.0001	0.0061	0.0052	0.0010
Fertilizer (F)	0.0002	0.0012	0.0001	0.0007	0.0021
S*F	0.0031	0.0001	0.0043	0.0214	0.1021

[z]NO_3-N immobilized = mg of NO_3-N immobilized per L substrate during a four day incubation.

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ (n = 3).

[v]Pine tree substrate was produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.2. Substrate solution nitrate nitrogen (NO_3-N $mg \cdot L^{-1}$) concentrations after 0 days incubation and after 4 days incubation in peat-lite (PL), pine bark (PB), and pine tree substrate (PTS) over 28 days (short-term experiment) when fertilized with two rates of N from potassium nitrate (KNO_3)[z].

	NO_3-N ($mg \cdot L^{-1}$)									
Substrates	Day 0		Day 7		Day 14		Day 21		Day 28	
Nitrogen rate ($mg \cdot L^{-1}$)[y]	0	4	0	4	0	4	0	4	0	4
PL[x]										
150	31.9 c[w]	23.0 c	39.3 c	29.0 c	41.7 c	31.0 b	54.0 d	44.2 b	65.0 cd	55.3 d
300	68.0 a	60.7 a	80.1 a	71.7 a	103.3 a	94.0 a	118.7 a	109.0 a	171.0 a	163.0 a
PB										
150	31.0 c	11.1 d	34.7 c	10.3 d	48.7 c	23.7 b	63.0 c	32.0 c	74.0 c	53.0 d
300	69.6 a	51.0 b	84.7 a	61.7 b	115.0 a	88.6 a	127.0 a	98.6 a	167.0 a	146.3 b
PTS[v]										
150	33.3 c	0.7 e	38.0 c	0.4 e	45.3 c	1.4 c	53.0 d	5.3 d	58.6 d	9.3 e
300	59.8 b	21.7 c	70.1 b	16.0 d	87.3 b	27.0 b	102.6 b	36.3 bc	147.0 b	94.0 c
Substrate (S)	0.0701	0.0011	0.2071	0.0001	0.0031	0.0001	0.0027	0.0001	0.0330	0.0041
Fertilizer (F)	0.0001	0.0003	0.0020	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
S*F	0.0601	0.0001	0.0041	0.0001	0.0034	0.0001	0.0401	0.0001	0.0501	0.0001

[z]Substrate solution extracted using a nitrogen drawdown procedure for determining nitrogen immobilization in substrates (Handreck, 1992a).

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ (n = 3).

[v]Pine tree substrate was produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.3. Substrate CO_2 efflux measured weekly in peat-lite, pine bark, and pine tree substrate over 28 days (short-term experiment) in containers when fertilized with three rates of nitrogen from potassium nitrate (KNO_3)[z].

Substrates	CO_2 efflux (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$)				
Nitrogen rate ($mg \cdot L^{-1}$)[y]	Day 0	Day 7	Day 14	Day 21	Day 28
Peat-lite[x]					
0	0.7	0.6	0.8	0.5	0.6
150	1.1	0.9	0.9	1.1	0.8
300	1.4	1.1	1.5	1.5	1.3
Significance[wv]	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
Pine bark					
0	0.7	0.5	0.8	0.7	0.7
150	1.6	2.9	2.4	2.5	2.1
300	1.7	3.4	3.6	3.6	3.4
Significance	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
Pine tree substrate[u]					
0	0.6	0.6	1.0	0.8	1.1
150	2.6	3.6	6.5	5.7	5.9
300	3.9	4.3	8.4	8.0	7.7
Significance	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***
Substrate (S)	0.0081	0.0021	0.0240	0.0061	0.0005
Fertilizer (F)	0.0001	0.0001	0.0001	0.0001	0.0001
S*F	0.0021	0.0010	0.0073	0.0260	0.0007

[z]CO_2 efflux measured with a LiCor 6200 infrared gas analyzer (n = 3).

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Nonsignificant or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***), respectively.

[v]L = linear; Q = quadratic response for concentration at *, **, or ***.

[u]Pine tree substrate produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.4. Nitrate nitrogen (NO_3-N) immobilization (mg) in peat-lite, pine bark, and pine tree substrate at five sampling dates when fertilized with four N rates from potassium nitrate (KNO_3) over 10 weeks (medium-term experiment)[z].

Substrates	NO_3-N immobilized					
Nitrogen rate ($mg \cdot L^{-1}$)[y]	Week 0	Week 2	Week 4	Week 6	Week 8	Week 10
Peat-lite[x]						
100	2.4	3.4	2.6	1.3	2.1	1.5
200	3.1	4.2	3.9	3.6	3.2	3.7
300	4.0	4.3	2.9	3.6	2.8	3.1
400	1.8	4.0	3.2	3.2	2.0	2.9
Significance[wv]	L** Q**	L** Q***	L*** Q**	L* Q**	L* Q**	L*** Q**
Pine bark						
100	4.1	7.0	5.5	6.7	2.4	3.0
200	5.7	8.8	5.9	8.6	7.5	6.6
300	7.0	7.4	6.7	11.2	6.5	6.1
400	4.9	7.3	5.9	6.8	5.3	5.3
Significance	L*** Q***	L*** Q***	L** Q**	L* Q*	L*** Q**	L** Q***
Pine tree substrate[u]						
100	8.7	9.3	10.2	10.4	7.4	8.2
200	12.4	15.9	12.5	12.0	10.4	10.2
300	14.1	19.1	19.1	17.4	15.6	11.3
400	12.6	16.1	12.6	15.0	11.3	10.2
Significance	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L** Q***
Substrate (S)	0.0001	0.0121	0.0029	0.0401	0.0001	0.0055
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0432	0.0001
S x F	0.0171	0.0210	0.0158	0.0107	0.0024	0.0241

[z]NO_3-N immobilization = mg of NO_3-N immobilized per L substrate during a four day incubation.

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Nonsignificant or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***), respectively.

[v]L = linear; Q = quadratic response for concentration at *, **, or ***.

[u]Pine tree substrate produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.5. Substrate solution nitrate nitrogen (NO_3-N $mg \cdot L^{-1}$) concentrations after 0 days incubation and after 4 days incubation in peat-lite (PL), pine bark (PB), and pine tree substrate (PTS) over 10 weeks (medium-term experiment) when fertilized with four rates of N from potassium nitrate (KNO_3)[z].

	NO_3-N ($mg \cdot L^{-1}$)											
Substrates	Week 0		Week 2		Week 4		Week 6		Week 8		Week 10	
Nitrogen rate ($mg \cdot L^{-1}$)[y]	0	4	0	4	0	4	0	4	0	4	0	4
PL[x]												
100	23.3	15.3	32.7	21.7	36.0	27.3	36.3	32.0	53.0	46.0	28.3	23.3
200	44.3	34.0	59.0	45.7	90.0	77.3	74.7	62.7	89.7	79.0	73.7	61.3
300	78.0	64.7	126.0	111.0	166.0	157.0	131.0	119.0	221.0	212.0	108.0	97.7
400	75.0	69.0	147.0	134.0	210.0	199.0	172.0	162.0	210.0	204.0	223.0	213.0
Significance[wv]	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L** Q***	L*** Q**	L*** Q***	L*** Q***
PB												
100	18.3	4.7	34.3	11.1	32.0	14.0	35.7	13.3	59.0	51.0	34.7	24.7
200	33.3	14.7	71.0	41.7	83.0	64.0	99.7	71.3	168.0	143.0	159.0	137.0
300	58.7	35.7	136.0	111.0	151.0	129.0	205.0	167.0	237.0	215.0	255.0	234.0
400	57.0	40.7	159.0	135.0	195.0	175.0	174.0	152.0	244.0	226.0	247.0	229.0
Significance	L** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L* Q**	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q**
PTS[u]												
100	29.3	0.3	32.3	1.3	36.7	2.67	38.7	4.17	37.3	12.8	35.3	8.1
200	42.7	1.3	55.0	2.0	67.3	22.7	87.0	47.0	71.0	36.7	61.0	27.0
300	72.3	25.3	115.0	51.0	158.0	94.7	115.0	57.0	166.0	114.0	93.0	55.7
400	72.7	30.7	159.0	105.0	174.0	132.0	175.0	125.0	172.0	134.0	161.0	127.0
Significance	L*** Q**	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q***	L*** Q**	L*** Q***	L*** Q***	L*** Q***
Substrate (S)	0.0471	0.0021	0.0502	0.0017	0.0720	0.0002	0.1320	0.0001	0.0209	0.0061	0.0001	0.0001
Fertilizer (F)	0.0051	0.0004	0.0001	0.0001	0.0001	0.0001	0.0031	0.0001	0.0001	0.0023	0.0001	0.0001
S*F	0.0621	0.0371	0.1601	0.0131	0.0369	0.0071	0.0201	0.0081	0.0008	0.0101	0.0151	0.0001

[z]Substrate solution extracted using a nitrogen (N) drawdown procedure for determining N immobilization (Handreck, 1992a; n = 3).
[y]1 $mg \cdot L^{-1}$ = 1 ppm.
[x]PL composed of 80% peat moss / 20% perlite (v/v).
[w]Nonsignificant or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***), respectively.
[v]L = linear; Q = quadratic response for concentration at *, **, or ***.
[u]PTS produced from12-year-old loblolly pine trees harvested, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.6. Substrate CO_2 efflux measured every two weeks on peat-lite, pine bark, and pine tree substrate when fertilized with four rates of nitrogen from potassium nitrate (KNO_3) for 10 weeks (medium-term experiment)[z].

Nitrogen rate ($mg \cdot L^{-1}$)[y]	Week 0	Week 2	Week 4	Week 6	Week 8	Week 10
	CO_2 efflux ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$)					
Peat-lite[x]						
100	0.7	1.3	1.5	1.3	1.3	1.0
200	1.2	1.7	1.6	1.8	1.2	1.0
300	1.1	1.4	1.6	1.9	1.5	1.4
400	0.7	1.3	1.2	0.8	1.0	0.9
Significance[wv]	L*** Q**	L*** Q***	L** Q***	L*** Q***	L** Q**	L** Q*
Pine bark						
100	2.1	2.0	1.9	1.8	1.9	1.5
200	2.5	2.9	1.9	2.9	1.5	1.5
300	3.1	3.0	4.0	2.6	2.1	1.4
400	2.1	2.0	1.9	1.7	1.5	1.5
Significance	L*** Q***	L** Q**	L*** Q***	NS Q*	L** Q**	L*** Q**
Pine tree substrate[u]						
100	2.7	3.4	3.1	2.7	3.5	2.5
200	3.3	5.1	5.4	4.5	3.1	3.2
300	5.3	6.9	6.3	4.5	3.6	2.6
400	2.9	1.9	2.0	2.2	1.9	1.7
Significance	L*** Q***	L*** Q***	L*** Q***	NS Q**	NS NS	L* Q**
Substrate (S)	0.0001	0.0001	0.0001	0.0001	0.0401	0.0001
Fertilizer rate (F)	0.0001	0.0001	0.0002	0.0001	0.0503	0.1820
S x F	0.0012	0.0001	0.0021	0.0037	0.0170	0.0510

[z]CO_2 efflux measured with a LiCor 6200 infrared gas analyzer (n = 3).

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Nonsignificant or significant at $P \leq 0.05$ (*), 0.01 (**), or 0.001 (***), respectively.

[v]L = linear; Q = quadratic response for concentration at *, **, or ***.

[u]Pine tree substrate produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.7. Nitrate nitrogen (NO_3-N) leached (nutrient leaching experiment) from peat-lite, pine bark, and pine tree substrates over 14 weeks when fertilized with two rates of N from potassium nitrate (KNO_3)[z].

Nitrogen rate ($mg \cdot L^{-1}$)[y]	Week 0	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12	Week 14
	NO_3-N leached per container (mg)							
Peat-lite[x]								
100	2.5 c[w]	3.8 e	20.4 c	29.9 d	14.3 c	28.7 d	20.4 d	36.7 c
300	4.7 c	10.3 cd	72.2 b	98.0 a	53.5 a	116.3 a	79.6 b	143.4 a
Pine bark								
100	8.1 b	11.7 bc	21.5 c	22.9 d	15.4 c	18.7 d	18.9 d	37.5 c
300	19.8 a	49.5 a	85.0 a	86.8 b	59.9 a	86.0 b	86.1 a	150.7 a
Pine tree substrate[v]								
100	2.2 c	5.6 de	9.0 d	7.2 e	4.0 d	4.0 e	6.2 e	10.6 d
300	8.4 b	16.8 b	62.5 b	65.5 c	35.1 b	69.8 c	68.7 c	109.1 b
Substrate (S)	0.0001	0.0001	0.0001	0.0001	0.0222	0.0001	0.0001	00001
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0011	0.0029	0.0135	0.0210	0.0040	0.0753	0.0541	0.0003

[z]Leaching data collected on six fallow containers of each substrate.

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Means separated within columns by Duncan's multiple range test, $P \leq 0.05$.

[v]Pine tree substrate produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.8. Phosphorus (P) leached (nutrient leaching experiment) from peat-lite, pine bark, and pine tree substrates over 14 weeks when fertilized with two rates of N from potassium nitrate (KNO_3) and 45 $mg \cdot L^{-1}$ P from H_3PO_4[z].

Nitrogen rate ($mg \cdot L^{-1}$)[y]	Week 0	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12	Week 14
	P leached per container (mg)							
Peat-lite[x]								
100	0.8 d[w]	1.0 d	3.4 c	7.0 b	4.8 b	10.2 d	7.3 c	11.5 d
300	2.1 c	2.4 bc	15.3 a	21.0 a	16.7 a	37.9 a	23.8 a	41.4 a
Pine bark								
100	3.3 b	2.0 cd	4.3 c	5.2 bc	5.2 b	7.6 de	6.1 c	9.8 de
300	8.9 a	8.7 a	16.0 a	18.3 a	16.7 a	22.4 c	18.2 b	29.4 c
Pine tree substrate[v]								
100	1.8 cd	1.0 d	2.6 c	2.9 c	2.4 b	5.6 e	4.3 d	7.2 e
300	4.0 b	3.2 b	12.2 b	17.1 a	15.7 a	30.3 b	23.3 a	35.5 b
Substrate (S)	0.0001	0.0001	0.0156	0.0201	0.0126	0.0001	0.0001	0.0001
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0001	0.0108	0.1429	0.2229	0.2965	0.0001	0.0001	0.0001

[z]Leaching data collected on six fallow containers of each substrate.

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Means separated within columns by Duncan's multiple range test, $P \leq 0.05$.

[v]Pine tree substrate (PTS) produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

Table 4.9. Potassium (K) leached (nutrient leaching experiment) from peat-lite, pine bark, and pine tree substrates over 14 weeks when fertilized with two rates of N from potassium nitrate (KNO_3)[z].

Nitrogen rate ($mg \cdot L^{-1}$)[y]	Week 0	Week 2	Week 4	Week 6	Week 8	Week 10	Week 12	Week 14
	K leached per container (mg)							
Peat-lite[x]								
100	5.1 d[w]	1.9 e	9.4 d	16.1 e	12.4 d	23.5 c	20.5 d	33.4 b
300	5.0 d	4.5 de	30.3 b	48.2 c	40.3 c	94.5 b	98.0 b	126.0 a
Pine bark								
100	23.0 c	10.6 c	20.4 c	22.4 d	18.8 d	27.0 c	21.6 d	40.1 b
300	33.7 a	35.5 a	57.4 a	68.3 b	57.2 b	84.6 b	74.8 c	128.3 a
Pine tree substrate[v]								
100	25.0 c	7.0 cd	18.2 c	19.2 de	13.3 d	31.3 c	21.5 d	35.0 b
300	30.0 b	15.9 b	58.5 a	77.9 a	74.4 a	132.0 a	107.3 a	130.8 a
Substrate (S)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0218
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0002	0.0037	0.0001	0.0001	0.0001	0.0001	0.0001	0.1688

[z]Leaching data collected on six fallow containers of each substrate.

[y]1 $mg \cdot L^{-1}$ = 1 ppm.

[x]Peat-lite composed of 80% peat moss / 20% perlite (v/v).

[w]Means separated within columns by Duncan's multiple range test, $P \leq 0.05$.

[v]Pine tree substrate (PTS) produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 2.38-mm screen.

CHAPTER V

Changes in Nutrient Availability, and Chemical and Physical Properties of Pine Tree Substrate and Pine Bark during Long-term Nursery Crop Production

Abstract: The objective of this study was to evaluate a pine tree substrate (PTS) for nutrient availability, decomposition and change in physical properties, and substrate CO_2 efflux (microbial activity) during a long-term production cycle under outdoor nursery conditions. Pine tree substrate was produced from loblolly pine trees (*Pinus taeda* L.) that were chipped, and hammer-milled to a desired particle size. Substrates used in this study were PTS constructed from a 4.76-mm screen and aged pine bark (PB). Plastic nursery containers (15-L) were filled with each substrate and amended with either 4.2 or 8.4 $kg \cdot m^{-3}$ Osmocote Plus fertilizer (15N-3.9P-10K) and planted with *Cotoneaster horizontalis* Decne. var. *perpusillus* C. K. Schneid. liners. Fallow containers were also incorporated in this study to compare changes in substrate shrinkage and physical properties without the influence of plants. Substrate solution chemical properties and nutrient concentrations were determined each month during the summers of 2006 and 2007 in addition to measuring substrate CO_2 efflux ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) as an assessment of microbial activity. Substrate breakdown (decomposition) was determined with particle size analysis and physical property determination on substrates at the conclusion of the study (70 weeks). Substrate solution pH was higher in PTS than in PB at both fertilizer rates in 2006 but pH levels decreased over time and were lower in PTS at both fertilizer rates in 2007. Substrate solution electrical conductivity (EC) levels, nitrate (NO_3-N), phosphorus (P) and potassium (K) concentrations were all generally higher in PB than in PTS at both fertilizer rates through both years. Pine tree substrate decomposition was

higher when plants were present in the containers [evident by an increase in fine substrate particles (<0.5 mm) after 70 weeks], but breakdown was equal at both fertilizer rates. Shrinkage of PTS in the presence of plants was equal to the shrinkage observed in PB with plants, but shrinkage was higher in fallow PTS containers than PTS with plants. Substrate air apace (AS) was highest in PTS and container capacity (CC) was equal in PB and PTS at potting. Substrate AS decreased and CC increased in both substrates after 70 weeks but remained in acceptable ranges for container substrates. Substrate CO_2 efflux rates were higher in PTS compared to PB at both fertilizer rates indicating higher microbial activity, thereby increasing the potential for nutrient immobilization and substrate breakdown.

Introduction

Beginning in the early 1970's, the search for organic soilless substrates for container production has been an important horticultural research topic with the introduction of hardwood and softwood barks as the primary component in container substrates (Aaron, 1982; Hoitink and Poole, 1979). Recently, supplies of pine bark in many areas across the southeastern states have been erratic. Growers who find a suitable pine bark supply often find the purchase price and cost of transportation prohibitive. Reduced availability and higher costs have been driven by the reduced supply resulting from decreased harvesting for the paper and timber industry and also by the use of PB as a fuel source, in retail potting media, and as landscape mulches.

Wood-based substrates have been some of the more heavily researched and successful alternative materials evaluated. Successful growth of woody nursery crops in

wood substrates have been reported using several wood materials including cedar chips (Brown and Emino, 1981), pruning and forest residue wastes (Riviere and Milhau, 1983), commercial wood fibre (Cultifibre®, Hortifibre®, and Toresa®; Bohne, 2004; Lemaire et al., 1989), and hardwood chips from ground whole oak and elm trees (Kenna and Whitcomb, 1985). Laiche and Nash (1986) were the first in the United States to produce a pine tree substrate (PTS) derived from PB with a considerable percentage of loblolly pine wood and a second PTS derived from whole pine trees (needles, twigs, bark, and wood). They reported that plant growth of several woody plants to be highest in 100% PB compared to the two PTSs and that additional work was needed before pine wood could be used as a container substrate. Two decades later, Wright and Browder (2005) demonstrated that woody and herbaceous plants could be grown in a 100% PTS referred to as *WoodGro*® (WoodGro LLC., Blacksburg, VA) produced from debarked loblolly pine logs. Wright et al. (2006), also evaluated the growth of numerous woody nursery species in a PTS produced from ground pine logs (including the bark) (approximately 90% wood and 10% bark) compared to PB. Fain et al. (2008a and 2008b) manufactured a PTS (referred to as *WholeTree*) by chipping and grinding freshly harvested 8- to 10-year-old pine trees including the wood, bark, limbs, and needles. They reported that herbaceous plants grown in their PTS were smaller than plants grown in 100% PB, but that growth index and visual quality of the plants were similar for both substrates. Further work by Boyer et al. (2008) showed that growth of annual bedding plants was comparable to 100% PB when grown in a substrate derived from a tree by-product (limbs, needles, bark, cones, etc.) known as clean chip residual that remains after pine trees are harvested for pulp wood.

Container substrates should maintain a balance between air space (AS) and container capacity (CC – total water holding capacity of substrate) during crop production so that growing conditions remain favorable for plant growth. Physical properties of substrates considered appropriate for plant growth at planting may change over time in containers as a result of several processes (Allaire-Lueng et al., 1999; Lemaire, 1995). Changes include AS reduction as a result of setting and segregation of particles of variable sizes (Bilderback and Lorscheider, 1995), shrinkage of the substrate (Bruckner, 1997), and organic matter decomposition and physical breakdown of particles (Bollen and Glennie, 1961; Nash and Laiche, 1981). Most research on the physical properties of substrates has used peat moss or pine bark, the two most commonly used substrates. Current guidelines for container substrates suggest that after irrigation and drainage, substrates should have between 10% and 30% air space (AS), 45% to 65% container capacity (CC), 25% to 35% available water, 25% to 35% unavailable water, 50% to 85% total porosity (TP), and 0.19 to 0.70 $g \cdot cm^{-3}$ bulk density (BD; Yeager et al., 2007). As the use of wood substrates increases, further evaluation of their management requirements and physical property characteristics during crop production is needed. Researchers have shown that initial physical properties of PTS can be engineered for optimal characteristics (Saunders et al., 2006; Wright et al., 2008b) for nursery and greenhouse crop production. The acceptable or optimal physical properties were based on initial physical characteristics determined at the time of planting/potting of plant growth trials, and provide no indication as to how long PTS retains satisfactory physical properties under long-term production conditions. However, work by Jackson et al.

(2008b) reports that PTS has similar (and within the suggested range) physical properties to PL after 14 weeks under fertilized greenhouse conditions.

Shrinkage of wood substrates in containers has been reported to range from 36% volume loss over 15 months (Fischer et al., 1993) to 50% volume loss over 51 weeks (Meinken and Fischer, 1997) during crop production. The wood substrates used in these reports were wood fiber (so named due to their manufacturing process and physical properties) and were derived from a mixture of various tree species; primarily spruce (*Picea abies* L.). Jackson and Wright (2008) and Jackson et al. (2008a) report no significant visual substrate shrinkage or decomposition of PTS during four month greenhouse and one year nursery crop production, and Fain et al. (2008b) reported less shrinkage of a PTS than a peat substrate during a five week greenhouse trial. Jackson et al. (2008b) reported similar shrinkage and change in physical properties of PTS under fertilized greenhouse conditions compared to a traditional peat substrate during a 14 week study. The change in physical properties [total porosity (TP), AS, and CC] of PTS during long-term nursery crop production have not been reported, and need to be addressed before large scale production and use of this substrate begins. Determination of the changes in substrate physical properties in undisturbed containers over time (during or at the end of crop production) is difficult to measure and rarely reported in the literature as a result of the absence of a generally accepted and official measurement procedure (Bilderback et al., 2005). Determining the physical properties of a substrate (removed from containers following crop production) with the same laboratory method [e.g. North Carolina State University (NCSU) Porometer] used to determine the initial properties (at

potting) is used as a comparison of the breakdown and change in properties of substrates over time under production conditions.

Substrate particle size analysis is often determined to make inferences on the physical properties (AS, CC, pore space, etc.) expected for that substrate (Bilderback et al., 2005). Substrate particle sizes are commonly grouped into three categories/classes; coarse (>2.0 mm), medium (0.5 to 2.0 mm), and fine (<0.5 mm) for discussion (Drzal et al., 1999; Richards et al., 1986). Determination of substrate particle analysis before and after crop production could be an estimate of substrate breakdown by evidence of a reduction in large particles and an increase in fine particles which is known to occur in organic substrates (Bilderback et al., 2005).

The environmental impact of fertilizer applications, especially N and P, has been of concern to growers and scientists over the years. Environmental contamination from nitrate and phosphorus has become an important concern of nursery operators in many areas. Nitrate (NO_3-N) levels >10 ppm in drinking water are considered unsafe for humans (Environmental Protection Agency, 2006), and PO_4-P often is associated with algal blooms and eutrophication of lakes and ponds (Hart et al., 2004) even though P is considered rather immobile in many mineral soils, it is more readily leached from soilless container substrates (Broschat, 1995; Yeager and Wright, 1982). Nitrate is readily leached from both mineral soils and soilless container substrates (Bugbee and Elliott, 1998; Yeager et al., 1993). Nutrient loss and availability from PTS during crop production (nursery or greenhouse) has not been reported in previous literature and remains an important issue in light of the higher fertilizer requirements for 100% PTS (Jackson et al., 2008a; Jackson and Wright, 2008; Wright et al., 2008a) that are required

for optimal plant growth. It has since been shown that PTS can be produced with a smaller hammer-mill screen [2.38-mm; resulting in a PTS with higher percentages of fine particles (<0.5 mm)] or amended with 25% peat moss to increase its WHC and nutrient retention, thereby increasing plant growth at lower fertilizer rates similar to those used with a peat substrate (Fain et al., 2008b; Jackson et al., 2008b).

In PTS the need for additional fertilizer is a result of higher microbial activity resulting in increased N immobilization in wood-based substrates compared to peat or PB. Numerous authors have reported N immobilization in wood substrates ranging from 10 to 300 mg N per L of substrate per week during crop production (Bodman and Sharman, 1993; Handreck, 1992b; Sharman and Bodman, 1991). Nitrogen immobilization in soils and organic materials results from microbial assimilation of ammonium nitrogen (NH_4-N) and NO_3-N into proteins, nucleic acids and other organic complexes contained within microbial cells (Davet, 2004). Carbon dioxide (CO_2) release represents the final stage of oxidation of organic substrates and is the older and still more commonly used method for estimation of microbial activity in soils (Wang et al., 2003). Since root respiration is also a source of CO_2 in the soil, it is important to take into account the sources of CO_2 evolution. Soil respiration/efflux is influenced by a number of factors, including soil/substrate quality and organic matter content, temperature, soil moisture, root biomass, and microbial activity and biomass (Davet, 2004; Ding et al., 2007; Fog, 1988; Wang et al., 2003).

The estimation of microbial activity could represent a possible strategy to improve the usefulness and fertilizer efficiency of substrates (Gagnon and Simard, 1999; Handreck, 1992a). Previous data on measuring microbial activity in container substrates

was reported by Pronk (1997) who used three methods to determine the microbial activity of peat and several compost mixes. The methods used were the Dewar self-heating test, a CO_2 release test, and a N release test. Pronk concluded that the Dewar self-heating test was unable to detect any changes in microbial activity while the CO_2 and N release tests were successful in determining changes in microbial activity in the substrates. However, data from these tests could not be positively correlated with one another and he suggested that more testing be done on each method independently for monitoring microbial activity. The objective of this study was to evaluate nutrient availability, changes in physical and chemical properties, substrate shrinkage, and biological (microbial) activity in PTS compared to PB during long-term nursery production.

Materials and Methods

The substrates used in this experiment were PTS and PB. Pine tree substrate was produced from loblolly pine trees (approximately 30-cm basal diameter) that were harvested at ground level and delimbed on 14 April 2006 in Warsaw VA. Trees were then chipped (including bark) with a Morbark Chipper (Winn, MI) operated by Wood Preservers Inc., (Warsaw, VA) on 15 April 2006. Wood chips (2.5-cm x 2.5-cm x 0.5-cm) were further ground in a hammer mill (Meadows Mills, Inc., North Wilkesboro, NC) on 17 May 2006 to pass through a 4.76-mm screen. Pine tree substrate was used fresh (uncomposted) and amended with 0.6 $kg \cdot m^{-3}$ calcium sulfate ($CaSO_4$) based on previous work by Saunders et al. (2005) that showed improved plant growth when $CaSO_4$ was incorporated in PTS. Samples of PTS were tested for pH prior to potting and not amended with lime due to the relatively high pH (~5.8) observed which has been shown

previously in freshly ground pine wood (Wright et al., 2008a). Pine bark was pre-plant amended with dolomitic lime at a rate of 3.6 $kg \cdot m^{-3}$ and $CaSO_4$ at a rate of 0.6 $kg \cdot m^{-3}$. Osmocote Plus (15N-3.9P-10K; O.M. Scott Horticulture Products, Marysville, OH) was preplant incorporated in PB and PTS at rates of 4.2, or 8.4 $kg \cdot m^{-3}$.

On 5 June 2006, cotoneaster (*Cotoneaster horizontalis* Decne. var. *perpusillus* C. K. Schneid.) liners (10-cm tall in 64 cm^3 containers) were potted in 15-L plastic containers [28-cm (h) x 30-cm (d)] containing either PTS or PB. Three liners were evenly spaced and planted along the container edges, leaving the center of the container open. Additional containers were also filled separately with each of the two substrates and left fallow to compare changes in substrate shrinkage and physical properties with and without plants. A 10.2-cm diameter x 5.1-cm high thin-walled polyvinyl chloride (PVC) collar was inserted 0.5 cm into the center of all containers which served as a cradle for a soil CO_2 flux chamber to be inserted and positioned securely above the substrate surface for CO_2 efflux measurements. These collars minimize soil surface disturbance during CO_2 measurements and reduce the sudden flux of CO_2 associated with soil disturbance (Wang et al., 2005). Collars remained in the containers for the duration of the experiment without disturbance. Cotoneaster was used because of its weeping growth habit which assured growth over the sides of the containers with minimal obstruction of the PVC collars. Plants in all containers were equally pruned throughout the study and plant growth was not recorded or analyzed. Containers were placed on a gravel nursery pad at the Urban Horticulture Center, Blacksburg, VA and over-head irrigated daily to supply 1.3-cm water. Substrate solution was extracted using the pourthrough (PT) method (Wright, 1986) one week after potting (WAP) and then once

per month through October 2006 and analyzed for pH and EC using a Hanna HI 9811 instrument (Hanna Instruments, Woonsocket, RI). Substrate solutions were frozen and later analyzed for NO_3-N with an Orion ion selective electrode (Thermo Electron, Beverly, MA) on 17 Nov. 2007, and phosphorus (P), and potassium (K) concentrations on 28 Nov. 2007 with a Spectro Ciros Vision ICP (Spectro Analytical Instrument, Muhwah, NJ). On 25 April 2007 containers were fertilized (top-dressed) with the same fertilizer rates mentioned above. Pourthrough's were conducted each month beginning in May and ending in September in 2007. Substrate shrinkage (cm) was determined by measuring the difference in substrate height (from the top of the containers to the substrate surface) at 1 WAP, and again at 70 WAP. Final measurements (70 WAP) for shrinkage determination were not made on fallow PB containers at either of the fertilizer rates and therefore will not be reported in the results.

As a measure of microbial activity in PB and PTS, substrate CO_2 efflux levels were determined as an indicator of the potential for N immobilization to occur (Wang et al., 2003). Substrate CO_2 efflux ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) was determined 1 WAP followed by every four weeks through October on six container replications of both substrates, at each fertilizer rate using a LiCor 6400 infrared gas analyzer (LI-COR, Lincoln, NE) fitted with a LiCor 6400-09 soil CO_2 flux chamber. The soil chamber was designed to take nondestructive CO_2 measurements from the substrate filled containers. The LiCor was recalibrated before each sampling date and the system was zeroed between treatment replications. The LiCor target value was set close to the ambient CO_2 concentration (~380 $\mu mol\ mol^{-1}$), and ΔCO_2 value was set as the factory default value (10 $\mu mol\ mol^{-1}$;

LiCor, 1997). Substrate efflux rates were measured on the same containers and at approximately the same time of day for each sampling date.

For substrate physical properties and particle size determination, 20-L samples of all substrates were collected on 5 June 2006 when plants were potted. These substrates were taken from the same source used to pot this experiment and therefore amended similarly. Substrate samples were air-dried for two days then bagged and dry-stored for the duration of the experiment (70 weeks). At 70 WAP, samples from 1) storage, 2) containers with plants and from 3) fallow containers were prepared for physical property and particle size determination.

Physical properties including AS, CC, TP, and BD were determined on three replicate samples of each substrate using the NCSU Porometer method as described by Fonteno et al. (1995). Particle size distribution of 150 g oven-dried substrate samples were determined with 14 sieves (ranging from > 6.3-mm to < 0.06-mm) plus a bottom pan (Table 1). Sieves and pan were shaken for 10 min with a RX-29 Ro-Tap sieve shaker (278 oscillations min^{-1}, 150 taps min^{-1}; W.S. Tyler, Mentor, OH) and the particle fractions retained on each sieve and the amount that passed through the smallest sieve and retained by the sieve pan were weighed.

The experimental design was completely randomized with two substrates, two planting methods (with and without plants), two fertilizer rates, and six replications per treatment for a total of 48 containers. Multiple comparison of means at $\alpha = 0.05$ were made with Duncan's Multiple Range Test the analysis of variance (ANOVA) procedures of SAS (version 9.1 SAS Institute, Inc. Cary, NC). Effect of substrate and fertilizer rate on substrate efflux were examined by a PROC GLM repeated measures ANOVA in SAS.

Results and Discussion

Particle size distribution: initial. Particle sizes were placed into texture groups of coarse (≥2.0 mm), medium (<2.0 mm to ≥0.5 mm), and fine (<0.5 mm). Pine bark had the highest percentage of coarse particles (49%) at the beginning of the study (initial) while PTS had only 5% coarse particles (Table 5.1). Pine tree substrate had higher percentages of medium (76%) and fine particles (20%) compared to PB (36 and 15% respectively) initially (Table 5.1).

Particle size distribution: final (data not available on PB in fallow containers so all 70 WAP data represents PB in containers with plants present). Coarse PB particle percentage decreased during 70 WAP equally at both high and low fertilizer rates with plants (Table 5.1). The percentage of medium PB particles did not change during 70 weeks regardless of fertilizer rate (39 and 39%) compared to the initial PB (36%). The percentages of fine particles in PB with plants were higher than the initial PB (15%) and equal (20 and 21% respectively) at both fertilizer rates (Table 5.1). The decrease in the amount of coarse particles and increase in the amount of fine particles is evidence of the decomposition in PB over the 70 week experiment.

Coarse PTS particle percentage decreased after 70 WAP to the same values at both high and low fertilizer rates and with or without (fallow) plants (Table 5.1). The percentage of medium PTS particles did not change from the initial PTS (76%) in fallow containers regardless of fertilizer rate, but percentages decreased when plants were present for both fertilizer rates (Table 5.1). The percentage of fine PTS particles did not change from the initial (20%) in fallow containers regardless of fertilizer rate, but percentages were higher when plants were present for both fertilizer rates (31 and 32%;

Table 5.1). The higher percentage of fine particles (and conversely a lower percentage of medium particles) in PTS when plants were present indicates accelerated breakdown apparently resulting from the presence of plant roots. Plant root exudates have been widely reported to play an active role in enhancing microbial activity in soils (Davet, 2004) which likely explains the increased breakdown of PTS resulting from increased microbial populations in containers with plants.

Substrate physical properties: initial. Total porosity was higher in PTS (91%) and above the recommended range (50-85%, Yeager et al., 2007) at the beginning of the study (initial) compared to PB (83%; Table 5.2). Air space was higher in PTS (36%) and also above the recommended range (10-30%) at the beginning of the study than PB (26%) which was within the suggested range. Container capacity was equal in PB and PTS initially (57 and 55%; Table 5.2). Bulk density was lower in PTS than PB initially, and both were below the recommended range (0.19-0.70). Previous studies have shown that PTS can have CC percentages within the recommended range (and often equal to PB) but have higher AS percentages than PB (Boyer, 2008; Wright and Browder, 2005; Wright et al., 2008b). In addition, research has shown that PTS can have equal CC to peat substrates and still have higher AS (Jackson et al., 2008b; Saunders et al., 2006).

Substrate physical properties: final (data not available on PB in fallow containers so all 70 WAP data represents PB in containers with plants present). Total porosity was unchanged in PB at 70 WAP compared to the initial TP and was not affected by either the high or low fertilizer rate (Table 5.2). Airspace percentages were lower in PB at 70 WAP than initially, but percentages remained within the recommended range and were not

affected by either fertilizer rate (Table 5.2). Inversely, CC and BD of PB increased at 70 WAP and was equal at both fertilizer rates.

Total porosity was unchanged in PTS at 70 WAP and was equal at both high and low fertilizer rates and with and without (fallow) plants (Table 5.2). Total porosity of fallow PTS at both fertilizer rates was similar to PB while PTS with plants at both fertilizer rates had higher TP. Air space percentages decreased at 70 WAP in PTS with and without plants and at both fertilizer rates and remained higher than PB (Table 5.2). Container capacity increased after 70 WAP in PTS with and without plants and at both fertilizer rates, and was equal to PB with the exception of the PTS with plants at the low fertilizer rate (Table 5.2). Bulk density remained lower in all PTS treatments than PB but remained within the recommended range (Table 5.2).

Shrinkage after 70 weeks was highest in fallow PTS at both fertilizer rates (22 and 24%) but equal in PTS that contained plants compared to PB with plants (Table 5.2). Shrinkage results from particle size breakdown (microbial decomposition) and substrate settling (finer particles fit between larger particles) caused by gravity and water movement through the substrate during irrigations (Bilderback and Lorscheider, 1995; Bures et al., 1993; Nash and Pokorny, 1990). Substrate shrinkage causes a decrease in AS and an increase in CC over time as observed in this study (Table 5.2) and reported in other works (Bohne and Gunter, 1997; Prasad and Chualain, 2005). Less shrinkage in PTS with plants in the containers compared to fallow PTS is likely a result of the plant roots that filled the voids created by decomposition and prevented substrate/rootball shrinkage.

Substrate solution pH and EC. Substrate solution pH was higher in PTS at both fertilizer rates compared to PB and decreased as fertilizer rate increased at all measuring dates in 2006 (Table 5.3). Substrate solution pH in PTS decreased one unit over the course of the sampling dates at each fertilizer rate in 2006, but remained higher than the pH of PB. Substrate solution EC values were higher at the higher fertilizer rate in both substrates (Table 5.3). Electrical conductivity levels were higher in PB than in PTS at both fertilizer rates and at all measuring dates (Table 5.3), showing that higher rates of fertilizer are required for PTS compared to PB to achieve comparable EC levels. Lower substrate EC (and substrate solution nutrients) and higher pH levels in PTS compared to PB have been previously reported by Boyer (2008), Jackson et al. (2008a), and Wright et al. (2006). Substrate solution EC values fell below the recommended range for nursery crops (0.5-1.0 dS/m; Yeager et al., 2007) in PTS at the low fertilizer rate (4.2 $kg \cdot m^{-3}$) in August while PB EC levels at the low fertilizer rate did not fall below recommended levels until September 2006 (Table 5.3). Substrate solution EC at the higher fertilizer rate (8.4 $kg \cdot m^{-3}$), which is recommended for woody plant production (Jackson et al., 2008a), remained within recommended levels until October (Table 5.3). In 2007, substrate solution pH levels were lower in PTS than PB at both fertilizer rates and the levels decreased as fertilizer rate increased (Table 5.3). The lower pH in 2007 was a continuation of the trend of decreasing pH which was observed in 2006 over the course of the summer months. The pH decline observed in PTS could potentially be a concern during long-term production and may require adjusting (increasing) depending on the crop (species) being grown. Substrate solution EC levels generally remained higher in PB than in PTS at both fertilizer rates with the exception of the May sampling date (Table

5.3). In contrast to 2006, during 2007 the substrate solution EC vales remained at or above the recommended range through all sampling dates in PTS at both the low and high fertilizer rates. Solution EC values were within or above the recommended levels for both fertilizer rates in PB (Table 5.3).

Substrate nutrient availability. Similar to the EC levels previously discussed, NO_3-N concentrations were higher in PB at both fertilizer rates compared to PTS in 2006 (Table 5.4). Nitrate N levels in substrate solution were below recommended levels (15-25 $mg \cdot L^{-1}$) in PTS beginning in July at the low fertilizer rate and also then in September for the high fertilizer rate (Table 5.4). Substrate solution P levels were equal in PB and PTS in 2006 with the one exception being at the low fertilizer rate in June when P levels were higher in PB (Table 5.4). All P concentrations were within or above the recommended level (5-10 $mg \cdot L^{-1}$) in both substrates at both fertilizer rates during all sample months in 2006 (Table 5.4). Substrate solution K concentrations were more often higher in PB than PTS at each fertilizer rate and at each sampling date in 2006 with a few exceptions when concentrations were equal in both substrates (Table 5.4) which is consistent with work published by Jackson et al. (2008a) and Wright et al. (2006). In contrast, PTS has been reported to have higher substrate solution K concentrations than peat substrates in the production of herbaceous crops (Jackson et al., 2008b; Wright et al., 2008a). Potassium concentrations were within or above recommended levels (10-20 $mg \cdot L^{-1}$) in PB and PTS at both fertilizer rates at all sampling dates in 2006 with the exception of PTS at the low fertilizer rate in September (Table 5.4).

In general the same trend was present in 2007 in that most all nutrient concentrations were higher in PB than in PTS at both fertilizer rates. Nutrient

concentrations in both substrates at both fertilizer rates were within or above recommended ranges (as shown above) in 2007 with the exception of the low fertilizer rate for both PB and PTS which both fell below the range in August and September which was also observed in 2006 (Table 5.5).

Lower substrate solution NO_3-N concentrations in PTS compared to PB over two growing seasons indicates that NO_3-N is likely being immobilized in the container substrate and not excessively leaching (in irrigation runoff) as once hypothesized by these authors (Brian Jackson and Robert Wright) as a reason for lower substrate solution EC levels in PTS even when applying high rates of fertilizer. Jackson and Wright (2007 and 2008) have reported increased microbial activity and higher rates of N immobilization in PTS compared to PB and peat. The reason for generally lower substrate solution P concentrations in PTS could likely be a result of microbial immobilization of P which occurs in wood-based substrates (Handreck, 1996) thus reducing the amount of soluble P in substrate solution.

Substrate CO_2 efflux. Substrate CO_2 efflux was higher in PTS than in PB at both fertilizer rates and at each measurement date in 2006 (Table 5.6). Similar to this data, higher substrate CO_2 efflux has been previously reported in PTS compared to PB during crop production (Jackson and Wright, 2007; Jackson et al., 2008a). Substrate CO_2 efflux was lower at the higher fertilizer rate in both substrates at each measuring date (Table 5.6) which has been previously reported in PTS by Jackson et al. (2008a). Substrate CO_2 efflux levels decreased through the summer measuring dates but remained higher in PTS than in PB even though the magnitude of difference was less by October (Table 5.6). Results were similar in 2007 with substrate CO_2 efflux remaining higher in PTS than in

PB at both fertilizer rates, but the CO_2 efflux levels were noticeably lower in 2007 than in 2006 (Table 5.6) indicating lower microbial activity possibly a result of less decomposition of the more stable year old substrates. The reduction in microbial respiration rates that we observed in response to increasing fertilizer rate is supported by several previous reports showing both long-term and short-term reductions in microbial activity following fertilization (Gough and Seiler, 2004; Thirukkumaran and Parkinson, 2000). One possible explanation for this response could be that increased salt concentration in the substrate may modify the microflora populations or reduce their activity (Allison, 1965).

Conclusions

This study demonstrates that PTS does decompose in containers under fertilized outdoor nursery conditions as indicated by a reduction in substrate particle size and greater substrate shrinkage in fallow PTS containers over time. The reduction in particle size changed the physical properties (AS and CC) of PTS based on analysis conducted after 70 weeks, but like PB, the structure (physical properties) of PTS remained desirable for plant growth. Substrate shrinkage in PTS is significant and would be a major concern if not for the plant roots that apparently filled the voids caused by decomposition allowing the rootball to stay intact just as rootballs of plants grown in PB. Despite the decomposition, this study illustrates that the stability of PTS for two growing seasons (70 weeks) is sufficient for desirable plant growth. For longer-term production (more than 70 weeks), production in larger containers, or production in warmer and wetter climates that may facilitate quicker decomposition of PTS, it may be possible to extend the stability

(and minimize decomposition) by utilizing a coarser PTS (i.e., 16.0-mm up to 2.5-cm particles) produced with larger hammer-mill screens which can then be amended with PB, sand, or other fine particle material to achieve the desired AS and WHC (Wright et al., 2008b).

The decrease in pH of PTS that was observed in this study may warrant pH adjustments, depending on the crop being grown. Currently the pH of PTS produced from fresh (recently harvested) pine wood is not adjusted (i.e., dolomitic lime additions) as a result of the desirable pH levels observed in short-term crop production, but based on results from this study, recommendations to increase the pH of PTS for long-term crop production may be needed. The lower substrate solution EC levels reported in PTS at the end of the summer (2006) also deserve close attention when using PTS, so that supplemental fertilizer applications (often supplied as a liquid fertilizer drench) can be made in the late summer or fall to ensure adequate nutrient levels during that time.

Further work is needed to assess the actual in-container physical properties of PTS during crop production. Determining substrate physical properties without altering/disturbing the density or geometry of the substrate in containers will be more informative of the conditions experienced by plants during production. In this present work the substrate was removed from containers and evaluated for physical properties. As briefly mentioned above, future work should evaluate PTS in other regions of the country with various temperatures, growing season length, rainfall, etc. that are different from Blacksburg VA, to determine an appropriate management strategy for utilizing PTS for nursery crop production in other areas.

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Table 5.1. Particle size distribution of pine bark (PB) and pine tree substrates (PTS) initially (at potting) and at 70 weeks after potting (WAP) in containers with plants when fertilized with 4.2 (L) or 8.4 (H) kg·m^{-3} of Osmocote Plus 15N-3.9P-10K) and maintained under outdoor nursery conditions[z]. Data are also reported for PTS in fallow containers at 70 WAP.

	Particle size distribution (%)[z]							
	0 WAP		70 WAP					
	Initial		Fallow		Containers with plants			
Sieve (mm)[y]	PB	PTS[x]	PTS-L	PTS-H	PB-L	PB-H	PTS-L	PTS-H
>6.3	10.5	0.1	0.0	0.2	5.6	6.7	0.0	0.0
6.3-4.8	8.3	1.0	0.0	0.0	6.4	8.0	0.0	0.0
4.8-2.4	25.5	1.4	0.7	1.5	23.9	20.4	1.0	1.7
2.4-2.0	4.9	2.6	1.4	0.7	5.6	5.5	1.6	0.6
2.0-1.4	10.9	10.4	16.1	16.2	12.3	8.7	12.3	22.3
1.4-1.0	8.8	24.4	23.3	28.0	8.2	10.3	22.0	25.6
1.0-0.71	8.4	25.0	23.2	19.8	9.2	10.4	20.0	13.2
0.71-0.5	7.7	15.8	10.1	7.1	8.8	9.5	12.0	6.7
0.5-0.36	3.3	6.3	9.6	11.0	4.8	4.6	14.6	11.3
0.36-0.25	3.5	4.4	4.5	4.4	2.8	4.5	6.2	4.9
0.25-0.18	3.6	3.3	4.5	5.9	2.4	2.3	4.5	6.9
0.18-0.13	1.6	3.3	2.7	2.7	4.7	3.8	2.8	2.7
0.13-0.09	1.3	1.4	2.4	1.3	3.2	2.0	1.4	1.7
0.09-0.063	0.7	0.7	1.3	1.3	1.2	2.6	1.2	1.9
<0.063	1.2	0.1	0.5	0.2	1.0	0.9	0.3	0.5
Texture[w]								
Coarse	49.2 a[v]	5.0 c	2.2 d	2.4 d	41.6 b	40.6 b	2.6 d	2.3 d
Medium	35.7 c	75.5 a	72.4 a	71.0 a	38.5 c	38.8 c	66.3 b	65.8 b
Fine	15.2 d	19.5 c	25.4 b	26.7 b	20.5 c	20.6 c	31.1 a	31.9 a

[z]Dry weight basis; Values are means of three air-dried samples.

[y]1 mm = 0.0394 inch.

[x]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through 4.76-mm screen.

[w]Texture grouping: coarse = >2.0 mm; medium = >0.5 - <2.0 mm; fine = <0.5 mm.

[v]Means within a row followed by the same letter are not significantly different based on Duncan's multiple range test ($P \leq 0.05$, n = 3).

Table 5.2. Physical properties of pine bark (PB) and pine tree substrates (PTS) initially (at potting) and at 70 weeks after potting (WAP) in containers with plants when fertilized with 4.2 (L) and 8.4 (H) kg·m^{-3} of Osmocote Plus 15N-3.9P-10K) and maintained under outdoor nursery conditions[z]. Data are also reported for PTS in fallow containers at 70 WAP.

Substrates	Total porosity[y] (% vol)	Air space[x] (% vol)	Container capacity[w] (% vol)	Bulk density[v] (g·cm^{-3})	Substrate shrinkage[u] (%)
Initial					
PB initial	83.2 b[t]	26.4 c	56.8 c	0.18 b	-
PTS initial[s]	91.2 a	35.9 a	55.3 c	0.14 d	-
70 WAP					
PB-L w/ plant	83.3 b	19.7 d	63.6 a	0.21 a	16.3 b
PB-H w/ plant	83.8 b	20.9 d	62.9 a	0.22 a	16.7 b
PTS-L w/ plant	89.2 a	29.3 b	59.9 b	0.16 c	17.4 b
PTS-H w/ plant	90.9 a	27.4 bc	63.5 a	0.16 c	16.8 b
PTS-L fallow	87.5 ab	26.0 c	61.5 a	0.17 bc	22.3 a
PTS-H fallow	86.1 ab	25.1 c	61.0 ab	0.18 b	24.4 a
Range[r]	50-85	10-30	45-65	0.19-0.70	-

[z]Data were collected from three samples per substrate and represented as means. Analysis performed using the North Carolina State University Porometer method (Fonteno et al., 1995).

[y]Total porosity is equal to container capacity + air space.

[x]Air space is the volume of water drained from the sample ÷ volume of the sample.

[w]Container capacity is (wet weight – oven dry weight) ÷ volume of the sample.

[v]Bulk density after forced-air drying at 105 °C for 48 h.

[u]Shrinkage = substrate height in container at 1 week after potting (WAP) - substrate height at 70 WAP.

[t]Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ (n = 3).

[s]PTS produced from 12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.

[r]Suggested range for container substrates = Best Management Practices recommended sufficiency ranges for physical properties of substrates used in general container production (Yeager et al., 2007).

Table 5.3. Substrate solution pH and electrical conductivity (EC) sampled in 2006 and 2007 from pine bark (PB) or pine tree substrate (PTS) in containers with plants when fertilized with two rates of Osmocote Plus 15N-3.9P-10K[z].

	2006									
	June		July		August		September		October	
Substrate Osmocote ($kg \cdot m^{-3}$)	pH	EC ($dS \cdot m^{-1}$)[y]	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)
PB										
4.2	5.7 b[x]	1.46 b	5.7 b	1.44 b	5.5 b	0.93 c	5.6 a	0.48 b	5.2 b	0.20 b
8.4	5.4 c	2.27 a	5.2 c	2.16 a	5.1 c	1.56 a	5.1 c	1.15 a	5.0 c	0.67 a
PTS[w]										
4.2	6.5 a	1.03 c	6.0 a	0.77 c	5.8 a	0.37 d	5.7 a	0.19 c	5.4 a	0.16 c
8.4	6.3 a	2.38 a	5.5 b	1.78 b	5.4 b	1.02 b	5.3 b	0.54 b	5.2 b	0.24 b
Substrate (S)	0.0071	0.0001	0.0001	0.0001	0.0001	0.0001	0.0851	0.0001	0.0032	0.0031
Fertilizer rate (F)	0.0003	0.0001	0.0101	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.0001
S x F	0.0521	0.0007	0.1802	0.0111	0.0517	0.0621	0.0510	0.0041	0.0577	0.0147

	2007									
	May		June		July		August		September	
Substrate Osmocote ($kg \cdot m^{-3}$)	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)	pH	EC ($dS \cdot m^{-1}$)
PB										
4.2	4.9 a	0.57 c	5.1 a	1.34 b	4.8 a	1.41 b	4.7 a	1.01 b	4.3 a	0.52 b
8.4	4.4 b	1.16 ab	4.8 b	2.61 a	4.6 a	1.81 a	4.1 b	1.75 a	3.9 b	0.81 a
PTS										
4.2	4.5 b	0.79 b	4.5 c	1.19 b	4.6 a	0.81 c	4.2 b	0.68 c	4.3 a	0.48 b
8.4	4.4 b	1.34 a	4.1 d	2.31 a	4.0 b	1.42 b	3.9 c	1.13 b	3.7 b	0.72 a
Substrate (S)	0.0512	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.1103	0.0810
Fertilizer rate (F)	0.0410	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0004	0.1771	0.0491	0.0401	0.0015	0.0401	0.0601	0.0184	0.0017	0.1420

[z]pH and EC of substrate solution obtained by the pour-through method (Wright, 1986).
[y]1 $dS \cdot m^{-3}$ = 1 mmho/cm.
[x]Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ (n = 4).
[w]PTS produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.

Table 5.4. Substrate solution concentrations of nitrate nitrogen (NO_3-N), phosphorus (P), and potassium (K) collected in 2006 from pine bark (PB) or pine tree substrate (PTS) in containers with plants when fertilized with two rates of Osmocote Plus 15N-3.9P-10K[z].

Substrate	NO_3-N ($mg \cdot L^{-1}$)[y]				
Osmocote ($kg \cdot m^{-3}$)	June	July	August	September	October
PB					
4.2	46.3 b[x]	26.3 c	15.2 b	2.2 c	2.1 b
8.4	93.3 a	81.8 a	28.1 a	22.8 a	9.0 a
PTS[w]					
4.2	18.3 c	8.3 d	3.4 c	0.9 c	1.0 b
8.4	63.8 b	41.3 b	15.4 b	12.8 b	1.2 b
Substrate (S)	0.0001	0.0001	0.0001	0.0041	0.4122
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0010
S x F	0.0810	0.0261	0.1602	0.0120	0.0081

Substrate	P ($mg \cdot L^{-1}$)				
Osmocote ($kg \cdot m^{-3}$)	June	July	August	September	October
PB					
4.2	35.6 b	34.7 b	6.9 b	5.8 b	5.0 ab
8.4	68.5 a	88.1 a	18.2 a	17.5 a	7.1 a
PTS					
4.2	18.3 c	21.7 b	5.6 b	8.9 b	5.2 a
8.4	52.6 a	62.8 a	13.2 a	17.9 a	6.4 a
Substrate (S)	0.0001	0.0001	0.0811	0.0400	0.0551
Fertilizer rate (F)	0.0001	0.0021	0.0001	0.0000	0.0120
S x F	0.1945	0.0371	0.0521	0.0254	0.1200

Substrate	K ($mg \cdot L^{-1}$)				
Osmocote ($kg \cdot m^{-3}$)	June	July	August	September	October
PB					
4.2	106.8 c	107.0 c	61.4 b	20.8 b	15.5 b
8.4	203.9 a	244.8 a	108.1 a	48.3 a	31.7 a
PTS					
4.2	95.5 c	78.9 d	18.3 c	9.2 c	11.4 b
8.4	166.3 b	153.2 b	49.5 b	37.3 a	26.4 a
Substrate (S)	0.0001	0.0003	0.0011	0.0001	0.0020
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0011	0.0071	0.0212	0.1901	0.2501

[z]pH and EC of substrate solution obtained by the pour-through method (Wright, 1986).
[y]1 $mg \cdot L^{-1}$ = 1 ppm.
[x]Means separated within columns by nutrient using Duncan's multiple range test, $P \leq 0.05$ (n = 4).
[w]PTS produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.

Table 5.5. Substrate solution concentrations of nitrate nitrogen (NO_3-N), phosphorus (P), and potassium (K) collected in 2007 from pine bark (PB) or pine tree substrate (PTS) in containers with plants when fertilized with two rates of Osmocote Plus 15N-3.9P-10K[z].

Substrate	NO_3-N ($mg \cdot L^{-1}$)[y]				
Osmocote ($kg \cdot m^{-3}$)	May	June	July	August	September
PB					
4.2	37.5 b[x]	30.5 b	43.8 b	11.1 b	4.8 b
8.4	67.2 a	109.3 a	61.8 a	18.4 a	17.1 a
PTS[w]					
4.2	19.8 c	25.5 b	31.9 c	6.0 b	2.8 b
8.4	61.1 a	88.0 a	48.3 b	19.8 a	16.3 a
Substrate (S)	0.2110	0.0001	0.0001	0.0092	0.0480
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0002
S x F	0.0400	0.0005	0.0201	0.0028	0.0021

Substrate	P ($mg \cdot L^{-1}$)				
Osmocote ($kg \cdot m^{-3}$)	May	June	July	August	September
PB					
4.2	17.0 b	34.4 b	29.8 c	10.7 b	7.5 b
8.4	28.0 a	56.1 a	64.7 a	24.5 a	19.5 a
PTS					
4.2	13.3 b	28.3 b	19.3 d	12.4 b	6.6 b
8.4	21.8 a	52.1 a	43.4 b	25.3 a	15.6 a
Substrate (S)	0.0004	0.0011	0.0621	0.0080	0.0004
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0287	0.0008	0.0391	0.0100	0.0100

Substrate	K ($mg \cdot L^{-1}$)				
Osmocote ($kg \cdot m^{-3}$)	May	June	July	August	September
PB					
4.2	89.9 b	169.7 b	76.5 c	78.3 c	26.6 b
8.4	171.2 a	276.0 a	201.8 a	150.7 a	61.5 a
PTS					
4.2	65.4 b	126.7 b	80.5 c	47.8 d	29.7 b
8.4	194.4 a	244.8 a	168.9 b	115.7 b	17.2 c
Substrate (S)	0.0041	0.0001	0.0004	0.0001	0.0621
Fertilizer rate (F)	0.0001	0.0001	0.0001	0.0001	0.0001
S x F	0.0010	0.0017	0.1020	0.0022	0.0001

[z]pH and EC of substrate solution obtained by the pour-through method (Wright, 1986).
[y]1 $mg \cdot L^{-1}$ = 1 ppm.
[x]Means separated within columns by nutrient using Duncan's multiple range test, $P \leq 0.05$ (n = 4).
[w]PTS produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.

Table 5.6. Substrate carbon dioxide (CO_2) efflux measured in 2006 and 2007 from containers filled with pine bark (PB) or pine tree substrate (PTS) with plants when fertilized with two rates of Osmocote Plus 15N-3.9P-10K[z].

	2006				
Substrate	CO_2 efflux (µmol CO_2·m^{-2}·s^{-1})				
Osmocote ($kg·m^{-3}$)	June	July	August	September	October
PB					
4.2	15.8 c[y]	10.9 c	5.7 c	7.0 c	3.5 b
8.4	12.5 d	8.8 d	5.5 c	5.8 d	3.3 b
PTS[x]					
4.2	31.3 a	22.1 a	19.9 a	20.3 a	11.1 a
8.4	25.4 b	18.3 b	15.9 b	16.8 b	12.3 a
Substrate (S)	0.0001	0.0031	0.0001	0.0007	0.0061
Fertilizer rate (F)	0.0120	0.0002	0.0814	0.0130	0.0370
S x F	0.0230	0.0014	0.0120	0.0017	0.0002
	2007				
Substrate	CO_2 efflux (µmol CO_2·m^{-2}·s^{-1})				
Osmocote ($kg·m^{-3}$)	May	June	July	August	September
PB					
4.2	3.2 c	8.7 c	7.2 b	6.5 b	5.5 c
8.4	2.1 d	5.2 d	6.6 b	5.7 c	2.8 d
PTS					
4.2	9.5 a	17.2 a	14.0 a	11.8 a	12.1 a
8.4	7.1 b	14.3 b	15.6 a	11.7 a	9.0 b
Substrate (S)	0.0071	0.0030	0.0025	0.0082	0.0081
Fertilizer rate (F)	0.1038	0.0190	0.0672	0.2310	0.0120
S x F	0.0204	0.0320	0.0082	0.0505	0.0841

[z]CO_2 efflux measured with a LiCor 6400 infrared gas analyzer fitted with a LiCor 6400-09 soil CO_2 flux chamber (n = 6).
[y]Means separated within columns using Duncan's multiple range test, $P \leq 0.05$ (n = 4).
[x]PTS produced from12-year-old loblolly pine trees harvested at ground level, delimbed, chipped, and hammer-milled to pass through a 4.76-mm screen.