Increasing amounts of coir dust in substrates do not improve physical properties or growth of tree seedlings in a novel air-pruning propagation tray[1]

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Abstract

Air-pruning can improve tree seedling root quality in propagation by subjecting root tips to desiccation, thereby avoiding deflections, but also increases substrate dry-out rates. Several studies have indicated that coconut (*Cocos nucifera* L.) coir dust can enhance water holding properties, possibly benefiting trees grown in air-pruning trays. However, water availability characteristics are influenced by particle size. In this experiment, coir dust was added into a sphagnum peat-perlite substrate mix at rates of 10, 15 and 20%. An industry standard peat-perlite mix was tested as a fourth substrate type. Red oak (*Quercus rubra* L.), red maple (*Acer rubrum* L.), quaking aspen (*Populus tremuloides* Michx.) and eastern white cedar (*Thuja occidentalis* L.) were grown from seed in these four substrate types. Physical and chemical properties of all substrate types were analyzed pre-experiment. The particle size distribution was finer and more even in the peat-perlite mix compared to the three coir mixes. The higher proportion of coarse particles in the 20% coir mix may have reduced water availability. Seedlings grown in the 15 and 20% coir mixes had lower above and below-ground growth compared to the 10% coir and peat-perlite mixes in all species except red oak.

Index words: soilless media, water holding capacity, air space, particle size distribution, chlorophyll content, tree growth.

Species used in the study: red oak (*Quercus rubra* L.); red maple (*Acer rubrum* L.); quaking aspen (*Populus tremuloides* Michx.); eastern white cedar (*Thuja occidentalis* L.).

Significance to the Horticultural Industry

The development of air-pruning tree propagation trays has been encouraged by the demand for better root systems. Although using air-pruning techniques can improve tree root systems by reducing the number of root deflections (e.g. root circling, ascending and descending roots), it causes quicker substrate dry-out, which complicates moisture management for the growers using this technology. More rapid substrate dry-out can result in greater use of water, which in turn increases cost of production. Commercially, there is a wide range of substrate mixes available for use, typically including several ingredients at different ratios (e.g. peat, perlite, coir). The goal of this study was to evaluate coir dust in an air-pruning propagation tray, RootSmart™, to determine if using higher proportions of coir dust in a peat and perlite mix could improve the water holding capacity and performance of the substrate. This is important to the industry, especially since air-pruning propagation trays are becoming more widely used by growers, which will require research into how substrates perform in these types of systems to improve moisture management. While the addition of higher proportions of coir dust in the experimental substrates resulted in reduced seedling growth—with the exception of red oak—further research is recommended to evaluate the performance of finer sized coir particles in similar proportions.

Introduction

Root formation of woody perennials can be significantly influenced by propagation tray and container design, which can lead to root deflection during nursery production. Root deflection typically occurs when roots come into contact with a solid surface (e.g. container wall), which can develop into circling, diving or ascending roots (Gilman 2001). If this issue is allowed to persist, this can lead to long-term issues in the landscape (Ortega et al. 2006). Due to these complications, propagation tray and container designs have evolved to improve root systems (McGrath et al. 2017). Air root-pruning has been one technique used to improve root architecture and to reduce the number of roots deflected during production. Exposing the substrate to air forces root tip desiccation, which leads to increased root branching and decreased root deflections. Utilizing air-pruning propagation trays however, can pose concerns around quicker substrate dry-out between watering.

New substrates are continually becoming commercially available and contain blends of multiple ingredients (Schmilewski 2008), which necessitates research into ideal ratios for specific plant material. In particular, researchers continue to investigate sustainable alternatives to sphagnum peat. Adoption of coconut (*Cocos nucifera* L. [Arecaceae]) coir dust for use as an organic component of soilless substrate mixes has grown greatly over the past decade (Carlile et al. 2015). Coconut coir used in growing media is composed of the short fibers and 'dust' derived from the mesocarp of coconut fruits, and is washed to remove excess salts (Carlile et al. 2015). In many parts of the world it is more accessible, sustainable and cost-effective than peat moss, and there are examples of it

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performing well as a viable component of growing substrates for a variety of plants (Cresswell 1992, Evans et al. 1996, Noguera et al. 1997). Numerous studies have examined its effectiveness as a substrate with many ornamental and food crops (Arenas et al. 2002, Raviv et al. 2001, Rose and Haase 2000) and it has been used widely as a peat replacement in floriculture and soft fruit production (Barrett et al. 2016). There are, however, a lack of studies that examine the effectiveness of coir added to peat-based substrates for tree seedling production (Landis et al. 1990, Rose and Haase 2000), especially when employing air-pruning methods.

Sphagnum peat has been widely used as a substrate material because it does not require many additives or treatments, which minimizes costs (Barrett et al. 2016). It possesses many beneficial characteristics, including the ability to adsorb and release nutrients, high aeration porosity, low bulk density and high water holding capacity (Barrett et al. 2016, Boudreault et al. 2014). Similar to peat, coir has many properties that make it ideal for use as a substrate (Hernández-Apaolaza et al. 2005). Coir has a comparable bulk density (Cresswell 1992), good drainage, a similar texture and resistance to degradation (Rose and Haase 2000). Although coir does contain many ideal substrate characteristics, there have been mixed results in regard to its water holding capacity. Coir dust has been found to have less (Noguera et al. 1997, 2000), equal or greater (Cresswell 1992, Evans et al. 1996, Fields et al. 2014, Handreck 1993) water holding properties compared to sphagnum peat. The ambiguity in terms of water and air properties of coir dust compared to more well-studied peat underscores the importance of understanding its variability and associated properties for different types of tree production.

Our objective was to evaluate the growth of four commonly grown temperate tree species (*Quercus rubra* [red oak], *Acer rubrum* [red maple], *Populus tremuloides* [quaking aspen] and *Thuja occidentalis* [eastern white cedar]) in several sphagnum peat-based substrates with a gradient of coir dust incorporations of 10, 15 and 20%, and in a different peat-perlite propagation mix. All four substrate types had similar proportions of perlite and were grown in an air-pruning tray with a high degree of air-exposure. The objective of this study was to determine if higher proportions of coir relative to sphagnum peat provide certain enhancements to the physical or chemical characteristics of the substrate mixes, which in turn could increase the growth of the tree seedlings.

Methods and Materials

Study site and experimental design. This study was conducted in a closed greenhouse (April to mid-May) and a retractable roof experimental greenhouse (Cravo Equipment Ltd., Brantford, Ontario, Canada; mid-May to September) at the Vineland Research and Innovation Centre, Vineland Station (Ontario, Canada; lat. 43.19 N, long. 79.40 E). Monthly average temperatures over the growing season for the greenhouses were 21, 21, 23, 25, and 25 C (70, 70, 73, 77, and 77 F) for April, May, June, July and August, respectively. Substrates used included

Table 1. The four growing substrate types used in the study.

Substrate Type	Components (by volume)
Sunshine® #5 /LP5 Mix (Peat-perlite mix)	70-80% Select Canadian sphagnum peat moss, 20-30% perlite, dolomitic limestone, low starter nutrient charge with gypsum, wetting agent
10% Coir Mix	60% Sphagnum peat moss, 30% perlite, 10% coconut coir dust, limestone, gypsum, low starter nutrient charge, magnesium oxide, wetting agent solution, RootShield® WP
15% Coir Mix	55% Sphagnum peat moss, 30% perlite, 15% coconut coir dust, Limestone, Gypsum, low starter nutrient charge, Magnesium oxide, wetting agent solution, RootShield® WP
20% Coir Mix	50% Sphagnum peat moss, 30% perlite, 20% coconut coir dust, Limestone, Gypsum, low starter nutrient charge, Magnesium oxide, wetting agent solution, RootShield® WP

Sunshine® Mix #5 / LP5 (Sun Gro® Horticulture, Agawam, MA; referred to in this paper as the peat-perlite or 0% coir mix) and a proprietary grow mix including 60% sphagnum peat moss, 30% perlite and 10% coconut coir dust by volume (10% coir; Table 1). The two remaining substrate types represent modifications of the proprietary grow mix with increased coir dust of 15 and 20% with proportional reductions in sphagnum peat moss. Coir dust is the sieved by-product that is left over after coconut husks have been processed for their longer fibers (Abad et al. 2005).

A randomized experiment was established where seedlings of the same species were grown in trays blocked together, but different substrate types were randomly assigned positions in each tray. Pre-stratified seeds of red oak, red maple and eastern white cedar, provided by Verbinnen's Nursery Ltd. (Dundas, ON, Canada), were used in this study. Red oak, red maple and eastern white cedar seeds were sown on April 8, 2016 and quaking aspen on June 1 into Ellepots™ at randomly determined cell locations within RootSmart™ air-pruning propagation trays (A.M.A. Plastics Ltd., Kingsville, ON, Canada). Ellepot™ dimensions within the RootSmart™ tray were 60 mm (2.36 in) diameter, 100 mm (3.94 in) height and a 283 cm^3 (17.3 in^3) volume. Ellepots™ had a paper thickness of 0.127 mm (0.005 in) (Ellegaard A/S, Esbjerg, DK). These tree species were selected because of their differences in root system development. Although red oak is classified as having a heart root system (Coutts 1987), in early stages of growth red oak develops a prominent thick diameter taproot as compared to lateral root development (Lyford 1980). Quaking aspen is capable as adapting to the conditions of the growing environment, also known as root growth plasticity, to access resource-rich zones in the soil (Friend et al. 1999). Red maple will form a short taproot in wet conditions but in drier conditions the taproot will lengthen and develop significantly shorter laterals from a young age (Walters and Yawney 1990). Eastern white cedar develops deep roots in well drained soils and shallow roots in saturated soils and has a wide-spread root system (Johnston 1990).

At least 15 ellepots™ of each substrate type per species were sown with seed. Red oak were spaced out to be one cell apart on May 2, 2016 (24 days after sowing) to avoid shading effects as the seedlings grew. All other species remained in adjacent cells. A total of 13 RootSmart™ trays were used. Red oak seedlings grew for a total of 130 days, red maple seedlings for 137 days, quaking aspen seedlings for 90 days and eastern white cedar seedlings for 144 days before being destructively harvested between late August and early September 2016.

All seedlings were watered with overhead irrigation at least once per day based on visual assessments of watering needs throughout the growing season. Tree seedlings were fertilized at least once on a weekly basis beginning April 27 for red oak and red maple, May 3 for eastern white cedar and June 29 for quaking aspen. The first two applications were made of Forestry Starter fertilizer (PlantProd® 11N-41P-8K; Master Plant-Prod Inc. Brampton, ON) at 200 ppm N to red oak and red maple and 100 ppm N to eastern white cedar seedlings. This was followed by regular applications of Forestry Feeder fertilizer (PlantProd® 20N-8P-20K) at 350 ppm N for all species. Quaking aspen was not given the Forestry Starter fertilizer, instead a lower rate of Forestry Feeder was used for the first two applications (100 ppm N). Fertilizer rates and application frequencies were adjusted on a weekly basis to keep substrate electrical conductivity values between 0.5 – 1.0 mS cm^{-1}. Substrate pH was adjusted throughout the study to bring the pH below 7.5 using Acid Fertilizer (PlantProd® 21N-7P-7K).

Trays were re-randomized biweekly in order to minimize location error (e.g. exposures to wind and sun). Repeated measures of substrate pH and electrical conductivity (EC) throughout the growing season were determined using a pour-through nutrient extraction method (Wright and Lundholm 1986) bi-weekly. Leachate collected from the pour-through extraction method was analyzed for pH and EC using a portable pH and EC meter (Oakton PC 300, Oakton Instruments, Vernon Hills, IL). Chlorophyll content (-9.9 to 199.9 SPAD units) was obtained on a bi-weekly basis by taking measurements on three mature leaves per seedling for red oak and red maple (May 16 – August 15, 2016) and quaking aspen (August 3 – August 30, 2016) using an indexed reading chlorophyll meter (SPAD 502 Plus Chlorophyll Meter, Spectrum Technologies, Inc., Aurora IL). Weekly measurements of tree seedling heights were taken, as well, throughout the growing season.

Destructive harvest growth measurements. Six red maple and quaking aspen, 8 red oak and between 13 and 18 eastern white cedar seedlings were destructively sampled and analyzed per substrate type. These plants were randomly selected at the end of the growing season. Plant growth was assessed by measuring seedling height, trunk cross-sectional area (TCSA), leaf area, above-ground dry weight and root dry weight. Plant height was measured from the root collar to the highest alive point of the seedling. Trunk cross-sectional area was calculated using the average diameter of the seedling stem measured in two opposite directions at 2.5 cm above the root collar. Total leaf area was determined using a leaf area meter (LI-3100, Licor Inc., Lincoln, NE). Final chlorophyll content (-9.9 to 199.9 SPAD units) was obtained by taking measurements on three mature leaves on all tree seedlings except eastern white cedar, using an indexed reading chlorophyll meter (SPAD 502 Plus Chlorophyll Meter, Spectrum Technologies, Inc., Aurora IL). Substrate was removed from the roots by washing. Above (leaves and stem) and below-ground (roots) dry weight was then determined by cutting plants at the root collar and drying all above and below-ground tissue at 75 C (167 F) until a constant weight was achieved. All remaining leaves were collected, crushed, mixed and subsampled for final foliar nutrient analysis (submitted to SGS-AgriFood Labs, Guelph, ON, Canada). Foliar analysis included: nitrogen, phosphorus, boron, calcium, copper, iron, manganese, magnesium, sulphur and zinc (Table 4).

Physical and chemical analysis of substrates. Subsamples were analyzed from mixed samples composed of substrate collected from at least 10 separate Ellepots™ from each substrate type prior to use in the experiment. Media Complete chemical analysis (pH, EC, nitrogen, phosphorus, boron, calcium, copper, iron, manganese, magnesium, sulphur and zinc) and Rooftop Substrate physical analysis (particle size distribution, air space, as is density, total porosity, saturated density, bulk density, water holding capacity, saturated hydraulic conductivity) packages were selected for analysis (submitted to SGS-AgriFood Labs, Guelph, ON, Canada). Particle size distributions of substrate types were analyzed based on thresholds above 0.5 mm (0.02 in), 1.0 mm (0.04 in) and 2.0 mm (0.08 in) based on findings from Abad et al. 2005, Bernier and Gonzalez 1995, and Noguera et al. 2003.

Statistical analyses. Data for substrate physical and chemical properties, as well as height, TCSA, above-ground dry weight and root dry weight of destructively harvested seedlings were subjected to one-way analysis of variance (ANOVA) or Kruskal-Wallis tests after being tested for normality and homogeneity of variance. Transformations of response variable data were performed when necessary before analysis to address any ANOVA violations. The Tukey's or Dunn's multiple comparisons tests were used as post-hoc tests. Two-way repeated measures ANOVA tests were conducted on substrate pH, EC, seedling chlorophyll content and height measurements collected throughout the growing season. Outlier data points were assessed in all data sets before conducting analysis using the ROUT Method with $Q = 1\%$. All data sets were analysed using GraphPad Prism version 7.03 software (GraphPad Software Inc., La Jolla, CA). All data were evaluated using a significance level of $p < 0.05$, or < 0.1 when specified.

Results and Discussion

Substrate – physical properties. Initial physical properties of each substrate type were assessed before tree seeds were sown (Table 2). The physical analysis revealed similar bulk densities and total porosity for each substrate.

Table 2. **Physical analysis of the four substrate types used in the study. Analysis was conducted on the substrates pre-experiment. Values in brackets are the standard error of the mean. Sample size is 3 for all mixes except for the peat-perlite mix (n=2), therefore statistical analyses compare only the 10, 15 and 20% coir mixes. Values bearing different letters represent substrate types with significantly different mean values (p<0.05).**

Substrate Type	Bulk Density (kg cm^{-3})	Total Porosity (%)	Air Space (%)	Water Holding Capacity (%)	Saturated Hydraulic Conductivity (cm hr^{-1})
Peat-Perlite Mix	120.9	76.6	13.4	66.9	30.5
10% Coir Mix	119.1 (3.9)a	83.8 (3.4)a	21.6 (4.6)a	59.4 (4.0)a	46.3 (2.6)a
15% Coir Mix	125.5 (3.5)a	79.3 (2.4)a	26.0 (3.7)a	53.2 (1.6)a	16.6 (6.1)ab
20% Coir Mix	117.8 (5.0)a	75.9 (8.5)a	23.9 (0.5)a	52.1 (8.9)a	9.3 (1.3)b
P-value	ns	ns	ns	ns	* [Z]

[Z]Indicates Kruskal-Wallis test using Dunn's Multiple Comparison Test. Significance notes: $p < 0.05$ = *; $p < 0.01$ = **; ns = not significant.

Although air space and water holding capacity were not statistically different among coir mixes (p>0.05), it appears as though the peat-perlite mix may have possessed less air space and greater water holding capacity. Clear differences emerged from the lower saturated hydraulic conductivity (p<0.05) of the 20% coir mix, compared to the 10% coir mix. Although the 10% coir mix was not significantly different compared to 15% coir for hydraulic conductivity, values were higher for the 10% coir compared to the 15% coir mix. Similarly, although not tested for significance, the peat-perlite mix was observed to have a trend towards greater saturated hydraulic conductivity compared to the 15 and 20% coir mixes (Table 2).

Saturated hydraulic conductivity is a commonly assessed metric in soilless media, largely because in the past unsaturated hydraulic conductivity was difficult to measure accurately. In addition, many container crops are kept at high moisture levels and application rates and efficiency of water use may be better understood through saturated hydraulic conductivity (Fields et al. 2017). Air-pruning propagation trays such as the RootSmart™ tray used in this study, however, subject growing substrates to higher levels of dry-out than closed cell trays. Fields et al. (2017) found very little correlation between saturated and unsaturated hydraulic conductivity in an experiment examining the performance of an ornamental container crop grown under sub-optimal water levels. While unsaturated hydraulic conductivity was found to be highly positively correlated with measures of plant vigor, saturated hydraulic conductivity was less strongly correlated with all plant physiological metrics. Therefore unsaturated hydraulic conductivity should be measured in future studies testing air-pruning trays. In the same paper, coir and peat samples performed similarly in terms of easily available water [water lost between -1 kPa (-0.15 psi) and -5 kPa (-0.73 psi)] and water-buffering capacity [water lost between -5 kPa (-0.73 psi) and -10 kPa (-1.45 psi)], despite the coir sample in this study having 64.0% fine sized particles [<0.71mm (0.028 in)] compared to the peat sample having only 51.6% (Fields et al. 2017).

Several studies have shown that the particle size distribution of peat and coir-based substrates has a significant influence on their physical properties (e.g. hydraulic conductivity, porosity, water holding capacity, air space, etc.; Abad et al. 2005, Bernier and Gonzalez 1995, Boudreault et al. 2014, Noguera et al. 2003). Particle sizes were more evenly distributed in the peat-perlite mix as opposed to the 10, 15 and 20% coir mixes (Fig. 1). The 10, 15 and 20% coir mixes possessed the same sources of peat, perlite and coir dust materials. The 20% coir mix had an average of 8.0% of particles larger than 2.0 mm (0.08 in) in comparison to the 2.9% and 3.0% in the 10 and 15% coir mixes, respectively (Fig. 2, p<0.05). The coir mixes did not differ in percentage of particles less than 0.25 mm (0.01 in) or 0.5 mm (0.02 in). The 20% coir mix did have a slightly higher percentage of particles greater than 1.0 mm (0.04 in) compared to the 15% coir mix (Fig. 2, p<0.10). The change in particle size for coir dust has a large influence on water retention and availability characteristics (Abad et al. 2005, Noguera et al. 2003). In a previous study, fractions between 0.5-1.0 mm (0.02-0.04 in) and 1-2 mm (0.04-0.08 in) possessed low easily available water properties, similar to particles >2.0 mm (0.08 in) in size. This is in contrast to smaller sized particles, as coir dust particles between 0.125-0.5 mm (0.005-0.02 in) provided the most easily available water and lower air space (Noguera et al. 2003).

Similarly, particle size of crushed quartz, river sand (Noguera et al. 2003), bark and wood-based substrates (Starr et al. 2012) and peat (Bernier and Gonzalez 1995) has also demonstrated significant impacts on air and water properties. Peat substrate mixes used for conifer tree propagation with greater proportions of fine sized particles [<1.3mm (0.05 in)] of both light and dark peat varieties demonstrated approximately two to four times more easily available water and significantly reduced air volume, which were highly correlated with greater white spruce (*Picea glauca* (Moench) Voss) seedling growth in contrast to coarser peat mixes (Bernier and Gonzalez 1995). Interestingly, black spruce (*Picea mariana* Mill.) seedling height was only slightly increased with the fines-enriched peat, highlighting different physiological needs between species. Handreck (1983) tested radiata pine (*Pinus radiata* D. Don) bark-based growing media for effects of particle size on physical characteristics and found that particles between 0.1-0.25 mm (0.004-0.01 in) possessed the largest water release and smallest air-filled porosity as compared those less than 0.1 mm (0.004 in) or between 0.25 and 0.5 mm (0.01 and 0.02 in). These findings demonstrate that different substrate components possess varying easily available water properties depending on particle sizes.

When comparing peat and coir dust as amendments into existing mixes for growing *Dieffenbachia maculate*

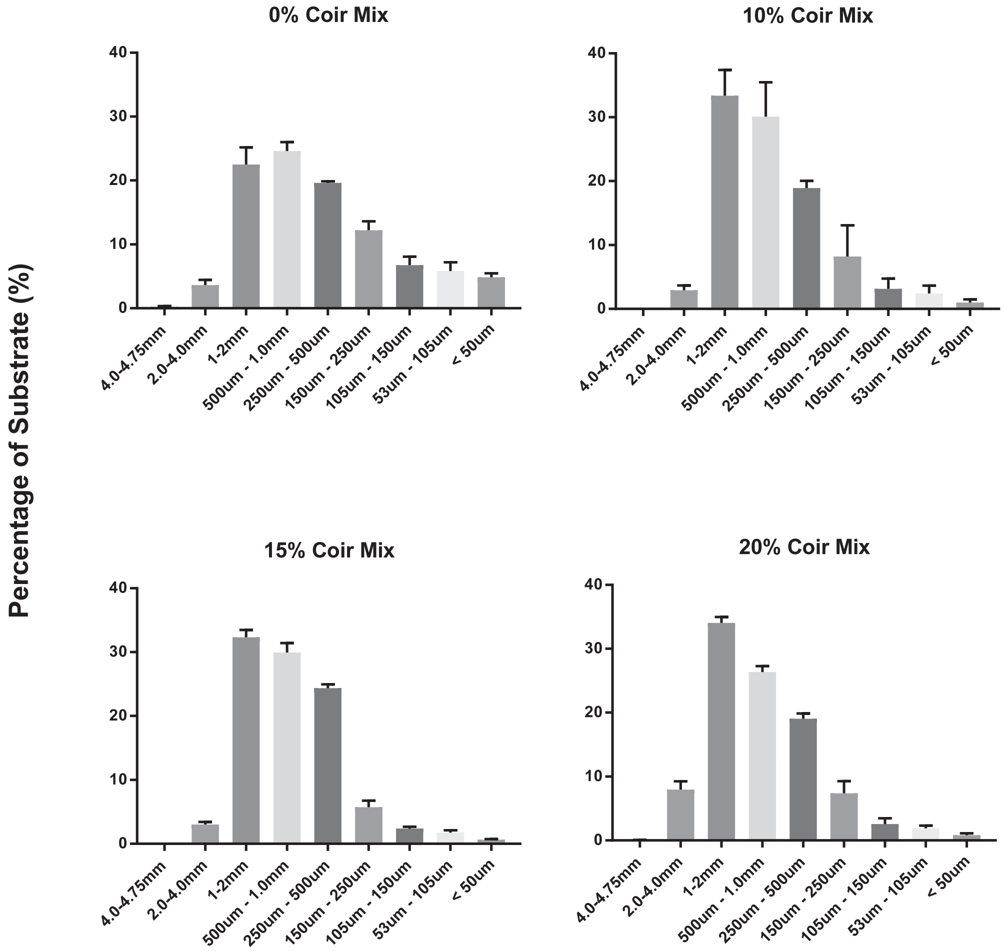

Fig. 1. Mean percentage by weight of particle sizes present in each substrate type prior to use. Error bars represent one standard deviation. Sample size = 3 for all mixes except for the 0% coir/peat-perlite mix (n=2).

[(Lodd.) G. Don] 'Camille', results showed that the addition of coir dust lowered air-filled pore space, increased water holding capacity and produced the largest, highest grade plants (Stamps and Evans 1997). This was attributed to the smaller average particle size of the coir dust compared to the peat. Stamps and Evans (1997) found that the inclusion of large-sized particles increased the pore space that acts in a non-capillary fashion, which can increase drainage and decrease water holding capacity.

In a comprehensive review of coir dust properties from various regions, Abad et al. (2005) assessed the physical properties of 13 types of coir dusts in comparison with sphagnum peat. The smaller coir dust particle sizes improved easily available and total water-holding capac-

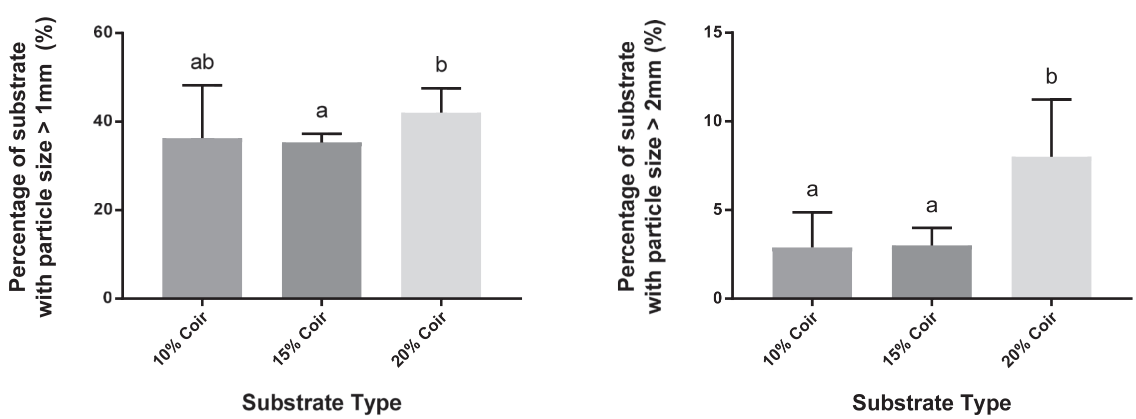

Fig. 2. Mean percentage by weight of particles larger than 1.0 mm (left) and 2.0 mm (right) in substrate types. Error bars are 95% confidence intervals. Letters indicate significance at $p < 0.1$ (left graph) and $p < 0.05$ (right graph) by one-way ANOVA.

Table 3. **Chemical analysis of the four growing substrates used in the study. Analysis was conducted on the substrates pre-experiment. Values in brackets are the standard error of the mean. Sample size = 3 for all substrate types. Values bearing different letters represent substrate types with significantly different mean values (p<0.05).**

Substrate Type	Electrical Conductivity ($mS\ cm^{-1}$)	pH	NO_3-N (ppm)	P (ppm)	K (ppm)	S (ppm)	Ca (ppm)	Mg (ppm)
Peat-Perlite Mix	0.70 (0.00)ab	4.4 (0.01)a	41.7 (0.3)a	8.8 (0.04)a	33.1 (0.1)a	147.1 (0.88)ac	22.8 (0.1)a	34.2 (0.2)a
10% Coir Mix	0.65 (0.01)ab	5.4 (0.08)a	15 (0.6)ab	7.7 (0.2)b	71.3 (1.3)bc	132.3 (2.13)ab	19.1 (3.8)ab	9.4 (1.3)b
15% Coir Mix	0.62 (0.01)a	6.3 (0.02)a	4.7 (0.7)b	5.8 (0.1)c	83.2 (0.6)c	121.3 (3.35)b	11.3 (0.5)b	3.6 (0.2)c
20% Coir Mix	0.81 (0.02)b	6.3 (0.05)a	9.3 (2.6)ab	8.3 (0.4)ab	103.7 (7.8)d	155.1 (5.5)c	15.8 (0.3)ab	8.0 (1.5)bc
P-value	*** Z	** Z	*** Z	***	***	***	*	***

Z Indicates Kruskal-Wallis test using Dunn's multiple comparisons. Significance notes: $p < 0.05$ = *; $p < 0.01$ = **; $p < 0.001$ = ***

ities, as well as relative hydraulic conductivity, but reduced air content (Abad et al. 2002 & 2005, Noguera et al. 2003). When particle size distributions were similar, coir dust demonstrated higher aeration and lower total water holding capacity and easily available water compared to peat (Abad et al. 2005). The micro structure and relatively greater surface porosity of the pithy tissue particles of coir dust (Fornes et al. 2003) make them more susceptible to water penetration and drainage compared to peat (Abad et al. 2005), lending some explanation to why as the proportion of coir dust increased from 10, to 15, to 20% in our experimental substrate mixes, tree seedlings tended to perform more poorly, despite similar particle size distributions (Fig. 1). Additionally, water can be removed at lower suctions in coir dust than peat due to the larger pores present in coir dust (Abad et al. 2005). Quintero et al. (2009) compared different substrate physical properties and their effects on cut rose production. The study found that coir had the lowest easily available water and the highest hardly available water content. Additionally, the coconut fiber substrates contained the largest particles. Based on the particle size distribution of the substrate types tested in our study, this helps explain the trend (although not significant) towards higher aeration and lower water holding capacity in mixes with greater coir dust added (Table 3).

Substrate – chemical properties. Initial pH was 4.4, 5.4, 6.3 and 6.3 for the peat-perlite mix, 10, 15 and 20% coir mixes, respectively (Table 3). Electrical conductivity levels were only marginally but significantly different between the 15% coir (0.62 $mS\ cm^{-1}$) and 20% coir (0.81 $mS\ cm^{-1}$) mixes. Nitrate nitrogen, phosphorous, calcium and magnesium levels were highest in the peat-perlite mix, although not always significantly higher compared to the other substrate types. Potassium levels were all significantly higher in the coir mixes than the peat-perlite mix; increasing with the amount of coir added. Sulfur levels were significantly greater in the peat-perlite and 20% coir mixes compared to the 15% coir mix.

Electrical conductivity values ranged from approximately 0.3 – 1.2 $mS\ cm^{-1}$ throughout the growing season and did not differ among substrate types for red oak, red maple and eastern white cedar (p=0.06, p=0.72, p=0.17 respectively, Fig. 3). Fertilization levels were adjusted according to observed pour-through EC and pH levels and applied to all substrate types equally. Irrigation water used through-

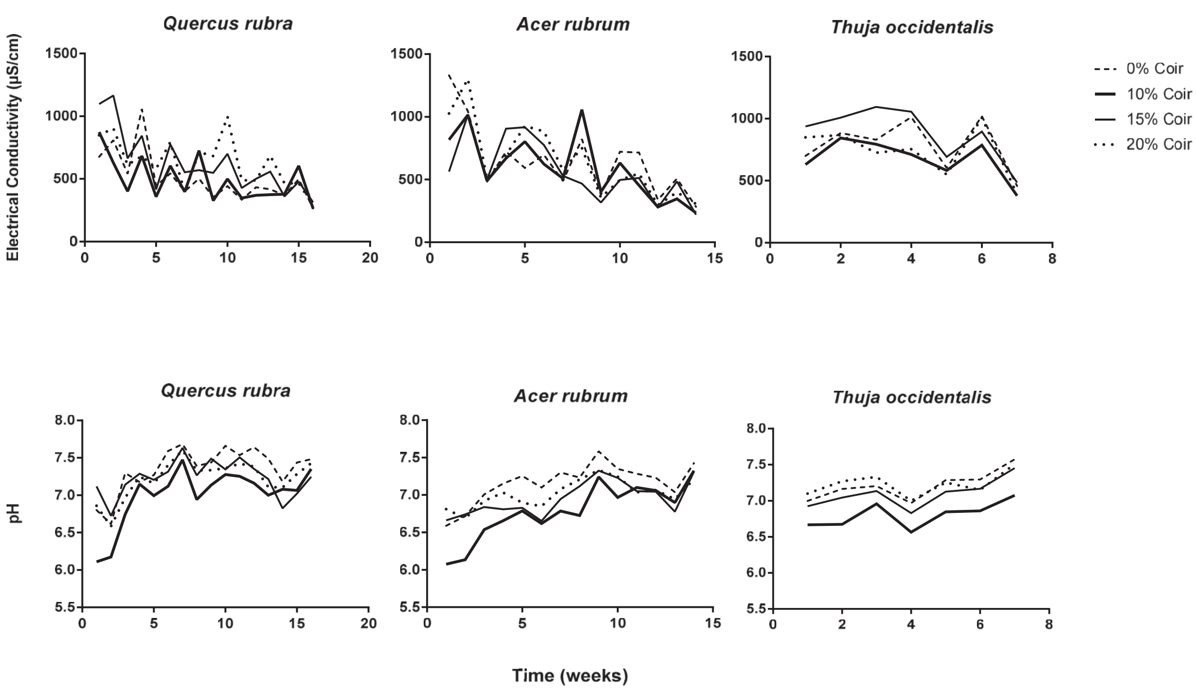

Fig. 3. Mean electrical conductivity (top) and pH (bottom) of pour-through samples taken on the four substrates during the growing season.

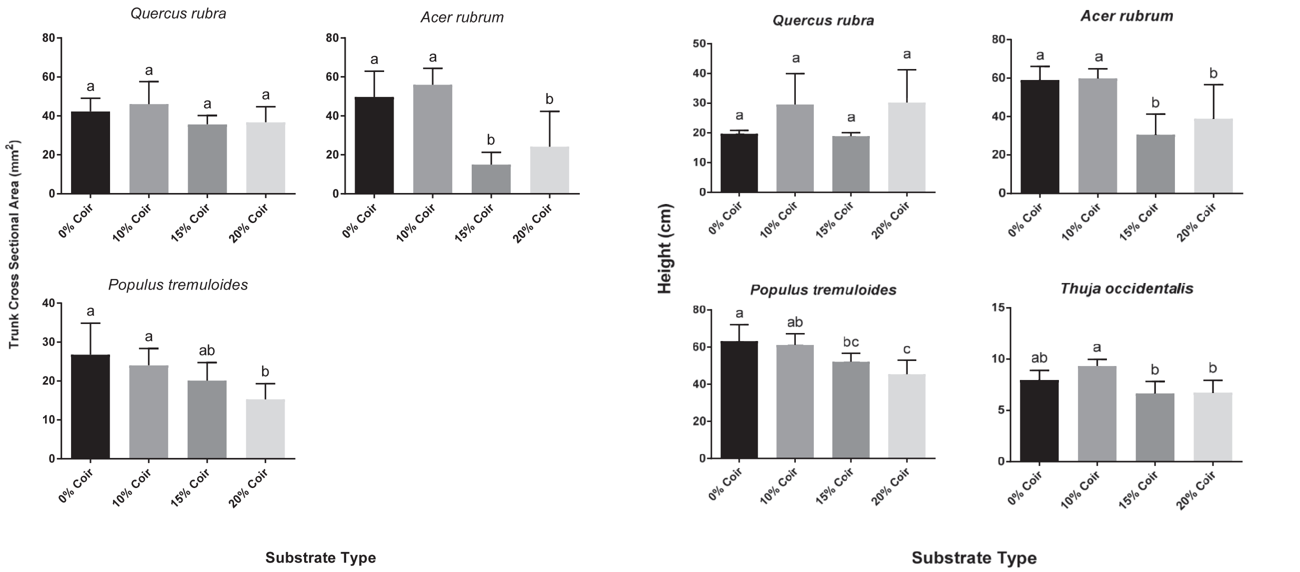

Fig. 4. Mean trunk cross-sectional area and height for red oak (n=8), red maple and quaking aspen (n=6) and eastern white cedar (n=13) seedlings after one growing season. Error bars indicate 95% confidence intervals. Different letters indicate a significant difference ($p < 0.05$) by one-way ANOVA (red oak TCSA, red maple TCSA and height, quaking aspen TCSA and height) and Kruskal-Wallis (red oak height, eastern white cedar height) tests.

out the study was slightly alkaline (pH: 7.6) and despite applications of acid fertilizer, pH tended to rise during the growing season. The pH range throughout the growing season was approximately 6.0 – 7.7. The pH was significantly lower in the 10% coir mix throughout parts of the growing season for red oak, red maple and eastern white cedar ($p<0.0001$, $p<0.01$, $p<0.01$, respectively), whereas the peat-perlite and 20% coir mixes most frequently possessed the highest pH (Fig. 3). For instance, while the 10% coir mix remained between 6.5 and 7.0 during 6 weeks of measurements for eastern white cedar, the peat-perlite and 20% coir mixes were between 7.0 and 7.5, followed just slightly below by the 15% coir mix. In both red oak and red maple, pH values in the 10% coir mix were lower than the rest of the substrate types for all observed measurements in the first 10 weeks (Fig. 3). The ideal pH for growing most plants, including tree seedlings, is between 5.5 and 6.5 (Carlile et al. 2015). At pH levels above 6.5, iron and boron, as well as other micronutrients, may not be available at sufficient levels in organic growing media (Carlile et al. 2015). Elevated pH may pose a concern in settings where plants are pH-sensitive and irrigation water is alkaline. Red oak and red maple are sensitive to high pH and the irrigation water used throughout the study was alkaline (pH of 7.6), causing pH levels in growing substrates to increase throughout the duration of the experiment despite applications of acid (Fig. 3). Despite concerns about elevated pH, the peat-perlite mix seedlings still performed well in terms of chlorophyll content (Fig. 6) and growth metrics (Figs. 4, 5 & 7). Chlorophyll content tended to be lower in the 15 and 20% coir compared to the 10% coir and peat-perlite mixes in red maple seedlings from May 16 – July 4th and in quaking aspen seedlings from August 3 – 30th. Chlorophyll content is a measure of vitality and lower values can indicate stress in trees (Johnstone et al. 2013).

There was no evidence of salinity (sodium or chlorine) issues in the plants grown in the coir mixes based on EC, which was monitored over the entire growing season. Initial analysis of the substrate also indicated no buildup of salts within the coir mixes prior to seed sowing. Toxicity due to soluble salts is one of the main concerns for use of coir. Tolerance to high soluble salt content in growing substrates is plant species and growth stage-specific; however a guideline for an acceptable initial EC of fresh substrate is 0.75 mS cm^{-1} (Robbins 2001). All the substrate mixes approached or slightly exceeded this level. Coir often also contains high levels of potassium. Higher levels of K in the coir mixes were observed, with the greatest levels in the 20% coir mix; however no observable impact was indicated based on the pour-through data. Coir typically contains potassium at rates of between 170 – 600 ppm (Robbins and Evans 2011), contrasted to levels of 71.3, 83.2 and 103.7 ppm for the 10, 15 and 20% coir mixes used this study (Table 3). Throughout the growing season, EC should not fluctuate much below 1.0 or above 3.0 mS cm^{-1}, depending on plant species (Ingram 2014). Electrical conductivity values were generally maintained within the recommended range through regular fertilization throughout the growing season, with the exception of the last few weeks when EC values across substrates tended to drop below 0.5 mS cm^{-1} (Fig. 3).

Tree seedling growth responses. Substrate physical and chemical properties, including particle size distribution, water availability, air space and nutrient retention influence tree seedling performance/ growth (Boudreault et al. 2014). Tree seedling growth responses varied by species; however, the trend among red maple, quaking

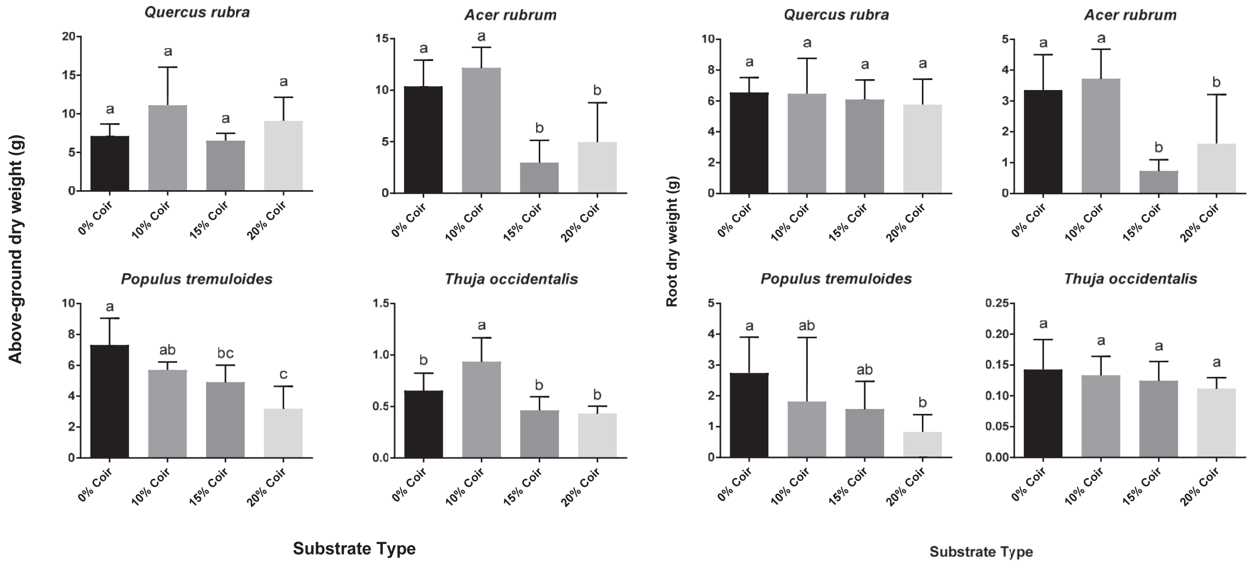

Fig. 5. Mean above-ground and root dry weight of red oak (n=8), red maple and quaking aspen (n=6) and eastern white cedar (n=13) seedlings after one growing season. Error bars indicate 95% confidence intervals. Different letters indicate a significant difference ($p < 0.05$) by one-way ANOVA.

aspen and eastern white cedar was greater above-ground growth in the peat-perlite and 10% coir mixes compared to the 15% and 20% coir mixes (Figs. 4 and 5). In contrast, red oak demonstrated no statistically significant ($p>0.05$) above or below-ground growth differences among substrate types. For red maple, growth in terms of height, TCSA and above and below-ground dry weight, was statistically greater for the peat-perlite and 10% coir mixes, compared to 15 and 20% coir mixes (Fig. 4 and 5). Average seedling height was ~60 cm (23.6 in) in both the 10% coir and peat-perlite mixes, compared to ~30 cm (11.8 in) and ~39 cm (15.4 in) in the 15 and 20% coir mixes, respectively. Similar statistical differences were also observed with the root dry weight. Average seedling root dry weight at the end of the growing season for the 10% coir mix was 3.72 g (0.13 oz) and for the peat-perlite mix was 3.36 g (0.12 oz). In comparison, average root dry weight was 0.73 g (0.03 oz) for the 15% coir mix and 1.62 g (0.06 oz) for the 20% coir mix (Fig. 5). For quaking aspen, statistically greater growth was observed with the peat-perlite mix for height, TCSA and above and below-ground dry weight compared with the 20% coir mix seedlings (Figs. 4 and 5). Average height of eastern white cedar seedlings was greater in the 10% coir mix compared to the 15 and 20% coir mixes, but was not statistically greater than seedlings grown in the peat-perlite mix (Fig. 4). Greatest above-ground dry weight in eastern white cedar was observed with the 10% coir mix compared to all other substrates, and averaged two times the weight of seedlings grown in the 15 and 20% coir mixes. Root dry weight did not differ between substrates types (Fig. 5).

Variable results from red oak seedlings suggest that tree seedlings with different root structures may respond differently in the substrate mixes amended with greater amounts of coir. Red oak forms a prominent taproot in early stages of development and may respond differently to the coir mixes as compared to species that increase lateral root branching in early stages of development like red maple, quaking aspen and eastern white cedar. Red oak taproots can reach up to 45 cm (17.7 in) in the first year in natural settings and up to 18 cm (7.1 in) formed before the first leaves emerge (Bourdeau 1954, Dey and Parker 1996, Lyford 1980). Young oak seedlings allocate more resources to root growth than stem and foliage growth (Dickson et al. 1990). In suboptimal conditions, red oak will slow shoot growth and allocate photosynthate to roots as this species preferentially maintains root growth over shoot growth as an ecological adaptation to persist in drier sites (Dey and Parker 1996). Red oak has been found to form taproots with root tips larger than laterals, i.e. 2-3 mm (0.08-0.12 in) thick compared to 0.17-1.5 mm (0.007-0.06 in) (Lyford 1980). This adaptation and high root-shoot ratio may explain why red oak growth was not inhibited as significantly by the 15 and 20% coir mixes as the other species. Additionally, taproots have been found to contain more vascular strands than lateral roots (Torrey and Wallis 1975), which may account for the less pronounced effects on red oak growth that particle size distribution had on water holding, water availability and aeration properties.

The differences in the physical properties of the substrate mixes most likely contributed to the observed growth differences for red maple, quaking aspen and eastern white cedar. The particle size distribution in the 20% coir mix, which had more particles greater than 2.0 mm (0.08 in) than other treatments, may have resulted in a decrease in easily available water and influenced seedling growth. Research suggests that for optimal plant growth to be achieved, media should have high levels of easily available water (20 to 30% by volume) and air space (20 to 30% by volume, Abad et al. 2005). Others have suggested acceptable plant growth ranges for total porosity between 50 to 85% of media volume, 10 to 30% for air space (Starr

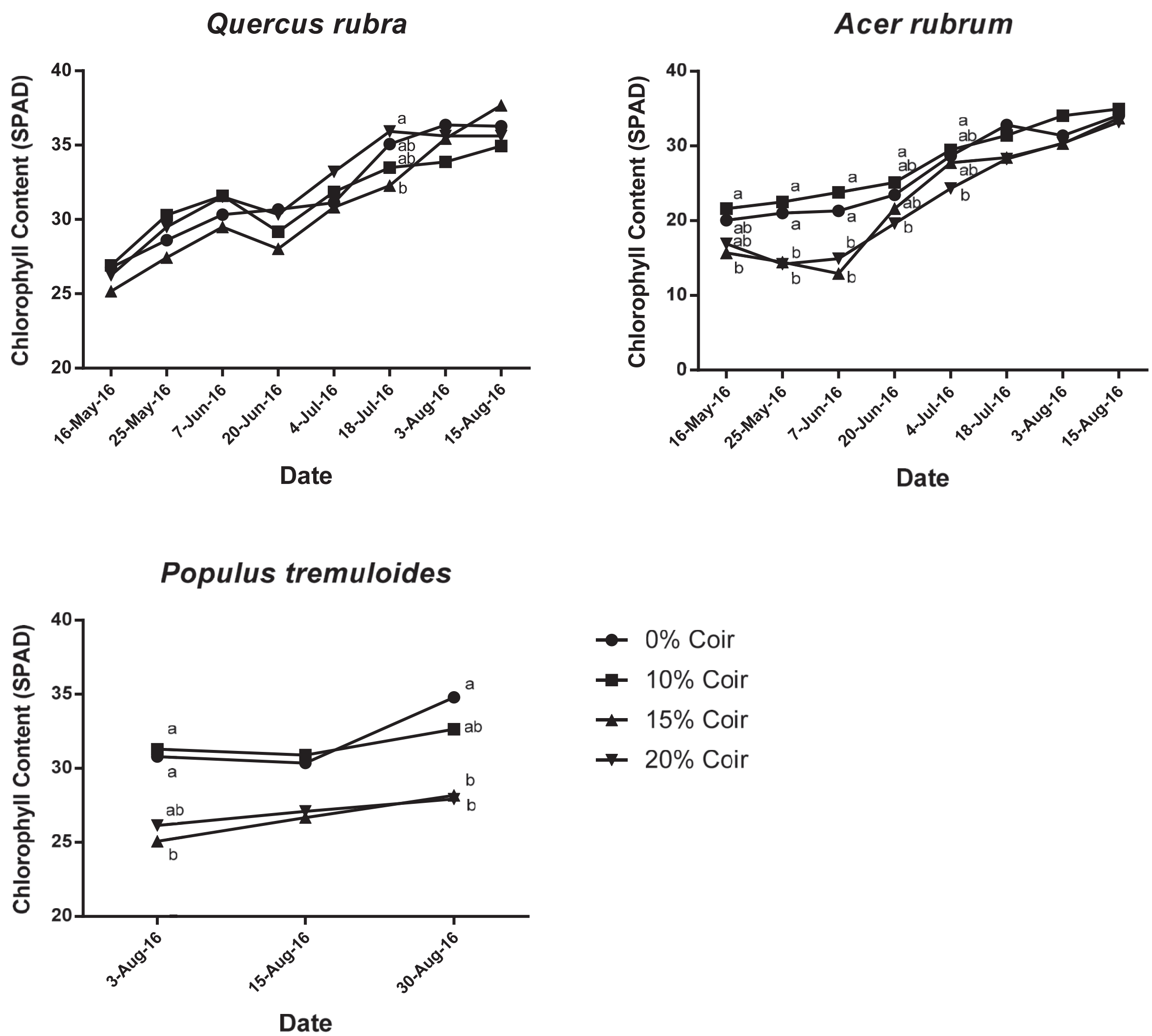

Fig. 6. Mean chlorophyll content of red oak (n=12), red maple (n=12) and quaking aspen (n=10 [August 3rd and 16th] and n=6 [August 30th – destructive harvest seedlings]) seedlings throughout the growing season. Different letters indicate a significant difference ($p < 0.05$). Red oak and red maple were evaluated using a two-way ANOVA. Significance of repeated measures of quaking aspen on August 3rd and 16th were evaluated by two-way repeated measures ANOVA. A subsample of destructively harvested seedlings were evaluated by Kruskall-Wallis test on August 30th.

et al. 2012) and 25 to 35% available water (Carlile et al. 2015). All mixes evaluated had air space and total porosity within these ranges. Future studies examining substrate mixes and seedling growth in air root-pruning systems should measure easily available water, water buffering capacity and unsaturated hydraulic conductivity (Fields et al. 2017).

Starr et al. (2012) found that tree seedling performance (above and below-ground dry weight) of baldcypress (*Taxodium distichum* (L.) Rich.), Chinese pistache (*Pistacia chinensis* Bunge) and silver maple (*Acer saccharinum* L.) was decreased due to greater incorporation of wood chips that contained larger particle sizes and decreased container capacity. This was linked to water stress vulnerability. Nkongolo and Caron (1999) found that 1-yr-old white spruce (*P. glauca*) seedlings experienced increased growth in a peat-based substrate amended with fine particles [<1.3 mm (0.05 in)] compared to the substrate without fine particles. The screen sizes used and the amount of time screened, along with the grinding levels of husk will largely determine the particle size distribution, which goes on to influence physical properties (Evans et al. 1996). Particle size distribution is critically important for the performance of tree seedlings particularly in early stage root development as demonstrated by this study; therefore, addition of coir to substrates requires screening for evenness and particle size should be kept less than 0.5 mm (0.02 in) (Noguera et al. 2003). Based on particle size distribution analysis, the added coir dust was likely composed substantially of particles larger than 0.5 mm (0.02 in), although this was not directly measured (Figs. 1 & 2).

Nutrient immobilization could have played a role in reduced seedling growth, and in the lower chlorophyll content observed in quaking aspen and, earlier in the season, in red maple seedlings in the 15 and 20% coir mixes. Average chlorophyll content in the quaking aspen seedlings at the end of the growing season in the peat-

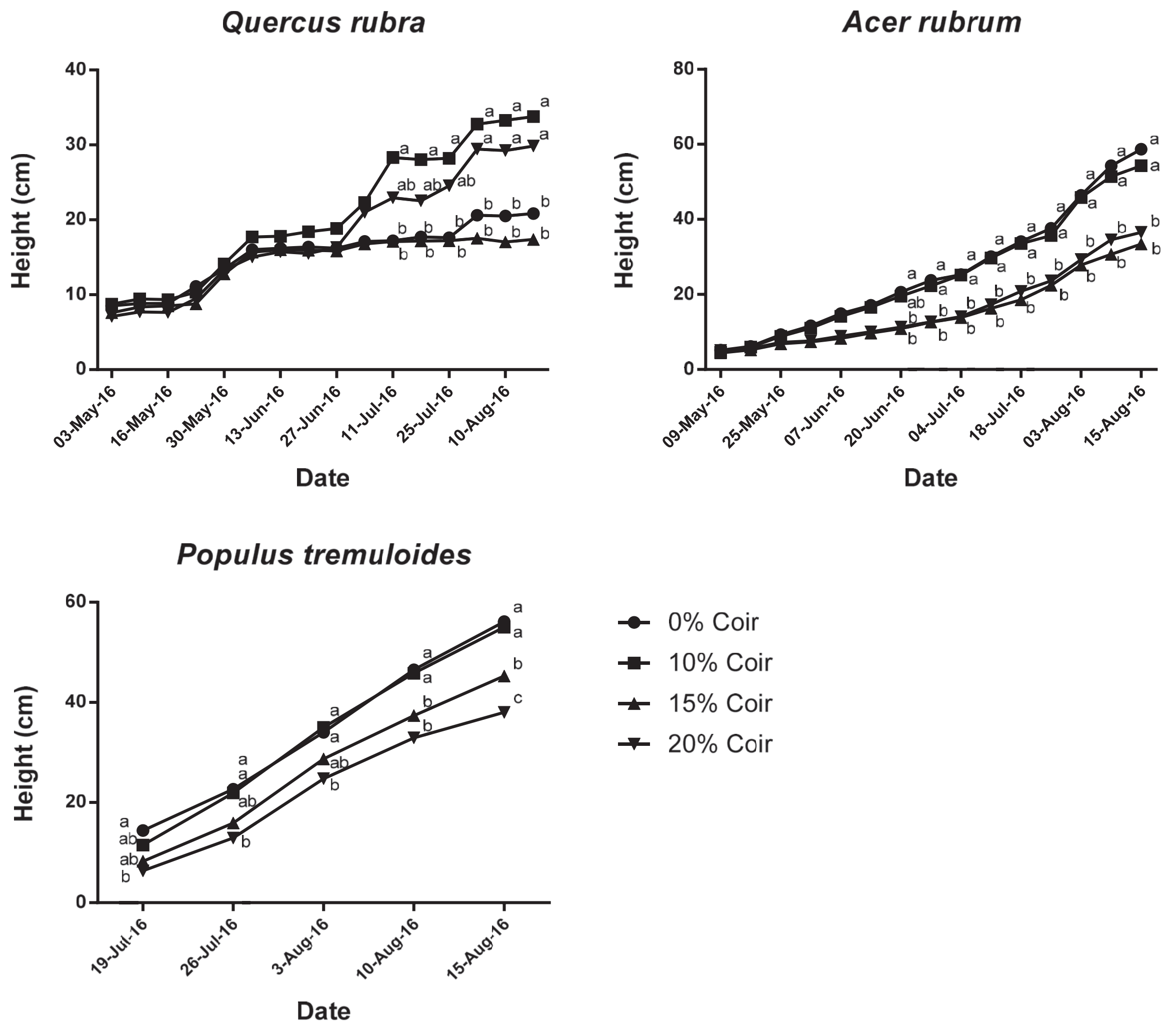

Fig. 7. Mean height of red oak (n=9), red maple (n=11) and quaking aspen (n=6) seedlings throughout the growing season. Different letters indicate a significant difference ($p < 0.05$) by two-way ANOVA.

perlite substrate was 34.8 SPAD units, compared to 32.7, 28.2 and 27.9 SPAD units for the 10, 15 and 20% coir mixes, respectively (Fig. 6). Both Cresswell (1992) and Handreck (1993) observed greater immobilization of soluble nitrogen occurring in coir dust compared to peat media. Arenas et al. (2002) found that tomato (*Lycopersicum esculentum* Mill.) transplants grew smaller in coir-based media than plants grown in peat-based media, which the authors suggested had to do with high N immobilization associated with micro-organisms and a higher C:N ratio in coir. Rose and Haase (2000) observed poorer growth of Douglas fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco.) seedlings grown in coir mixes compared to a control peat mix. Seedlings grown in coir mixes also had lower foliar N, Ca and Mn concentrations and coir mixes possessed lower cation exchange capacity (CEC), which could have contributed to greater leaching (Rose and Haase 2000).

Nutrient immobilization primarily of nitrogen and to a lesser extent, phosphate, by microorganisms that consume nutrients while decomposing organic carbon compounds can also be a concern with organic substrate components (Barrett et al. 2016). Due to the anaerobic and acidic conditions in peatlands, microbial populations tend to be low in peat. In contrast, coir-based substrates have been reported to possess as many as two orders of magnitude more microorganisms than peat (Carlile et al. 2015). Immobilization rates can also be influenced by climatic factors and moisture levels, in addition to the composition of different substrates (Barrett et al. 2016). Because watering and fertilization levels were consistent across substrate treatments, and trays were re-randomized throughout the growing season to account for microclimatic effects, different coir levels may have had an influence on nutrient immobilization. Foliar tissue analysis at the end of the growing season, however, did not indicate nutrient deficiencies in the 15 or 20% coir mixes compared to the peat-perlite and 10% coir mixes (Table 4). Repeated tissue testing in a future experiment is recommended to better understand potential nutrient immobilization in coir mixes during the early stages of tree growth in propagation, as well as measurement of CEC. As others have pointed to the higher C:N ratio in coir mixes (Rose and Haase 2000), and in other high C:N ratio materials such as wood chips

Table 4. **Foliar nutrient analysis at the end of the growing season.**

Substrate	Species	(%) N	Ca	P	K	Mg	S	(ppm) Cu	Mn	Zn	Fe	B
Peat-perlite mix	***A. rubrum***	1.84	1.34	0.21	0.87	0.52	0.17	6.25	54.06	30.38	42.18	36.07
10% coir mix		1.89	1.27	0.19	0.91	0.41	0.16	6.38	35.12	28.81	52.23	28.06
15% coir mix		2.23	1.55	0.29	1.22	0.44	0.24	7.95	85.41	32.27	61.28	31.37
20% coir mix		1.94	1.43	0.23	1.17	0.49	0.22	6.21	57.22	35.07	46.87	36.07
Peat-perlite mix	***Q. rubra***	2.28	1.29	0.23	0.75	0.57	0.15	7.17	91.99	41.62	61.93	44.47
10% coir mix		1.98	1.22	0.19	0.82	0.39	0.15	6.67	87.74	33.33	64.39	43.77
15% coir mix		2.26	1.41	0.20	0.82	0.42	0.17	7.87	96.10	40.00	66.73	49.93
20% coir mix		2.01	1.26	0.20	0.78	0.47	0.14	6.48	81.65	36.52	68.71	46.77
Peat-perlite mix	***P. tremuloides***	2.47	1.39	0.28	1.62	0.69	0.38	10.07	78.20	47.43	56.99	24.51
10% coir mix		2.76	1.45	0.30	1.78	0.60	0.35	12.9	40.71	68.49	60.33	28.50
15% coir mix		2.26	1.40	0.27	1.60	0.56	0.32	9.95	53.92	57.58	52.04	23.55
20% coir mix		2.74	1.32	0.31	2.15	0.51	0.39	11.21	49.56	50.36	59.57	19.70

and saw dust (Jackson 2008, Sax and Scharenbroch, 2017), use of coir mixes for tree seedling production may require increased fertilizer use to compensate for nitrogen immobilization.

Based on growth measurements of seedlings and physical and chemical analyses of substrates, coir dust added in percentages greater than 10% would currently not be recommended for tree seedling propagation in air-pruning systems. The differences in physical and chemical properties of coir dust likely contributed to reduced tree seedling above-ground and below-ground growth of red maple, quaking aspen and eastern white cedar. Further evaluation is required for propagating tree seedlings above this range to understand if adding in finer coir particles can improve above and below-ground seedling growth.

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