Stem Cutting Propagation in Whole Pine Tree Substrates

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Summary. **Wood-based substrates have been extensively evaluated for greenhouse and nursery crop production, yet these substrates have not been evaluated for propagation. The objective of this study was to evaluate processed whole loblolly pine trees (WPT) (*Pinus taeda*) as a rooting substrate for stem cutting propagation of a range of ornamental crops. Substrates included processed WPT, pine (*Pinus* sp.) bark (PB), and each mixed with equal parts (by volume) peatmoss (PM) (WPT:PM and PB:PM, respectively). Substrate physical (air space, container capacity, total porosity, bulk density, and particle size distribution) and chemical [pH and electrical conductivity (EC)] properties were determined for all substrates. Rooting percentage, total root length, total root volume, and total shoot length were evaluated for four species in 2008 and five species in 2009. Substrate air space was similar between PB and WPT in the 2008 experiment, and likewise between PB:PM and WPT:PM. In the 2009 experiment, PB and WPT had similar substrate air space. The addition of PM to PB and WPT resulted in reduced air space and increased container capacity in both experiments. The proportion of fine particles doubled for PB:PM and WPT:PM compared with PB and WPT, respectively. Substrate pH for all substrates ranged from 6.0 to 6.9 at 7 days after sticking (DAS) cuttings and 6.9 to 7.1 at 79 DAS. Substrate EC was below the acceptable range for all substrates except at 7 DAS. Rooting percentage was similar among substrates within each species in both experiments. The addition of PM resulted in significantly greater total root length for PB:PM and WPT:PM compared with PB and WPT, respectively, for five of the eight species. Shoot growth was most vigorous for PB:PM compared with the other substrates for all species. The study demonstrated a range of plant species can be propagated from stem cuttings in whole pine tree substrates alone or combined with PM.**

Cutting propagation is the most widely used method for cloning nursery and floriculture crops. Some of the factors that affect successful cutting propagation include stock plant quality, timing of propagation, propagation environment, container size, rooting substrate, and auxin treatment. A proper balance of air space and container capacity are critical for healthy root development, so the combined effects of propagation environment (mist application volume and frequency) and container size must be well understood when selecting a propagation substrate (Threadgill et al., 1985).

Sphagnum PM, PB, perlite, and vermiculite are commonly used as substrates for propagation, either individually or in combination at various proportions. The high transportation costs and variable annual harvest of Canadian PM have negatively impacted greenhouse crop producers in the United States (Fain et al., 2008; Harrison, 2011). Before the housing market decline of the late 2000s, nursery crop producers experienced a reduction in PB supplies and a rise in cost due to both PB's use as boiler fuel and a decline in the timber market (Lu et al., 2006). Although PB supplies have rebounded in recent years, the long-term availability of PB will remain a concern. Although many alternative substrates have been used to produce quality container-grown crops, it has not been determined if such substrates are suitable for propagation. Ideally, an alternative substrate component should be cost effective, sustainable, and regionally available.

Alternative substrates should be evaluated within a propagation environment before extensive use. Offord et al. (1998) demonstrated coconut coir was a suitable alternative to PM for propagation of sydney bush pea (*Pultenaea parviflora*). Shah et al. (2006) reported silt and sawdust as acceptable substrates for long-leaf fig (*Ficus binnendijkii* 'Amstel Queen') cutting propagation, yet a traditional substrate was not included for comparison. Composts derived from a variety of materials have also been used for cutting propagation. Cuttings of three foliage plant species had similar root development in composts mixed with PM or PB and in a standard substrate (Chen et al., 2003). Chong (1999) noted composted municipal waste blended with perlite was a satisfactory substrate for cutting propagation of several woody plant species.

Wood-based substrates have been identified as acceptable supplements

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
16.3871	inch^3	cm^3	0.0610
0.5933	lb/yard^3	kg·m^{-3}	1.6856
1	mmho/cm	dS·m^{-1}	1
1.7300	oz/inch^3	g·cm^{-3}	0.5780
1	ppm	mg·L^{-1}	1
0.7646	yard^3	m^3	1.3080
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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or replacements for PM and PB in crop production. Wood-based materials derived from pine trees are readily available throughout the southeastern United States and include clean chip residual (bark, limbs, and needles), processed whole pine trees (wood, bark, limbs, and needles), and chipped pine logs (wood and bark). These substrates have been extensively evaluated for greenhouse and nursery crop production (Boyer et al., 2008; Fain et al., 2008; Jackson et al., 2009; Wright and Browder, 2005). Although crops grown in these substrates commonly required additional fertilizer when compared with those grown in traditional substrates (Fain et al., 2008; Jackson et al., 2008; Wright et al., 2008), nutrient and water availability issues can be readily managed during crop production.

The suitability of loblolly pine wood-based substrates for cutting propagation has not been investigated. Demonstrating the versatility of these substrates is essential to expanding their commercial availability and use. The objective of the current experiments was to evaluate processed whole pine tree as a rooting substrate for stem cutting propagation of ornamental crops.

Materials and methods

Root development of stem cuttings in four substrates was evaluated in two experiments conducted in 2008 and 2009 at the U.S. Department of Agriculture Thad Cochran Southern Horticultural Laboratory in Poplarville, MS (lat. 30°50′12.6″N, long. 89°32′45.3″W). The substrates included processed WPT, PB, and each mixed with equal parts PM by volume to produce two additional substrates (WPT:PM and PB:PM). In the 2008 experiment, WPT was produced from 12-year-old loblolly pine trees harvested, then processed with a portable heavy-duty horizontal grinder with 4-inch screens (Peterson 4700B; Peterson Pacific Corp., Eugene, OR) in Jan. 2007 and the resulting material was stored outside in full sun. In Apr. 2007, the material was further processed through a hammer mill (No. 30; C.S. Bell, Tiffin, OH) fitted with a 3/16-inch screen and stored in 2.4-yard^3 polypropylene bulk bags placed under a canopy. In the 2009 experiment, WPT was produced from 7.8- to 9.8-inch (diameter

Table 1. Plant type, cutting date, rooting period, cutting description, auxin treatment, and stock plant type/location for eight plant species used in two rooting experiments (2008 and 2009).

Species	Plant type	Cutting date	Rooting period (d)	Cutting description^z	Auxin treatment^y	Stock plant type/location^x
Chrysanthemum	Herbaceous perennial	22 Jan. 2008	52	Terminal	1000 ppm IBA	Yoder Brothers, Barberton, OH
Texas privet	Large shrub	11 Feb. 2008	90	Subterminal; semihardwood; 2.25–3.5 inches	1000 ppm IBA	Landscape planting; MSU, Poplarville, MS
Mexican bush sage	Herbaceous perennial	11 Mar. 2008	49	Subterminal	1000 ppm IBA	Landscape planting in Rancho Cucamonga, CA
Leyland cypress	Large shrub	14 Feb. 2008	138	Subterminal; 4.25 inches; brown wood of previous year's growth	1000 ppm IBA	Avery Christmas Tree Farm, Purvis, MS
Wintercreeper	Evergreen groundcover	24 Apr. 2009	81	Subterminal; 2 inches	1000 ppm IBA	Container plants; MSU greenhouse, Poplarville, MS
Evolvulus	Herbaceous perennial	24 Apr. 2009	66	Subterminal; three node	1000 ppm IBA	Container plants; MSU greenhouse, Poplarville, MS
Persicaria	Herbaceous perennial	1 May 2009	33	Subterminal; single node	none	Container plants; MSU greenhouse, Poplarville, MS
Rose	Ground cover/climbing rose	17 Apr. 2009	60	Subterminal; single node	1000 ppm IBA	Container plants; MSU shade house, Poplarville, MS
Mexican bush sage	Herbaceous perennial	14 May 2009	40	Subterminal	1000 ppm IBA	Container plants; USDA greenhouse, Poplarville, MS

[z] 1 inch = 2.54 cm.

[y] 1-s basal quick-dip indole-3-butyric acid (Dip′N Grow Lite; Dip′N Grow, Clackamas, OR); 1 ppm = 1 mg·L^{-1}.

[x] MSU = Mississippi State University South Mississippi Branch Experiment Station, USDA = U.S. Department of Agriculture.

at breast height) loblolly pine trees harvested in Macon County, AL, and chipped (model 334 Biomass Chipper; Woodsman, Farwell, MI) on 19 Jan. 2009. Chips were ground with a hammer mill (Meteor Mill #40; Williams Patent Crusher and Pulverizer Co., St. Louis, MO) to pass a 3/8-inch screen. A small-scale hammer mill was used to process WPT in the 2008 experiment, but the authors had access to an industrial-scale hammer mill to process WPT in the 2009 experiment. Although the industrial hammer mill was fitted with a larger screen size, the higher velocity and greater capacity resulted in a material with physical properties comparable to material processed with a smaller hammer mill and screen size.

In both experiments, each substrate was amended with 4 lb/yard^3 16N–2.6P–10K (5-month formulation plus micronutrients; Harrell's, Sylacauga, AL) and 5 lb/yard^3 dolomitic limestone. Individual 6.6-cm^2 (232 mL volume) plastic containers (SVD-250; T.O. Plastics, Clearwater, MN) were filled with substrate, completely randomized in six carry trays (SPT-250-32-PF, T.O. Plastics), and placed under a greenhouse mist system 24 to 48 h before use to thoroughly moisten substrates.

The plant species used in the two experiments were chosen based on accessibility and to represent a range of plant types and rooting difficulty. In the 2008 experiment, species used were chrysanthemum (*Chrysanthemum ×morifolium* 'Dazzling Stacy'), leyland cypress [*Cupressus ×leylandii* (synonym × *Cupressocyparis leylandii*) 'Murray'], texas privet *(Ligustrum japonicum* 'Texanum'), and mexican bush sage (*Salvia leucantha*). In the 2009 experiment, species used were wintercreeper (*Euonymus fortunei* 'Kewensis'), evolvulus (*Evolvulus glomeratus* 'Blue Daze'), persicaria [*Polygonum microcephalum* (synonym *Persicaria microcephala*) 'Red Dragon'], rose (*Rosa* 'Red Cascade'), and mexican bush sage (*Salvia leucantha*).

Stem cuttings from individual plant species were prepared (Table 1), all species (except persicaria) received a 1-s basal quick-dip in a 1000 ppm indole-3-butyric acid solution (Dip'N Grow Lite; Dip'N Grow, Clackamas, OR), and a single cutting was inserted into each container for a total of 192 experimental units per species. Intermittent mist was maintained for all species at 8 s every 15 min from 8:00 AM to 6:00 PM (2008 experiment) and at 5 s every 15 min from 7:00 AM to 6:00 PM (2009 experiment). Pin-Perfect nozzles (Dramm Corp., Manitowoc, WI) were used in the 2008 experiment and mister nozzles (809 Series; Ein-Dor Co., Yavne, Israel) were used in the 2009 experiment. In the 2008 experiment, average monthly greenhouse temperature was 20 °C (February), 20 °C (March), 20 °C (April), 22 °C (May), and 25 °C (June). In the 2009 experiment, average monthly greenhouse temperature was 22 °C (April), 22 °C (May), 24 °C (June), and 27 °C (July). Day length ranged from 11 to 13.8 h in 2008 and 13 to 14.1 h in 2009.

Rooting periods varied by species, but all cuttings within a species were harvested at the same time (Table 1). Upon harvest, roots (if present) were washed and digitally scanned for analysis (total root length and total root volume) using WinRhizo software (version 2007d; Regent Instruments, Sainte-Foy, QC, Canada). New shoot growth (if present) was recorded as total shoot length. In the 2009 experiment, substrate solution was extracted from fallow containers (n = 4) at 7, 29, 52, and 79 DAS the cuttings via the pour-through method (Wright, 1986). Substrate solution pH and EC were analyzed using a multiparameter meter (Accumet Excel

Table 2. Physical properties of pine bark and whole pine tree substrates in a 2008 cutting propagation experiment.[z]

Substrate	Air space (% vol)	Container capacity (% vol)	Total porosity (% vol)	Bulk density (g·cm^{-3})[y]
Pine bark	35.5 a[x]	52.0 b	87.3 a	0.292 a
1 Pine bark:1 peatmoss	16.3 b	66.6 a	82.9 b	0.264 b
Whole pine tree[w]	31.0 a	51.7 b	82.7 b	0.184 c
1 Whole pine tree:1 peatmoss	16.5 b	64.8 a	81.3 b	0.219 d
Pine bark vs. whole pine tree[v]	0.1067	0.214	0.0168	<0.0001
Peat vs. none[u]	<0.0001	<0.0001	0.0238	0.6703

[z] Data presented as means (n = 3) and obtained using the North Carolina State University porometer method (Fonteno et al., 1995).

[y] 1 g·cm^{-3} = 0.5780 oz/inch^3.

[x] Means followed by different letters within columns indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

[w] 12-year-old whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.47-cm screen; 1 cm = 0.3937 inch.

[v] Tested differences between substrates containing pine bark and substrates containing whole pine tree; $P < 0.05$.

[u] Tested differences between substrates amended with peatmoss (peat) and substrates with no peatmoss (none); $P < 0.05$.

Table 3. Physical properties of pine bark and whole pine tree substrates in a 2009 cutting propagation experiment.[z]

Substrate	Air space (% vol)	Container capacity (% vol)	Total porosity (% vol)	Bulk density (g·cm^{-3})[y]
Pine bark	24.0 b[x]	53.9 b	77.9 b	0.312 a
1 Pine bark:1 peatmoss	17.7 c	58.0 ab	75.7 b	0.248 b
Whole pine tree[w]	31.7 a	55.5 b	87.1 a	0.163 c
1 Whole pine tree:1 peatmoss	22.6 b	60.5 a	83.1 a	0.190 d
Pine bark vs. whole pine tree[v]	<0.0001	0.1437	<0.0001	<0.0001
Peat vs. none[u]	<0.0001	0.006	0.0182	0.0235

[z] Data presented as means (n = 3) and obtained using the North Carolina State University porometer method (Fonteno et al., 1995).

[y] 1 g·cm^{-3} = 0.5780 oz/inch^3.

[x] Means followed by different letters within columns indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

[w] 20- to 25-cm diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen; 1 cm = 0.3937 inch.

[v] Tested differences between substrates containing pine bark and substrates containing whole pine tree; $P < 0.05$.

[u] Tested differences between substrates amended with peatmoss (peat) and substrates with no peatmoss (none); $P < 0.05$.

XL50; Fisher Scientific, Pittsburgh, PA). Substrate air space, container capacity, total porosity, and bulk density were determined ($n = 3$) using the North Carolina State University porometer method (Fonteno et al., 1995). Substrate particle size distribution (PSD) was determined by passing 500-mL air-dried substrate samples ($n = 3$) through 11 sieves (9.5 to 0.05 mm). Sieves were shaken for 3 min with a sieve shaker [278 oscillations/min, 159 taps/min (Ro-Tap RX-29; W.S. Tyler, Mentor, OH)]. Particles collected on each sieve and in the pan (<0.05 mm) were weighed and grouped into three texture classes [coarse (>2.0 mm), medium (2.0 to 0.5 mm), and fine (<0.5 mm)].

Assumptions of normality and common variance were tested (except for rooting percentage) using the GLM and UNIVARIATE procedures of SAS (version 9.3; SAS Institute, Cary, NC). Rooting percentage data were analyzed using the MULTTEST procedure of SAS, with differences between treatment means determined using Fisher's exact test with a permutation adjustment for multiple comparisons ($P < 0.05$). Total root length, total root volume, total shoot length, porometer data, PSD data, pH, and EC were analyzed with linear models using the GLIMMIX procedure of SAS. Differences between treatment means were determined using the Shaffer-Simulated method ($P < 0.05$). Linear contrasts were used to test differences between means for PM-amended substrates (included PB:PM and WPT:PM) and the non-PM-amended substrates (included PB and WPT), and differences between means for whole pine tree substrates (included WPT and WPT:PM) and PB substrates (included PB and PB:PM).

Results and discussion

Substrate air space ranged from 16.3% (PB:PM) to 35.5% (PB) in the 2008 experiment (Table 2), and from 17.7% (PB:PM) to 31.7% (WPT) in the 2009 experiment (Table 3). Substrate air space was similar between PB and WPT in the 2008 experiment, and likewise between PB:PM and WPT:PM. In the 2009 experiment, PB and WPT had similar substrate air space. Substrate container capacity ranged from 51.8% to 66.6% (2008 experiment) and 53.9% to 60.5% (2009 experiment).

The addition of PM to PB and WPT resulted in reduced air space and increased container capacity in both experiments. Substrate air space was significantly lower in PB:PM and WPT:PM compared with PB and WPT, respectively, in both experiments. In the 2008 experiment,

Table 4. Particle size distribution (PSD) of pine bark and whole pine tree substrates in a 2008 cutting propagation experiment.[z]

	Substrate			
	Pine bark	1 Pine bark:1 peatmoss (v:v)	Whole pine tree[x]	1 Whole pine tree:1 peatmoss (v:v)
Sieve opening (mm)[y]	PSD (%)			
6.3	10.1	6.1	0.1	0.0
3.4	29.7	15.4	8.6	5.4
2.4	17.3	9.4	21.4	13.0
2.0	6.6	3.9	10.2	6.0
1.4	11.3	10.0	16.3	10.7
1.0	6.1	9.1	10.3	8.0
0.5	7.3	18.3	13.3	16.0
0.25	7.3	17.1	9.9	16.0
0.106	3.0	7.9	7.5	17.2
0.053	0.6	1.9	1.8	5.9
Pan	0.6	0.9	0.6	1.7
Texture class[w]				
Coarse	63.8 a[v]	34.9 c	40.2 b	24.4 d
Medium	24.8 d	37.4 b	40.0 a	34.8 c
Fine	11.5 d	27.8 b	19.8 c	40.9 a

[z] Data presented as means ($n = 3$) of percent of particles collected on sieves and in pan.

[y] 1 mm = 0.0394 inch.

[x] 12-year-old whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.47-cm screen; 1 cm = 0.3937 inch.

[w] Texture classes: coarse (>2.0 mm), medium (2.0–0.5 mm), and fine (<0.5 mm).

[v] Means followed by different letters within rows indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

Table 5. Particle size distribution (PSD) of pine bark and whole pine tree substrates in a 2009 cutting propagation experiment.[z]

	Substrate			
	Pine bark	1 Pine bark:1 peatmoss (v:v)	Whole pine tree[x]	1 Whole pine tree:1 peatmoss (v:v)
Sieve opening (mm)[y]	PSD (%)			
6.3	20.4	16.7	0.0	2.2
3.4	17.9	15.1	1.7	5.2
2.4	10.1	7.7	9.1	7.0
2.0	3.8	2.7	8.8	5.1
1.4	9.9	7.6	24.4	15.3
1.0	8.1	6.6	17.7	11.5
0.5	14.3	14.5	21.1	18.5
0.25	8.6	12.9	11.3	15.9
0.106	4.6	11.3	4.9	14.0
0.053	1.4	3.5	0.8	4.1
Pan	0.9	1.5	0.2	1.3
Texture class[w]				
Coarse	52.2 a[v]	42.1 b	19.6 c	19.5 c
Medium	32.2 c	28.7 d	63.2 a	45.3 b
Fine	15.5 d	29.2 b	17.2 c	35.2 a

[z] Data presented as means ($n = 3$) of percent of particles collected on sieves and in pan.

[y] 1 mm = 0.0394 inch.

[x] 20- to 25-cm diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen; 1 cm = 0.3937 inch.

[w] Texture classes: coarse (>2.0 mm), medium (2.0–0.5 mm), and fine (<0.5 mm).

[v] Means followed by different letters within rows indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

substrate container capacity was significantly greater in PB:PM and WPT:PM compared with PB and WPT, respectively. Total porosity was greatest in PB compared with the other substrates in the 2008 experiment, but similar between PB and PB:PM and between WPT and WPT:PM in the 2009 experiment. Bulk density decreased with the addition of PM to PB, but increased with the addition of PM to WPT in both experiments. Peatmoss has high water retention properties and is routinely used to enhance the container capacity of substrates used for crop production (Robbins and Evans, 2005).

Substrate air space between 15% and 40% is recommended for adequate aeration during propagation, whereas substrate container capacity between 20% and 60% is recommended for adequate water retention. Also, 0.3 to 0.8 g·cm^{-3} bulk density is recommended for propagation substrates (Hartmann et al., 2002; Threadgill et al., 1985). Substrate air space was within the recommended range for substrates used in both experiments, whereas substrate container capacity was slightly greater than the recommended range for PB:PM and WPT:PM in the 2008 experiment.

Pine bark substrate had the lowest proportion of fine particles followed by WPT, PB:PM, and WPT:PM in both experiments (Tables 4 and 5). The proportion of fine particles doubled for PB:PM and WPT:PM compared with PB and WPT, respectively. It has been reported that substrate particles less than 0.5 mm can have a significant effect on substrate air space and container capacity (Jackson et al., 2010; Owen and Altland, 2008). The greater proportion of fine particles most likely resulted in the greater substrate container capacity and lower substrate air space of the substrates amended with PM.

Rooting percentage was similar among substrates within each species in both experiments (Table 6). Rooting percentage was 90% or greater for all species except texas privet. The high rooting success is an indication that substrate did not have a significant effect on root initiation or rooting percentage in either experiment. Root development response to substrate varied by species in both experiments. Root development in WPT was less vigorous compared with the other substrates, yet the differences were not always significant. Total root length (Table 7) and total root volume

Table 6. Mean rooting percentage of cuttings from eight species rooted in pine bark and whole pine tree substrates.

	Substrate			
	Pine bark	1 Pine bark:1 peatmoss (v:v)	Whole pine tree[z]	1 Whole pine tree:1 peatmoss (v:v)
Species	Rooting (%)			
2008 experiment				
Chrysanthemum	100 a[y]	100 a	100 a	100 a
Leyland cypress	94 a	96 a	90 a	96 a
Texas privet	88 a	83 a	75 a	75 a
Mexican bush sage	100 a	100 a	100 a	100 a
2009 experiment				
Wintercreeper	100 a	100 a	100 a	100 a
Evolvulus	100 a	100 a	94 a	94 a
Persicaria	100 a	100 a	100 a	100 a
Rose	94 a	98 a	94 a	100 a
Mexican bush sage	100 a	100 a	100 a	100 a

[z] 12-year-old whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.47-cm screen (2008 experiment); 20- to 25-cm-diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen (2009 experiment); 1 cm = 0.3937 inch.

[y] Means followed by different letters within rows indicate significant difference at $P < 0.05$ using Fisher's exact test with a permutation adjustment for multiple comparisons.

Table 7. Mean total root length of cuttings from eight species rooted in pine bark and whole pine tree substrates.

	Substrate					
	Pine bark	1 Pine bark:1 peatmoss (v:v)	Whole pine tree[z]	1 Whole pine tree: 1 peatmoss (v:v)	Pine bark vs. whole pine tree[y]	Peat vs. none[x]
Species	Total root length (cm)					
2008 experiment						
Chrysanthemum	1353 b[w]	1481 a	1046 c	1051 c	<0.0001	0.0635
Leyland cypress	570 a	379 b	249 c	295 c	<0.0001	0.0144
Texas privet	474 a	485 a	277 b	330 b	<0.0001	0.3616
Mexican bush sage	990 a	1036 a	623 c	790 b	<0.0001	0.0011
2009 experiment						
Wintercreeper	165 b	226 a	111 c	165 b	<0.0001	<0.0001
Evolvulus	752 b	1173 a	462 c	907 b	<0.0001	<0.0001
Persicaria	1055 b	1469 a	916 b	1431 a	0.0608	<0.0001
Rose	236 c	647 a	91 d	398 b	<0.0001	<0.0001
Mexican bush sage	801 a	793 a	632 a	738 a	0.0231	0.3179

[z] 12-year-old whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.47-cm screen (2008 experiment); 20- to 25-cm diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen (2009 experiment); 1 cm = 0.3937 inch.

[y] Probability values for tests of differences between substrates containing pine bark and substrates containing whole pine tree.

[x] Probability values for tests of differences between substrates amended with peatmoss (peat) and substrates with no peatmoss (none).

[w] Means followed by different letters within rows indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

(Table 8) were similar in WPT and PB for persicaria, whereas total root length was similar among all substrates for mexican bush sage in the 2009 experiment. Total root length and total root volume was similar between PB and WPT:PM for wintercreeper and evolvulus. Maximum total root length was observed in PB:PM for all species except leyland cypress and mexican bush sage (2009 experiment). In most cases, results for total root length mirrored the results for total root volume within a species.

The addition of PM resulted in significantly greater total root length for PB:PM compared with PB for chrysanthemum, wintercreeper, evolvulus, persicaria, and rose. The increased total root length between PB and PB:PM ranged from 9% (chrysanthemum) to 174% (rose). Similarly, significantly greater total root length in WPT:PM compared with WPT occurred for mexican bush sage (2008 experiment), wintercreeper, evolvulus, persicaria, and rose. The increase in total root length using WPT:PM compared with WPT ranged from 26% (mexican bush sage—2008 experiment) to 337% (rose).

Shoot growth was most vigorous for PB:PM compared with the other substrates for all species (Table 9). A positive response for total shoot length was observed in PB:PM and WPT:PM, compared with PB and WPT, respectively.

Peatmoss has a greater water-holding capacity and lower aeration compared with PB and wood-based substrates (Raviv and Lieth, 2008).

Table 8. Mean total root volume of cuttings from eight species rooted in pine bark and whole pine tree substrates.

Species	Substrate				Pine bark vs. whole pine tree[y]	Peat vs. none[x]
	Pine bark	1 Pine bark:1 peatmoss (v:v)	Whole pine tree[z]	1 Whole pine tree: 1 peatmoss (v:v)		
	Total root vol (cm^3)[w]					
2008 experiment						
Chrysanthemum	2.16 a[v]	2.36 a	1.81 b	1.9 b	<0.0001	0.0411
Leyland cypress	1.75 a	1.20 b	0.79 c	0.94 c	<0.0001	0.025
Texas privet	3.41 a	3.24 a	2.18 b	2.31 b	<0.0001	0.947
Mexican bush sage	2.00 a	2.01 a	1.38 b	1.66 ab	<0.0001	0.2115
2009 experiment						
Wintercreeper	0.21 b	0.28 a	0.15 c	0.22 b	<0.0001	<0.0001
Evolvulus	1.12 b	1.80 a	0.69 c	1.35 b	0.0003	<0.0001
Persicaria	0.56 b	0.85 a	0.53 b	0.96 a	0.3499	<0.0001
Rose	0.31 c	0.84 a	0.15 d	0.54 b	<0.0001	<0.0001
Mexican bush sage	1.28 a	1.33 a	0.87 b	1.16 ab	0.0059	0.0988

[z] 12-year-old whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.47-cm screen (2008 experiment); 20- to 25-cm diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen (2009 experiment); 1 cm = 0.3937 inch.
[y] Probability values for tests of differences between substrates containing pine bark and substrates containing whole pine tree.
[x] Probability values for tests of differences between substrates amended with peatmoss (Peat) and substrates with no peatmoss (none).
[w] 1 cm^3 = 0.0610 $inch^3$.
[v] Means followed by different letters within rows indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

Table 9. Mean total shoot length of cuttings from eight species rooted in pine bark and whole pine tree substrates.

Species	Substrate				Pine bark vs. whole pine tree[y]	Peat vs. none[x]
	Pine bark	1 Pine bark:1 peatmoss (v:v)	Whole pine tree[z]	1 Whole pine tree: 1 peatmoss (v:v)		
	Total shoot length (cm)					
2008 experiment						
Chrysanthemum	NA	NA	NA	NA	NA	NA
Leyland cypress	NA	NA	NA	NA	NA	NA
Texas privet	NA	NA	NA	NA	NA	NA
Mexican bush sage	30.9 b[w]	37.1 a	23.7 c	31.6 b	<0.0001	<0.0001
2009 experiment						
Wintercreeper	NA	NA	NA	NA	NA	NA
Evolvulus	18.3 b	30.0 a	10.5 c	26.6 a	0.0016	<0.0001
Persicaria	16.9 b	31.0 a	13.2 b	26.3 a	0.01	<0.0001
Rose	6.0 b	11.7 a	3.3 b	7.0 b	0.0024	0.0001
Mexican bush sage	15.3 a	15.5 a	11.6 b	14.8 a	0.0036	0.0223

[z] 12-year-old whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.47-cm screen (2008 experiment); 20- to 25-cm diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen (2009 experiment); 1 cm = 0.3937 inch.
[y] Probability values for tests of differences between substrates containing pine bark and substrates containing whole pine tree.
[x] Probability values for tests of differences between substrates amended with peatmoss (peat) and substrates with no peatmoss (none).
[w] Means followed by different letters within rows indicate significant difference at $P < 0.05$ using the Shaffer-simulated method.

Table 10. Substrate pH and electrical conductivity (EC) of pine bark and whole pine tree substrates in fallow containers at 7, 29, 52, and 79 d after sticking cuttings (DAS) in a 2009 cutting propagation experiment.

	7 DAS		29 DAS		52 DAS		79 DAS	
Substrate	pH	EC ($dS·m^{-1}$)[z]	pH	EC ($dS·m^{-1}$)	pH	EC ($dS·m^{-1}$)	pH	EC ($dS·m^{-1}$)
Pine bark	6.9 a[y]	0.47 a	7.2 a	0.19 a	7.1 a	0.21 a	7.1 a	0.15 ab
1 Pine bark:1 peatmoss	6.1 c	0.81 a	7.1 b	0.20 a	6.9 ab	0.18 a	7.1 a	0.12 b
Whole pine tree[x]	6.4 b	0.91 a	7.2 a	0.18 a	7.1 a	0.23 a	7.0 a	0.17 a
1 Whole pine tree:1 peatmoss	6.0 c	0.84 a	7.0 b	0.16 a	6.7 b	0.18 a	6.9 a	0.13 b

[z] 1 $dS·m^{-1}$ = 1 mmho/cm.

[y] Means followed by different letters within columns indicate significant difference at $P < 0.05$ ($n = 4$) using the Shaffer-simulated method.

[x] 20- to 25-cm diameter whole loblolly pine trees harvested, chipped, and hammermilled to pass a 0.95-cm screen; 1 cm = 0.3937 inch.

Therefore, greater substrate container capacity and lower substrate air space was expected for PB:PM and WPT:PM. High rooting percentages and subsequent root development was an indication that sufficient water content and adequate aeration was present in all substrates and maintained within the propagation system used for these experiments.

Disparities in root development among substrates are rarely attributed to differences in physical properties, unless extreme values are observed. Typically, low substrate air space (<10%) and high substrate container capacity (>60%) are considered undesirable for cutting propagation due to low oxygen content (Chen et al., 2003). Substrate air space above the recommended values, or a high proportion of coarse particles, may provide inadequate moisture or hinder contact between roots and substrate particles, but such conditions have not been widely reported for cutting propagation.

In the 2008 experiment, root development was superior in PB:PM compared with WPT:PM, despite similar substrate air space. In the 2009 experiment, root development was similar (for most species) in PB and WPT:PM corresponding to similarities in substrate air space. As a result, differences in root development cannot be attributed solely to substrate air space. Although substrate nutrient content is not a critical factor during root initiation, newly developed roots require an external source of nutrients for continued growth. Substrate cation exchange capacity refers to how effectively mineral nutrients (cations specifically) are bound to the substrate particles. Peatmoss and aged PB have a greater cation exchange capacity compared with wood-based substrates (Jackson et al., 2010; Raviv and Lieth, 2008). Nitrogen immobilization is another issue associated with wood-based substrates. Less nitrogen is available for plant absorption due to high microbial activity when comparing alternative substrates and PB with PM (Boyer et al., 2012).

In the 2009 experiment, substrate pH for all substrates ranged from 6.0 to 6.9 at 7 DAS and 6.9 to 7.1 at 79 DAS (Table 10). Substrate pH was above the recommended range (5.5 to 6.5) for all substrates at 29 DAS and thereafter. An increase in substrate pH was observed between 7 and 29 DAS for all substrates, yet remained relatively stable within substrates from 29 to 79 DAS. Substrate EC was in an acceptable range for plug production [0.5 to 1.0 $dS·m^{-1}$, (Cavins et al., 2000)] for all substrates except PB at 7 DAS, but was in the low range for all substrates at 29 DAS and thereafter. Substrate EC was similar among all substrates throughout the experiment. Changes in substrate pH and EC within the first 29 d are likely due to the nutrient release rate of the controlled-release fertilizer (Merhaut et al., 2006).

During propagation, nutrients are more readily leached from the substrate due to high substrate porosity and frequent mist application rates (Santos et al., 2011). Although water and nutrient availability can be readily managed in wood-based substrates used for crop production, such issues are more difficult in a propagation environment. The combined effects of leaching, low cation exchange capacity, and reduced nitrogen availability most likely contributed to less vigorous root and shoot growth in WPT.

The authors demonstrated that a range of plant species can be propagated from stem cuttings in WPT substrates. Combinations of WPT and PM or other organic components with a high cation exchange capacity may be required for optimum root development in WPT substrates. A single, universal propagation substrate has not been developed due to the unique set of factors associated with species variation and individual cultural practices. Rooting success is ultimately determined by the combined effects of container size, mist application rate and frequency, and substrate. Development of guidelines for propagation in WPT substrates would benefit manufacturers and growers interested in alternatives to traditional substrates.

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