Suitability of Sphagnum Moss, Coir, and Douglas Fir Bark as Soilless Substrates for Container Production of Highbush Blueberry

Patrick H. Kingston

Department of Horticulture, 4017 Agriculture and Life Sciences Building, Oregon State University, Corvallis, OR 97331

Carolyn F. Scagel¹ and David R. Bryla

U.S. Department of Agriculture, Agricultural Research Service, Horticultural Crops Research Unit, 3420 NW Orchard Avenue, Corvallis, OR 97330

Bernadine Strik

Department of Horticulture, 4017 Agriculture and Life Sciences Building, Oregon State University, Corvallis, OR 97331

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Abstract. The purpose of the present study was to investigate the suitability of different soilless substrates for container production of highbush blueberry (*Vaccinium* sp.). Young plants of ‘Snowchaser’ blueberry were grown in 4.4-L pots filled with media containing 10% perlite and varying proportions of sphagnum moss, coconut (*Cocos nucifera* L.) coir, and douglas fir [*Pseudotsuga menziesii* Mirb. (Franco)] bark, as well as a commercially available mix of peatmoss, perlite, and other ingredients for comparison. Total plant dry weight (DW) was similar among the treatments at 72 days after transplanting, but at 128 days, total DW was nearly twice as much in the commercial mix and in media with ≥60% peat or coir than in media with ≥60% bark. Inadequate irrigation likely played a role in poor plant growth in bark. Bark had lower porosity and water holding capacity than peat, coir, or the commercial mix and, therefore, dried quickly between irrigations. Bark also reduced plant uptake efficiency of a number of nutrients, including N, P, K, S, Ca, Mg, Mn, B, Cu, and Zn. Uptake efficiency of P, K, and Mg also differed between plants grown in peat and coir, which in most cases was a function of the initial concentration of nutrients in the media. Before planting, peat had the highest concentration of Mg and Fe among the media, whereas coir had the highest concentration of P and K. Leachate pH was initially lowest with peat and highest with coir but was similar among each of the media treatments by the end of the study. Electrical conductivity (EC) of leachate never exceeded 0.84 dS·m⁻¹ in any treatment. Overall, peat and coir appear to be good substrates for container production of highbush blueberry. Bark, on the other hand, was less suitable, particularly when it exceeded 30% of the total media composition.

Worldwide production of highbush blueberry (*Vaccinium* sp.) has increased tremendously in recent years, from ≈42,000 ha in 2005 to over 109,000 ha in 2014 (Brazelton, 2016). This rapid growth is driven by strong

consumer demand for the fruit and recent development of new cultivars and production systems that have increased availability of fresh blueberries in the market year-round.

Highbush blueberry is a member of the Ericaceae family and has unique characteristics relative to other crop plants, including a very fine root system with no root hairs, low soil pH requirements (4.5–5.5), and a preference for ammonium-N (NH₄-N) over nitrate-N (NO₃-N) (Retamales and Hancock, 2012). Compared with many non-ericaceous crops, blueberry plants contain much lower concentrations of most macronutrients and, therefore, tend to have lower nutrient requirements than other fruit crops (Korcak, 1988), including apple (*Malus domestica* Mill.; Righetti et al., 1998), raspberry (*Rubus idaeus* L.; Hart et al., 2006b), and blackberry (*Rubus* sp.) (Hart et al., 2006a). Because of these unusual requirements, many producers are looking

for novel ways to grow the plants in regions with suboptimal soil conditions. One such method involves cultivation in containers with soilless substrate and highly controlled fertigation management systems (Voogt et al., 2014). Although nurseries have been growing blueberry in soilless substrate for many years, the concept of commercial fruit production in containers is a relatively novel idea (Fulcher et al., 2015). Substrate mixes used in nurseries frequently contain peatmoss, coir, bark, and/or perlite, but it is unclear whether these components are also suitable for longer term fruit production of blueberry.

Partially decomposed peatmoss, derived from sphagnum peat, has historically been used for production of container-grown plants. High water holding capacity, high ion exchange capacity, resistance to decomposition, and relative abundance of peat bogs in the northern hemisphere often makes peatmoss an ideal choice for use in soilless substrates (Hammond, 1975). Peatmoss is also naturally low in pH (3.5–4.5) and, therefore, often considered a good substrate for acid-loving plants such as highbush blueberry (Knight et al., 1998; Scagel, 2003).

Coir is the pithy and fibrous material from the husk of coconuts and is a common alternative to peat because of its high water-holding capacity and widespread geographic availability (Evans et al., 1996). Although coir has a higher pH (5.6–6.9; Evans et al., 1996) than peat, it has been shown to be suitable for container production of ericaceous plants. Scagel (2003) reported improved growth in a wide range of ericaceous species when the plants were grown in media with coir instead of peat; however, the media never contained >20% peat or coir by volume. Berruti and Scariot (2011) substituted a peat-based medium with up to 50% coir and found improved growth of several *Rhododendron* sp. in the mixes with coir.

Growers also often use inexpensive, locally available organic products such as milled tree bark as a substrate for containers. In the northwestern United States, douglas fir bark is widely available as a by-product from the logging industry and is commonly used for production of nursery plants in the region (Buamscha et al., 2007). Douglas fir bark varies widely in quality and properties, depending on how it is treated (fresh, aged, or composted), but it usually has a low pH (3.7–4.4) considered appropriate for blueberry (Altland and Buamscha, 2008).

The purpose of the present study was to investigate the suitability of different combinations of sphagnum moss, coconut coir, and douglas fir bark for container production of highbush blueberry. These ingredients were chosen because of their low cost and widespread use in soilless cultivation. We hypothesized that blueberry would grow best in substrates with a high proportion of peat or douglas fir bark because of the lower pH. To test the hypothesis, southern highbush blueberry (a complex hybrid based largely on *Vaccinium corymbosum* L. and *Vaccinium darrowii* Camp.) plants were grown in media mixes with different proportions of the substrates.

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¹Corresponding author. E-mail: carolyn.scagel@ars.usda.gov.

Materials and Methods

Experimental setup. The study was conducted in a glasshouse located at the USDA-ARS Horticultural Crops Research Unit in Corvallis, OR (lat. 44°34'3" N, long. 123°17'19" W). Eleven media mixtures were evaluated, including 10 of which contained 10% perlite (Horticulture expanded grade; OBC Northwest Inc., Canby, OR) by volume for drainage and 0% to 90% sphagnum moss (Sun Gro Horticulture, Hubbard, OR), coconut coir (Sun Gro Horticulture), and aged douglas fir bark (The Bark Place, Philomath, OR) (Table 1). These 10 treatments were set up as a simplex-lattice design with each media component treated as a continuous variable. This design enabled us to estimate treatment response to media mixtures not included in the study (Cornell, 2011). A commercially available potting mix (Sunshine Professional Growing Mix #4 'LA4 P'; Sun Gro Horticulture Distribution Inc., Agawam, MA) containing peat, perlite, pumice, and other proprietary ingredients was also included in the study for comparison (Table 1). The components of this substrate are commonly used in nursery production of blueberry (J. Umble, personal communication).

On 18 Mar. 2015, 70-mL containers of 'Snowchaser' blueberry were obtained from a commercial nursery (Fall Creek Farm & Nursery, Lowell, OR) and transplanted into 4.4-L pots (19.7-cm diameter × 16.5-cm tall, #2 Short; Anderson Pots, Portland, OR) filled with the media mixtures. One plant was placed in each pot, and each treatment had 10 pots, for a total of 110 plants in the experiment. Treatments were arranged in a randomized complete block design with two pots per treatment in each of five blocks. The pots were located on two adjacent greenhouse benches and spaced 0.1 m apart on each bench.

Each bench was illuminated from 0700 to 2100 HR using two 1000-W high-pressure sodium lamps. A thermostat was set to cool the glasshouse when temperature was >27 °C and to heat it when temperature was <15 °C. Air temperature, relative humidity, and photosynthetically active radiation (*PAR*) were measured every 15 min at the top of the canopy using a data logger (model LI-1400; LI-COR Biosciences, Lincoln, NE) connected to a combination temperature and humidity probe (model Humitter 50 YC; Vaisala Inc., Woburn, MA) and a pyranometer (model LI-190; LI-COR Biosciences). The data logger was installed on 22 Apr. 2015 but malfunctioned between 29 May and 26 June. Mean daily air temperature in the glasshouse ranged from 14 to 38 °C and averaged 22 °C from 22 Apr. to 29 May and 26 °C from 26 June to 24 July. Relative humidity and *PAR* averaged 51% and 20.8 mol·m⁻²·d⁻¹, respectively.

The plants were irrigated as needed from 18 Mar. to 5 Apr. using a 2 L·h⁻¹ drip emitter in each pot (model DPC02-MA-AL-Blue; Toro Company, El Cajon, CA). From 6 Apr. onward, plants were fertigated daily

through the drip system with a modified Hoagland's nutrient solution (Hoagland and Arnon, 1938). The solution contained 5.5 mM N from (NH₄)₂SO₄ and (NH₄)₂HPO₄ + 1.14 mM N as a chelating agent used to deliver Ca; 0.51 mM P from (NH₄)₂HPO₄; 3.07 mM K from K₂SO₄; 2 mM Ca from a chelated Ca product (ProNatural Calcium; Wilbur Ellis, Aurora, CO); 0.74 mM Mg from MgSO₄·7H₂O; 25 μM Fe from Fe-DTPA; 25 μM B from H₃BO₃; 3 μM Mn from MnCl₂·4H₂O; and 4 μM Zn from ZnSO₄·7H₂O. Sulfuric acid was also added to reduce the pH of the fertigation solution to 5.2. Each plant received the same volume of nutrient solution. All pots received the same volume of solution via fertigation, and leached solution

was captured to evaluate percent drain (percent drain = volume solution collected per volume solution added to pot). Drainage was evaluated two to three times per week by collecting water that drained through the bottom of each pot in one block of the study. If needed, plants were supplemented with additional irrigation through a separate drip system (same emitter set-up as described previously) to produce 25% drainage of the total solution applied to the pots. Frequency of fertigation/irrigation varied during the experiment from three times per week at the beginning (≈167 mL/pot per fertigation event) to daily near the end of the experiment (≈100 mL/pot per fertigation event). Plants were fertigated with 3.3 L of nutrient solution

Table 1. Irrigation drainage from different media mixes used to grow potted plants of 'Snowchaser' blueberry.

Medium ^z	Composition (%)				Drainage (%) ^y	
	Peatmoss	Coir	Bark	Perlite	0–72 d	73–128 d
S ₃₀ C ₃₀ B ₃₀	30	30	30	10	37	26
S ₉₀	90	0	0	10	40	30
S ₆₀ B ₃₀	60	0	30	10	38	32
S ₆₀ C ₃₀	60	30	0	10	44	25
C ₉₀	0	90	0	10	37	33
C ₆₀ B ₃₀	0	60	30	10	39	26
C ₆₀ S ₃₀	30	60	0	10	36	25
B ₉₀	0	0	90	10	60	47
B ₆₀ C ₃₀	0	30	60	10	48	40
B ₆₀ S ₃₀	30	0	60	10	45	38
Commercial mix	55–65	0	0	25–30	45	24

^zLetters represent the component(s) of the medium (S = sphagnum moss, C = coconut coir, B = douglas fir bark) and the numbers represent the percent of each component (e.g., S₃₀C₃₀B₃₀ is 30% peatmoss, 30% coir, and 30% bark). Each non-commercial medium also contained 10% perlite. Remainder of commercial mix was pumice and proprietary ingredients (5% to 20%).

^yPercentage of added solution (mL fertilizer per pot + mL water per pot) that drained from the pots between 0 and 72 d and 73 and 128 d after transplanting. Drainage was not included from 26 to 33 d after transplanting due to a malfunction in the irrigation system (2 L of water was applied to each pot over the 7-d period).

Table 2. Initial physical characteristics of different media mixes used to grow potted plants of 'Snowchaser' blueberry.

Medium ^z	Bulk density (g·cm ⁻³)	Porosity (%)	Particle size (%) ^y			Cation exchange capacity (meq/100 g soil)
			Coarse	Medium	Fine	
S ₃₀ C ₃₀ B ₃₀	0.16	82	52.6	22.8	24.6	21
S ₉₀	0.08	86	58.1	20.8	21.1	27
S ₆₀ B ₃₀	0.14	84	62.2	20.0	17.8	28
S ₆₀ C ₃₀	0.08	86	47.1	24.5	28.4	22
C ₉₀	0.08	85	19.9	31.6	48.5	15
C ₆₀ B ₃₀	0.18	80	44.9	25.5	29.6	18
C ₆₀ S ₃₀	0.08	86	34.9	25.8	39.3	19
B ₉₀	0.31	76	59.7	25.9	14.3	24
B ₆₀ C ₃₀	0.25	77	51.3	26.9	21.8	23
B ₆₀ S ₃₀	0.24	79	58.7	24.9	16.4	23
Commercial mix	0.14	82	47.6	26.2	26.3	28
Media component correlations ^x						
Peatmoss	NS	0.6801	NS	−0.8581	NS	0.6068
Coir	NS	NS	−0.9535	0.6594	0.9535	−0.9340
Bark	0.9837	−0.9535	NS	NS	−0.7119	NS
Dry weight correlations ^x						
72 d	−0.6889	0.6150	NS	NS	NS	NS
128 d	−0.6855	0.6273	0.7000	NS	0.7636	NS

^zLetters represent the component(s) of the medium (S = sphagnum moss, C = coconut coir, B = douglas fir bark) and the numbers represent the percent of each component (e.g., S₃₀C₃₀B₃₀ is 30% peatmoss, 30% coir, and 30% bark). Each non-commercial medium also contained 10% perlite (see Table 1).

^yCoarse > 2.4 mm; medium = 0.85–2.4 mm; fine < 0.85 mm.

^xSpearman *R* values (*P* ≤ 0.05) for relationships between the proportion of peat, coir, or bark in the media and the physical characteristics of the media, and between the total plant dry weight at either 72 or 128 d after transplanting and the physical characteristics of the media. No significant relationship denoted by ns. The commercial mix was not included in the dry weight analyses.

by 72 d and 9.7 L by 128 d. The combined total of irrigation and fertigation provided to plants was 9.2–10.7 L at 72 d and 17.1–24.9 L at 128 d.

At $\approx$ 6 weeks after transplanting, plants in 90% bark had red-tinged leaves, a common symptom of N deficiency in blueberry (Hart et al., 2006b). Following this discovery and coupled with data on differences in percent drainage among treatments (Table 1), the fertigation schedule was changed from every other day to every day to reduce large discrepancies in drainage. This change in fertigation frequency kept more fertilizer solution in the root-zone and eliminated any N deficiency symptoms by 78 d after transplanting.

Measurements. Physical and chemical properties of the media were analyzed by a commercial laboratory (Soil Control Laboratory, Watsonville, CA) to compare initial differences in media properties. Bulk density and porosity of the media were determined using the method described by Niedziela and Nelson (1992). Particle-size distribution was determined using displacement by shaking 100 g of dry media through stacked sieves with openings decreasing in size (25, 16, 9.5, 6.3, 4.0, 2.0, and 0.85 mm) for 5 min and obtaining the percent of material (w/w %) in each sieve. Media cation exchange capacity (CEC) was determined using sodium acetate solution. Percent C and N were determined using a combustion analyzer (TruSpec CN; Leco Corp., St. Joseph, MI), concentration of $\text{NH}_4\text{-N}$ was determined with a selective ion electrode procedure (Sims et al., 1995), concentrations of Cl and S-SO_4 were determined by ion chromatography, and EC and pH were measured in a 1:5 substrate: deionized water extract (Robbins and Wiegand, 1990). Nutrient composition of media samples was determined by inductively coupled

plasma (ICP) spectrophotometry after extraction using Mehlich 1 for P, K, Ca, Mg, and Na, DPTA for Cu, Zn, Fe, and Mn, and hot water for B (Gavlak et al., 2003).

To monitor pH and EC changes in media over time, leachate was collected from the pots every 2 weeks from three blocks per treatment using a modified pour-through method (Wright, 1986) and was analyzed for pH and EC using a pH/ion/conductivity meter (model SevenGo Duo pro with an InLab Expert Pro-ISM-IP67 probe for pH and an InLab 738 ISM conductivity probe for EC; Mettler-Toledo, Columbus, OH). The procedure of Wright (1986) was modified by irrigating all pots simultaneously by using drip emitters with 67 mL of irrigation water per container at $\approx$ 1 h after a fertigation event. This modification improved the uniformity of leachate volume collection ($\approx$ 50 mL/pot) by reducing the amount of time required to manually add deionized water. The leachate was then stored at 3 °C until analysis and later measured at 25 °C in a water bath. Leachate data were only collected from a subset of treatments with ion-selective membrane probes (i.e., $\text{S}_{30}\text{C}_{30}\text{B}_{30}$, S_{90} , C_{90} , and B_{90} ; Table 1; WesternAg Innovations, Saskatoon, Saskatchewan, Canada). In these treatments, two anion and two cation probes were inserted vertically into the medium at 2.5 cm from the edge of each pot. The probes were buried every 2 weeks for a period of 7 d (removed on the same day as the pour-throughs) and then sent to the manufacturer for analysis of NO_3^- , NH_4^+ , P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, Al, Pb, and Cd absorbed on the membranes.

Plants were destructively harvested at 0, 72, and 128 d after transplanting. At each harvest, the shoots were cut off at the surface of the media, rinsed with distilled water, separated into stems and leaves, and oven-dried at

60 °C until no change in mass was observed over a 24-h period. The pots were then placed in a cooler set at 3 °C, and roots were later removed from the media by washing and oven-dried at 60 °C. Each plant component was then weighed and ground to pass through a 1-mm screen. The ground samples were analyzed for N using a combustion analyzer (TruSpec CN; Leco Corp.; Scagel et al., 2007) and for P, K, S, Ca, Mg, Fe, B, Cu, Mn, Zn, and Na by ICP-optical emission spectrometry (Perkin Elmer Optima 3000DV; Perkin Elmer, Wellesley, MA) after microwave digestion with 70% (v/v) nitric acid in a microwave (Gavlak et al., 2003; Jones and Case, 1990). Reference standard apple (*M. domestica* L.) leaves (no. 151, National Institute of Standards and Technology) were included in each set of samples to ensure accuracy of instrument and digestion procedures.

Whole plant DW was obtained by adding the dry mass of all plant tissues for a given experimental unit. Nutrient content of each plant tissue was calculated by multiplying the DW of each tissue by its nutrient concentration. For each nutrient, whole plant concentration was calculated by adding the nutrient content in each tissue and dividing the sum by whole plant DW. Nutrient uptake efficiency (NUE) was calculated by dividing net uptake of each nutrient [i.e., difference in the total content of the nutrient at transplanting (day 0) and at 128 d after transplanting] by the quantity of that nutrient available from the medium (obtained from chemical analysis of each medium) and added during fertigation.

Data analysis. Data were analyzed using RStudio (version 0.99.903; RStudio INC., Boston, MA) running R (version 3.3.1; R Core Team, 2016). For DW, NUE, and nutrient concentration data, linear polynomial models were fit to account for the

Table 3. Initial chemical characteristics of different media mixes used to grow potted plants of 'Snowchaser' blueberry.

Medium ^z	pH	EC (dS·m ⁻¹)	Total N (%)	C:N ratio	Nutrient concn (ppm)											
					NH ₄ -N	P	K	Ca	Mg	SO ₄ -S	Fe	Mn	B	Cu	Zn	Na
$\text{S}_{30}\text{C}_{30}\text{B}_{30}$	5.6	0.46	0.42	73	2.4	169	2,973	287	105	65	1,047	98	1.9	6.1	8.0	443
S_{90}	4.4	0.31	0.83	44	3.1	7	128	8,017	1,304	68	411	21	1.4	1.0	7.0	85
$\text{S}_{60}\text{B}_{30}$	5.1	0.19	0.59	54	3.0	39	479	4,788	965	48	1,260	86	1.2	5.2	8.1	300
$\text{S}_{60}\text{C}_{30}$	5.2	0.66	0.68	52	3.5	121	2,999	5,774	2,128	98	284	26	2.9	1.2	8.1	469
C_{90}	6.6	1.20	0.50	70	3.4	493	8,669	3,124	155	183	40	29	4.8	1.5	9.1	1,260
$\text{C}_{60}\text{B}_{30}$	5.9	0.74	0.39	80	2.5	89	3,290	3,471	1,039	86	436	47	1.9	3.0	5.0	661
$\text{C}_{60}\text{S}_{30}$	5.8	0.91	0.60	55	2.2	280	6,185	5,380	1,533	140	137	29	4.0	1.5	7.9	912
B_{90}	5.8	0.22	0.31	103	1.8	10	570	3,059	646	24	885	29	1.0	5.1	4.4	307
$\text{B}_{60}\text{C}_{30}$	5.8	0.45	0.35	80	1.8	25	1,459	3,033	749	55	848	52	1.4	5.0	5.0	437
$\text{B}_{60}\text{S}_{30}$	5.4	0.22	0.34	78	2.0	13	602	3,701	797	31	1,056	77	1.0	5.9	6.6	345
Commercial mix	5.7	4.95	0.59	31	3.4	590	1,386	5,539	2,489	2,353	134	23	1.3	1.2	10.3	152
Media component correlations ^y																
Peatmoss	-0.9202	NS	0.7437	-0.8671	NS	NS	NS	0.7437	NS	NS	NS	NS	NS	NS	NS	NS
Coir	0.7523	0.9534	NS	NS	NS	0.8454	0.9535	NS	NS	0.8327	-0.7119	NS	0.8917	NS	NS	0.9534
Bark	NS	NS	-0.9090	0.8193	-0.8129	NS	NS	NS	NS	-0.8772	0.7373	0.6376	-0.7922	0.7396	-0.7100	NS
Dry weight correlations ^y																
72 d	NS	NS	0.6438	-0.5900	NS	NS	NS	NS	0.7517	NS	NS	NS	NS	0.6034	NS	NS
128 d	NS	0.6727	0.7016	-0.6330	0.6849	NS	NS	NS	0.6818	0.7909	-0.6364	NS	0.6865	-0.6758	NS	NS

^zLetters represent the component(s) of the medium (S = sphagnum moss, C = coconut coir, B = douglas fir bark) and the numbers represent the percent of each component (e.g., $\text{S}_{30}\text{C}_{30}\text{B}_{30}$ is 30% peatmoss, 30% coir, and 30% bark). Each non-commercial medium also contained 10% perlite (see Table 1).

^ySpearman *R* values ($P \leq 0.05$) for relationships between the proportion of peat, coir, or bark in the media and the physical characteristics of the media, and between the total plant dry weight at either 72 or 128 d after transplanting and the physical characteristics of the media. No significant relationship denoted by NS. The commercial mix was not included in the dry weight analyses.

EC = electrical conductivity.

Fig. 1. Total dry weight (DW) (g/plant) of 'Snowchaser' blueberry plants at (A) 72 d and (B) 128 d after transplanting. Each side of the triangle represents the proportion of the substrate contained in the media. Black circles represent the proportions used in experiment, and contour lines represent the linear response of total plant DW to various proportions of peat, coir, and bark in the media mix ($P \leq 0.05$).

Table 4. Dry weight (DW) of 'Snowchaser' blueberry plants grown in pots containing different media mixes.

Medium ^z	Dry wt (g/plant) ^y							
	72 d after transplanting				128 d after transplanting			
	Total	Roots	Stems	Leaves	Total	Roots	Stems	Leaves
S ₃₀ C ₃₀ B ₃₀	6.6	2.1	1.4	3.1	42.8	9.4	12.3	21.1
S ₉₀	8.0	1.9	1.4	4.6	45.3	10.4	13.4	21.5
S ₆₀ B ₃₀	6.5	1.8	1.3	3.3	39.9	9.5	11.4	19.0*
S ₆₀ C ₃₀	8.2	2.1	1.8	4.3	48.0	9.4	14.1	24.5
C ₉₀	6.2	1.9	1.3	3.0	43.1	10.5	11.5	21.1
C ₆₀ B ₃₀	8.1	2.1	1.6	4.5	47.7	11.2	14.1	22.4
C ₆₀ S ₃₀	8.4	2.2	1.5	4.6	46.3	13.2	12.7	20.5
B ₉₀	5.3	1.8	1.3	2.2	15.3*	3.8	4.7*	6.8*
B ₆₀ C ₃₀	5.3	1.6	1.3	2.4	28.3*	8.2	7.7	12.4*
B ₆₀ S ₃₀	7.3	2.1	1.4	3.7	24.9*	6.5	7.5*	11.0
Commercial mix	7.6	2.1	1.5	4.0	45.7	9.7	11.4	24.6
Mixture model results ^y								
<i>P</i> value	0.0473	0.6425	0.4375	0.0105	<0.0001	0.0005	<0.0001	<0.0001
<i>r</i> ² _{adj}	0.1216	0.0187	0.0573	0.1762	0.6392	0.2800	0.5743	0.6566
Coefficients (β)								
Peat	8.1 a	2.0 a	1.5 a	4.5 a	46.9 a	10.3 a	13.8 a	22.7 a
Coir	7.4 ab	2.0 a	1.5 a	3.8 a	49.2 a	12.2 a	13.5 a	23.4 a
Bark	5.5 b	1.8 a	1.3 a	2.3 b	18.3 b	5.0 b	5.5 b	7.9 b

^zLetters represent the component(s) of the medium (S = sphagnum moss, C = coconut coir, B = douglas fir bark) and the numbers represent the percent of each component (e.g., S₃₀C₃₀B₃₀ is 30% peatmoss, 30% coir, and 30% bark). Each non-commercial medium also contained 10% perlite (see Table 1).

^yMixture model *P* values, adjusted correlation coefficients (*r*²_{adj}), and coefficients (β) for each model component. Coefficients followed by the same lower-case letter within a column are not significantly different based on Tukey's honestly significant difference test ($P \leq 0.05$). *Significantly different from the commercial mix at a 95% level using Dunnett-Hsu adjustment.

simplex-lattice design and estimate the effect of each ingredient proportion using the 'lm' function (Scheffé, 1958); the commercial mix treatment was excluded from the analysis. One plant died in a pot filled with a 2:1 mix of peat and bark before the second harvest date (due to an accidental loss of irrigation) and, therefore, was also removed from the analysis. Spearman rank order correlation (*R*) was used to estimate relative relationships of physical and chemical properties of the media mixtures with individual media proportions and plant DW at 72 and 128 d after transplanting using Statistical

analytical software system (Version 13; Dell, Inc., Tulsa, OK). Comparisons between all treatments and the commercial control were done using the PROC MIXED procedure in SAS (v. 9.4; SAS Institute Inc., Cary, NC) and the Duncan-Hsu adjustment for multiple group comparisons. Data from pour-through leachate and ion-selective membrane probes were analyzed using a linear mixed model (package "nlme"), and all pairwise comparisons were made using Tukey's honestly significant difference test at the 0.05 level in the "lsmeans" package (Lenth, 2016; Pinheiro et al., 2016).

Results

Initial media composition. Initial physical and chemical characteristics differed among the 11 media (Tables 2 and 3). Adding more peat increased porosity, CEC, total N, and Ca concentration in the medium and reduced the percentage of medium-sized particles, pH, and the C:N ratio. Adding more coir, on the other hand, increased the percentage of medium- and fine-sized particles, pH, EC, and P, K, SO₄-S, B, Cl, and Na concentration in the medium and reduced the percentage of coarse-sized particles, CEC, and Fe concentration in the medium (Cl concentration data not shown). Finally, more bark increased bulk density, the C:N, and Fe and Cu concentration in the medium and reduced porosity, the percentage of fine-sized particles, total C and N, and NH₄-N, SO₄-S, B, Mn, Zn, and Cl concentration in the medium (total C and Cl concentration data not shown). More bark also reduced water holding capacity and, therefore, resulted in more drainage (Table 1).

Plant DW. At 72 and 128 d after transplanting, total plant DW increased with greater proportions of peat or coir and decreased with greater proportions of bark in the medium (Fig. 1). Based on estimates from the simplex-lattice design, media with >30% bark resulted in less plant DW than those with ≥60% coir or peat. The latter treatments resulted in the same amount of DW in each plant part as the commercial mix (Table 4). A high percentage of bark in the medium reduced leaf DW at 72 d after transplanting and decreased DW of each organ at 128 d. Total plant DW was positively correlated to a number of media characteristics at 72 or 128 d, including porosity, the percentage of coarse- and fine-sized particles, EC, total N, and concentration of NH₄-N, SO₄-S, Mg, and B, and was negatively correlated to bulk density,

CN ratio, and concentration of Fe (Tables 2 and 3). Total plant DW was also correlated to the concentration of Cu in the media, but in this case, it had a positive relationship at 72 d and a negative relationship at 128 d.

Whole-plant nutrient concentration. Adding more bark to the media resulted in higher concentrations of Fe, Mn, and B in the plants than adding more peat or coir, whereas more peat resulted in a higher N concentration and lower K and Cu concentrations, and more bark resulted in higher Fe and Mn concentrations than the commercial mix (Table 5). The media treatments had no effect on concentration of P, Ca, Mg, S, or Zn in the plants. At 128 d after transplanting, concentrations of these nutrients ranged from 0.07 to 0.14 mg·g⁻¹ P, 0.27 to 0.95 mg·g⁻¹ Ca, 0.12 to 0.29 mg·g⁻¹ Mg, 0.09 to 0.29 mg·g⁻¹ S, and 6 to 22 mg·kg⁻¹ Zn.

NUE. Nutrient uptake efficiency was consistently higher in media with more peat or coir than in those with more bark (Table 6). Adding more peat also improved P and K uptake efficiency relative to more coir in the media, whereas more coir improved Mg uptake efficiency relative to more peat. With few exceptions, plant uptake of many nutrients, including N, P, S, Ca, Mg, Mn, and Zn, was less efficient in the commercial mix than in media containing ≥60% peat or coir, whereas K, Ca, B, Cu, and Zn uptake was more efficient in the commercial mix than in media containing ≥60% bark.

Leachate pH and EC. Initially, leachate pH was highest in medium with 90% coir and lowest in medium with 90% peat (Fig. 2). However, differences in pH diminished during the experiment, and by 78 d after transplanting, values were similar among the measured treatments. Over time, leachate pH increased from 4.3 to 5.5 with 90% peat, from 5.9 to 6.9 with 90% bark, and from 5.5 to 6.5 in the S₃₀C₃₀B₃₀ mix. The pH of leachate in the treatment with 90% coir changed little during the experiment.

Leachate EC was greater in 90% bark (0.84 dS·m⁻¹) than in 90% peat or coir (0.34 and 0.46 dS·m⁻¹, respectively) at 35 d after transplanting and was greater in 90% coir (0.38 dS·m⁻¹) than in 90% peat or bark (0.12 and 0.16 dS·m⁻¹, respectively) at 119 d after transplanting. Mean leachate EC varied over time but never exceeded 0.87 dS·m⁻¹ in any treatment during the experiment (data not shown). An EC of <2 dS·m⁻¹ is considered safe for highbush blueberry (Machado et al., 2014).

Nutrient availability. Availability of NH₄-N was similar among media with 90% peat, 90% coir, 90% bark, or an equal mix of peat, coir, and bark (Fig. 3A). However, 90% coir had more available NO₃-N, P, and K over time than the other three media treatments (Fig. 3B–D). Furthermore, 90% peat had more P than 90% bark or the peat–coir–bark mix and more available Ca than 90% coir (Fig. 3C and E). The mix containing 30% of each ingredient, on the other hand, had more K than 90% peat or bark (Fig. 3D), whereas 90% bark and the mix had more Fe

and Mn than 90% peat or coir (Fig. 3E and G). Availability of the other measured elements, including S, B, Cu, Zn, Al, Pb, and Cd, increased over time and were similar among the treatments (data not shown).

Discussion

Media containing a high proportion of douglas fir bark resulted in less plant growth

in highbush blueberry than media containing high proportions of peatmoss or coconut coir. The negative influence of the bark on growth was likely because of its suboptimal physical properties, particularly water holding capacity (i.e., higher drainage) and its effect on substrate water relations. Peat and coir had higher water holding capacity than bark, which at 47% is at the low end of the range recommended for media used for container

Table 5. Nutrient concentrations in ‘Snowchaser’ blueberry plants grown in pots containing different media mixes.^a

Medium ^y	Macronutrients (mg·g ⁻¹)		Micronutrients (μg·g ⁻¹)			
	N	K	Fe	Mn	B	Cu
S ₃₀ C ₃₀ B ₃₀	9.2	5.7	116	480*	28	14
S ₉₀	10.7	4.9	74	134	27	11
S ₆₀ B ₃₀	9.8	5.3	153	542*	28	13
S ₆₀ C ₃₀	9.4	5.1	86	130	25	10
C ₉₀	9.2	6.5	84	114	28	15
C ₆₀ B ₃₀	8.9	6.4	197	385*	31	15
C ₆₀ S ₃₀	8.8	5.4	69	135	23	13
B ₉₀	9.5	6.2	267*	589*	32	12
B ₆₀ C ₃₀	9.1	5.7	341*	495*	30	17
B ₆₀ S ₃₀	9.8	5.6	218*	552*	28	12
Commercial mix	9.7	5.5	69	87	26	13
Mixture model results ^x						
P value	0.0214	0.0190	<0.0001	<0.0001	0.0037	0.0861
r ² _{adj}	0.1539	0.1583	0.3337	0.9209	0.2163	0.1011
Coefficients (β)						
Peat	10.2 a	4.8 b	75 b	138 b	25 b	10 b
Coir	8.7 b	6.5 a	94 b	118 b	27 b	15 a
Bark	9.4 ab	6.0 a	373 a	518 a	32 a	14 ab

^aMeasured on whole plants (roots, leaves, and stems) at 128 d after transplanting.

^yLetters represent the component(s) of the medium (S = sphagnum moss, C = coconut coir, B = douglas fir bark) and the numbers represent the percent of each component (e.g., S₃₀C₃₀B₃₀ is 30% peatmoss, 30% coir, and 30% bark). Each non-commercial medium also contained 10% perlite (see Table 1).

^xMixture model P values, adjusted correlation coefficients (r²_{adj}), and coefficients (β) for each model component. Coefficients followed by the same lower-case letter within a column are not significantly different based on Tukey’s honestly significant difference test (P ≤ 0.05). *Significantly different from the commercial mix at a 95% level using Dunnett-Hsu adjustment.

Table 6. Nutrient uptake efficiency by ‘Snowchaser’ blueberry plants grown in pots containing different media mixes.

Medium ^z	Nutrient uptake efficiency (%) ^y									
	N	P	K	S	Ca	Mg	Mn	B	Cu	Zn
S ₃₀ C ₃₀ B ₃₀	58*	27	10*	3.6*	19*	33*	32	35	14*	6
S ₉₀	74*	41*	26*	5.2*	6	14*	79*	47	154*	16*
S ₆₀ B ₃₀	61*	33*	20	3.7*	5	10*	44	40	18	8
S ₆₀ C ₃₀	67*	36*	15	4.0*	7*	10*	64*	39	125	14*
C ₉₀	69*	24	10*	4.2*	11*	41*	46	32	129	11
C ₆₀ B ₃₀	63*	38*	11*	3.7*	6	8*	53*	42	30*	12
C ₆₀ S ₃₀	61*	30*	10*	3.6*	7*	11*	59*	31	122	13*
B ₉₀	21*	12	7*	1.3	1*	2*	24	14*	3*	3*
B ₆₀ C ₃₀	35	22	8*	2.2	2*	4	27	22*	8*	4*
B ₆₀ S ₃₀	34	22	11*	2.2	2*	4	18	22*	5*	3*
Commercial mix	39	19	17	1.8	4	5	28	41	75	8
Mixture model results ^x										
P value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
r ² _{adj}	0.5916	0.4663	0.6388	0.5712	0.5527	0.5466	0.5037	0.4737	0.8838	0.6698
Coefficients (β)										
Peat	76 a	37 a	22 a	5 a	7 a	13 b	69 a	46 a	140 a	13 a
Coir	67 a	21 b	7 b	4 a	11 a	25 a	52 a	37 a	146 a	14 a
Bark	25 b	15 b	6 b	1 b	2 b	3 c	14 b	17 b	2 b	2 b

^zLetters represent the component(s) of the medium (S = sphagnum moss, C = coconut coir, B = douglas fir bark) and the numbers represent the percent of each component (e.g., S₃₀C₃₀B₃₀ is 30% peatmoss, 30% coir, and 30% bark). Each non-commercial medium also contained 10% perlite (see Table 1).

^yPercent of each nutrient supplied by fertilizers and the media mix at 128 d after transplanting.

^xMixture model P values, adjusted correlation coefficients (r²_{adj}), and coefficients (β) for each model component. Coefficients followed by the same lower-case letter within a column are not significantly different based on Tukey’s honestly significant difference test (P ≤ 0.05). *Significantly different from the commercial mix at a 95% level using Dunnett-Hsu adjustment.

Fig. 2. Leachate pH from four media mixes used to grow 'Snowchaser' blueberry in pots for 128 d. Each treatment contained 10% perlite, by volume, and 90% sphagnum moss (S_{90}), 90% coir (C_{90}), 90% douglas fir bark (B_{90}), or 30% each of peat, coir, and bark ($S_{30}C_{30}B_{30}$). Symbols represent the mean of three replicates, and error bars represent the least significant difference ($P \leq 0.05$). The gray shading represents the optimum soil pH range for highbush blueberry (Retamales and Hancock, 2012).

production of nursery plants (Bilderback et al., 2013). In soilless substrate, plants will experience drought stress at much higher tensions (less water depletion) than soil-grown plants (-10 and -1500 kPa, in substrate and soil, respectively; Raviv et al., 2001).

de Boodt and Verdonck (1971) defined easily available water (EAW, the volume of water released between -1 and -5 kPa) and water buffering capacity (WBC, the volume released between -5 and -10 kPa) as two critical aspects of substrate water relations. Fields et al. (2014) measured EAW and WBC for peat, coir, and pine bark and found that the EAW of bark was $\approx 20\%$ of that for peat and coir. Gabriel et al. (2009) observed a positive linear relationship of EAW with the addition of peat to douglas fir bark, which may explain why blueberry responded well to a 2:1 mix of peat and bark in the present study.

The effects of physical properties of media on water distribution may also play a role in growth and production of potted blueberry plants. Owen and Altland (2008) observed vertical stratification of water availability in containers of douglas fir bark, where it was as much as 50% lower in the top 2.5 cm of a 15-cm tall container than in the bottom. Given that the root system of the plants was only 7-cm long at transplanting in the present study, it is likely that the plants grown in media containing a high proportion of bark experienced periods of water stress between irrigations. A small decrease in available water will reduce stomatal conductance (g_s) (Améglio et al., 2000), cell expansion, and photosynthetic productivity in blueberry (Andersen et al., 1979; Cameron et al., 1988). Because all treatments were irrigated on the same schedule, media with high amounts of bark likely reached stressful tension levels and growth limiting conditions sooner than media with more peat or coir. In fact, when plants were grown in 90% bark,

Fig. 3. Cumulative availability of (A) ammonium-N (NH_4-N), (B) nitrate-N (NO_3-N), (C) P, (D) K, (E) Ca, (F) Fe, and (G) Mn in four media mixes used to grow potted plants of 'Snowchaser' blueberry. The mixes contained 10% perlite, by volume, and 90% sphagnum moss (S_{90}), 90% coir (C_{90}), 90% douglas fir bark (B_{90}), or 30% each of peat, coir, and bark ($S_{30}C_{30}B_{30}$). Symbol represents the mean of three replicates, and error bars represent the least significant difference ($P \leq 0.05$).

altering fertigation from every other day to every day improved growth and reversed N deficiency symptoms observed shortly after planting. When commercial growers use media containing high amounts of bark, they tend to increase irrigation and give plants more fertilizer than when using media containing more peat (J. Umble, personal communication).

The influence of substrate moisture retention on nutrient availability can also affect plant response to media components. Dry substrate in the top of the container can lead to water channeling and quick drainage of solution (Hoskins et al., 2014). Higher cumulative drainage in douglas fir bark compared with peat and coir treatments confirmed a reduction in fertigation solution retention, which likely contributed to the reduced nutrient availability of P and K

compared with peat and coir treatments. The reduced N uptake efficiency of N in douglas fir bark as compared with peat- and coir-grown plants, coupled with observations of N deficiency, higher C:N, and lower NH_4-N availability, suggest that early N deficiency may also have contributed to reduced plant growth in bark.

Growth was similar when blueberry was grown in media with high proportions of peat and coir and was comparable in both cases to the commercial peat mix. However, there were a few notable differences in NUE between these substrates. Increasing peat improved the efficiency of P and K uptake relative to increasing coir in the media but reduced the efficiency of Mg and Fe uptake.

Differences in Mg and Fe uptake efficiency between peat and coir were related to relative differences content of the nutrients

supplied by the media and not to their availability in the media or the plants ability to absorb these nutrients. Peat, for example, contained an order of magnitude more Mg and Fe than coir; however, peat- and coir-grown plants did not differ in DW, whole plant concentration of Mg and Fe, or availability of Mg and Fe (as estimated by ion-selective membrane probes) during the experiment. These results indicate the initial Mg and Fe nutrient content of the media (the denominator in the nutrient use efficiency calculation) was the driving factor for the observed differences in uptake efficiency between peat and coir for these nutrients. Others have also reported that Mg and Fe uptake was similar between media containing coir and peat (Scagel, 2003).

Differences in K uptake efficiency between peat and coir were related to relative differences in K content between the media and K availability during the experiment. Peat had greater K uptake efficiency than coir, but K availability in the media and plant tissue K concentrations were greater with coir. Uptake of K occurs through diffusion and is dependent on the concentration of K cations in solution that is in contact with the roots (Nieves-Cordones et al., 2014). The higher K concentration in coir-grown plants was not enough to offset the effects of the very high K concentration in the coir media on its nutrient use efficiency. Coir is known to contain high amounts of K and can increase K uptake (Evans et al., 1996; Scagel, 2003).

Differences in P uptake efficiency between peat and coir may be related to how these ingredients alter media pH. Although coir contained more P than peat and had greater P availability during the experiment than peat, peat- and coir-grown plants did not differ in whole plant P concentration. Uptake of P is highly dependent on pH, not only just for the availability of P in the root environment, but also the ability of plants to absorb P (Schachtman et al., 1998). Coir can contain more P than peat, and P uptake in coir-based mixes can be greater than that in peat when mixes containing peat and coir have similar pH (Evans et al., 1996; Scagel, 2003). In our experiment, lower leachate pH in peat than in coir may have contributed to greater P uptake efficiency in peat.

Interestingly, availability of $\text{NO}_3\text{-N}$ was elevated in the medium with 90% coir. Coir-containing media can contain greater levels of available $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ than similar peat-containing media and may result in greater N uptake when media has similar pH (Scagel, 2003; Stamps and Evans, 1999). Higher pH can increase the likelihood of nitrification and N losses (Havlin et al., 2014). In substrate production using coir, frequent fertigation that supplies $\text{NH}_4\text{-N}$ to plants might overcome N losses to nitrification at higher pH. However, in our study, the concentration of N in the plants was lower in coir than in peat, which over time could become an issue. Blueberry prefers $\text{NH}_4\text{-N}$ to $\text{NO}_3\text{-N}$ (Retamalos and Hancock, 2012), and these findings illustrate the importance of

pH management of substrate, particularly in long-term production to maintain N in the desired $\text{NH}_4\text{-N}$ form. More N fertilizer may be needed for longer term fruit production in coir, but further research is warranted.

Most of the differences in nutrient use efficiency in this study were the result of differences initial media concentrations. After 128 d, it did not appear that blueberry plants grown in peat or coir required different fertilization as growth was similar between these ingredients. However, the multiyear duration of fruit production could lead to changes in media properties such as nutrient retention or porosity. Numerous studies have documented the change in substrate physical and chemical properties as a result of long-term plant growth and media decomposition (Jackson et al., 2009; Raviv, 2016). Future research on media selection for blueberry should also focus on changes in media properties over the long term and on maintaining equal or adequate moisture levels in the medium. Although blueberry generally starts producing fruit earlier in substrate than in the field, the plants must be grown in containers for at least several years for substrate-production to be considered economical (B. Strik, personal observation).

Literature Cited

- Altland, J.E. and M.G. Buamscha. 2008. Nutrient availability from douglas fir bark in response to substrate pH. *HortScience* 43:478–483.
- Améglio, T., X. Le Roux, M. Mingeau, and C. Perrier. 2000. Water relations of highbush blueberry under drought conditions. *Acta Hort.* 537:273–278.
- Andersen, P.C., D.W. Buchanan, and L.G. Albrigo. 1979. Water relations and yields of three rabbiteye blueberry cultivars with and without drip irrigation. *J. Amer. Soc. Hort. Sci.* 104:731–736.
- Berruti, A. and V. Scariot. 2011. Coconut fiber: A peat-like substrate for acidophilic plant cultivation. *Acta Hort.* 952:629–635.
- Bilderback, T.E., C.R. Boyer, M. Chappell, G.B. Fain, D. Fare, C. Gilliam, B.E. Jackson, J. LeCox, A.V. LeBude, A.X. Niemiera, J.S. Owen, J. Ruter, K. Tilt, S. Warren, S. White, T. Whitewell, R. Wright, and T. Yeager. 2013. Best management practices: Guide for producing nursery crops. 3rd ed. Southern Nursery Association, Acworth, GA.
- Brazelton, C. 2016. World blueberry production summary and trends. Presentation at the 2016 SE Regional Fruit and Vegetable Conference and Tradeshow, 7–10 Jan. 2016. 6 July 2017. <<http://dev.manicmoosemedia.com/SERegional/wp-content/uploads/4-Cort-Brazelton-World-Blueberry-Acreage-and-Production-2016.pdf>>.
- Buamscha, M.G., J.E. Altland, D.M. Sullivan, D.A. Horneck, and J. Cassidy. 2007. Chemical and physical properties of douglas fir bark relevant to the production of container plants. *HortScience* 42:1281–1286.
- Cameron, J.S., C.A. Brun, and C.A. Hartley. 1988. The influence of soil moisture stress on the growth and gas exchange characteristics of young highbush blueberry plants (*Vaccinium corymbosum* L.). *Acta Hort.* 241:254–259.
- Cornell, J.A. 2011. Experiments with mixtures: Designs, models, and the analysis of mixture data. 3rd ed. Wiley, New York.
- de Boodt, M. and O. Verdonck. 1971. The physical properties of the substrates in horticulture. *Acta Hort.* 26:37–44.
- Evans, M.R., S. Konduru, and R.H. Stamps. 1996. Source variation in physical and chemical properties of coconut coir dust. *HortScience* 31:965–967.
- Fields, J.S., W.C. Fonteno, B.E. Jackson, J.L. Heitman, and J.S. Owen. 2014. Hydrophysical properties, moisture retention, and drainage profiles of wood and traditional components for greenhouse substrates. *HortScience* 49:827–832.
- Fulcher, A., N.W. Gauthier, W.E. Klingeman, F. Hale, and S.A. White. 2015. Blueberry culture and pest, disease, and abiotic disorder management during nursery production in the southeastern US: A review. *J. Environ. Hort.* 33:33–47.
- Gabriel, M.Z., J.E. Altland, and J.S. Owen. 2009. The effect of physical and hydraulic properties of peatmoss and pumice on douglas fir bark based soilless substrates. *HortScience* 44:874–878.
- Gavlak, R.G., D.A. Horneck, and R.O. Miller. 2003. Plant, soil, and water reference methods for the western region. Western Region Extension Publication WREP-25. Corvallis, OR.
- Hammond, R.F. 1975. Origin, formation and distribution of peatland resources. In: D.W. Robinson and J.G.D. Lamb (eds.). *Peat in horticulture*. Academic Press, London, UK.
- Hart, J., B.C. Strik, and H. Rempel. 2006a. Caneberries. Nutrient management guide. Oregon State Univ. Ext. Serv., EM8903-E. 6 July 2017. <<http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/20427/em8903-e.pdf>>.
- Hart, J.M., B.C. Strik, L. White, and W. Yang. 2006b. Nutrient management for blueberries in Oregon. Ore. St. Univ. Ext. Serv. Publ. EM 8918. Ore. St. Univ., Corvallis, OR. 6 July 2017. <<http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/20444/em8918.pdf>>.
- Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2014. Soil fertility and fertilizers: An introduction to nutrient management. 8th ed. Prentice Hall, Upper Saddle River, NJ.
- Hoagland, D.R. and D.I. Arnon. 1938. The water-culture method for growing plants without soil. University of California, College of Agriculture, Agricultural Experiment Station, Berkeley, CA. Circular 347:1–39.
- Hoskins, T.C., J.S. Owen, and A.X. Niemiera. 2014. Water movement through a pine-bark substrate during irrigation. *HortScience* 49:1432–1436.
- Jackson, B.E., R.D. Wright, and J.R. Seiler. 2009. Changes in chemical and physical properties of pine tree substrate and pine bark during long-term nursery crop production. *HortScience* 44:791–799.
- Jones, J.B. and V.W. Case. 1990. Sampling, handling, and analyzing plant tissue samples, p. 389–427. In: R.L. Westerman (ed.). *Soil testing and plant analysis*. 3rd ed. Soil Sci. Soc. Amer., Madison, WI.
- Knight, P.R., J.M. Anderson, and R.A. Parks. 1998. Impact of coir-based media in azalea growth. *Proc. Southern Nursery Assn. Res. Conf.* 43:28–31.
- Korcak, R.F. 1988. Nutrition of blueberry and other calcifuges. *Hort. Rev.* 10:183–227.
- Lenth, R.V. 2016. Least-squares means: The R package lsmmeans. *J. Stat. Softw.* 69:1–33.
- Machado, R.M.A., D.R. Bryla, and O. Vargas. 2014. Effects of salinity induced by ammonium sulfate fertilizer on root and shoot growth of highbush blueberry. *Acta Hort.* 1017:407–414.

- Niedziela, C.E. and P.V. Nelson. 1992. A rapid method for determining physical properties of undisturbed substrate. *HortScience* 27:1279–1280.
- Nieves-Cordones, M., F. Alemán, V. Martínez, and F. Rubio. 2014. K⁺ uptake in plant roots. The systems involved, their regulation and parallels in other organisms. *J. Plant Physiol.* 171:688–695.
- Owen, J.S. and J.E. Altland. 2008. Container height and douglas fir bark texture affect substrate physical properties. *HortScience* 43:505–508.
- Pinheiro, J., D. Bates, S. DebRoy, and D. Sarkar. R Core Team. 2016. nlme: Linear and nonlinear mixed effects models. R package version 3.
- R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 6 July 2017. <<https://www.R-project.org/>>.
- Raviv, M. 2016. Substrate's end-of-life: Environmental and horticultural considerations. *Acta Hort.* 1112:281–290.
- Raviv, M., J.H. Lieth, D.W. Burger, and R. Wallach. 2001. Optimization of transpiration and potential growth rates of 'Kardinal' rose with respect to root-zone physical properties. *J. Amer. Soc. Hort. Sci.* 126:638–643.
- Retamales, J.B. and J.F. Hancock. 2012. Blueberries. Crop production science in horticulture series. CABI International, Wallingford, UK.
- Righetti, T., K. Wilder, R. Stebbins, D. Burkhart, and J. Hart. 1998. Apples: Nutrient management guide. Ore. St. Univ. Ext. Serv. EM8712.
- Robbins, C. and C.L. Wiegand. 1990. Field and laboratory measurements, p. 76–78. In: K.K. Tanji (ed.). Standard methods for the examination of waste water. Agricultural Salinity Assessment and Management. Amer. Soc. Civil Engineers, New York, NY.
- Scagel, C.F. 2003. Growth and nutrient use of ericaceous plants grown in media amended with sphagnum moss peat or coir dust. *HortScience* 38:46–54.
- Scagel, C.F., G. Bi, L.H. Fuchigami, and R.P. Regan. 2007. Seasonal variation in growth, nitrogen uptake and allocation by container-grown *Rhododendron* cultivars. *HortScience* 42:1440–1449.
- Schachtman, D.P., R.J. Reid, and S.M. Ayling. 1998. Phosphorus uptake by plants: From soil to cell. *Plant Physiol.* 116:447–453.
- Scheffé, H. 1958. Experiments with mixtures. *J. Royal Stat. Soc. Ser. B (Methodological)* 20:344–360.
- Sims, G.K., T.R. Ellsworth, and R.L. Mulvaney. 1995. Microscale determination of inorganic nitrogen in water and soil extracts. *Commun. Soil Sci. Plant Analysis* 26:303–316.
- Stamps, R.H. and M.R. Evans. 1999. Growth of *Dracaena marginata* and *Spathiphyllum* 'Petite' in Sphagnum peat- and coconut coir dust-based growing media. *J. Environ. Hort.* 17:49–52.
- Voogt, W., P. van Dijk, F. Douven, and R. van der Maas. 2014. Development of a soilless growing system for blueberries (*Vaccinium corymbosum*): Nutrient demand and nutrient solution. *Acta Hort.* 1017:215–221.
- Wright, R.D. 1986. The pour-through nutrient extraction procedure. *HortScience* 21:227.