Influence of Pine Bark Particle Size and pH on Cation Exchange Capacity

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SUMMARY. **Cation exchange capacity (CEC) describes the maximum quantity of cations a soil or substrate can hold while being exchangeable with the soil solution. Although CEC has been studied for peatmoss-based substrates, relatively little work has documented factors that affect CEC of pine bark substrates. The objective of this research was to determine the variability of CEC in different batches of pine bark and determine the influence of particle size, substrate pH, and peat amendment on pine bark CEC. Four batches of nursery-grade pine bark were collected from two nurseries, and a single source of sphagnum moss was obtained, separated in to several particle size classes, and measured for CEC. Pine bark was also amended with varying rates of elemental sulfur and dolomitic limestone to generate varying levels of substrate pH. The CEC varied with pine bark batch. Part of this variation is attributed to differences in particle size of the bark batches. Pine bark and peatmoss CEC increased with decreasing particle size, although the change in CEC from coarse to fine particles was greater with pine bark than peatmoss. Substrate pH from 4.02 to 6.37 had no effect on pine bark CEC. The pine bark batch with the highest CEC had similar CEC to sphagnum peat. Amending this batch of pine bark with sphagnum peat had no effect on composite CEC.**

Cation exchange capacity is a commonly used soil chemical property that describes the maximum quantity of cations a soil or substrate can hold while being exchangeable with the soil solution. Cation exchange capacity is often associated with a soil or substrate's ability to hold added mineral nutrients, with higher CEC soils providing more consistent cation supply (Manning and Tripepi, 1995). Broschat (2011) attributed increased growth of downy jasmine (*Jasminum multiflorum*) and areca palm (*Dypsis lutescens*) to greater absorption of ammonium and potassium (K), respectively, from higher CEC in substrates amended with clinoptilolitic zeolite. Bigelow et al. (2001) evaluated various amendments to a sand-based medium used for putting greens and found that ammonium leaching decreased proportionally to increasing CEC of the amendment.

Cation exchange capacity is also related to pH buffering, as many of the cation exchange sites are pH dependent (Helling et al., 1964). Argo and Biernbaum (1997) reported that CEC influenced buffering of pH, calcium (Ca), and magnesium (Mg) in six greenhouse substrates. Rippy and Nelson (2007) reported that peatmoss samples with higher CEC had a greater pH buffering capacity than those with lower CEC, resulting in less pH drift.

Despite the importance of CEC in container nutrition and pH buffering, little has been documented on factors affecting CEC of conventional bark-based substrates. Nursery substrates vary by region of the country. In the northeastern United States, most nursery substrates are comprised primarily of pine bark (60% to 80% by volume) and sphagnum moss (10% to 30% by volume), with minor additions of other components such as compost, sand, gravel, and humus (personal observation). Pine bark CEC has been studied sparingly in the scientific literature. Nash and Pokorny (1990) reported a value of 96.6 meq/L for a milled pine bark, and Rideout and Tripepi (2011) reported a CEC of 81.9 meq/L for 90% pine bark amended with 10% sand. The most thorough analysis of pine bark CEC to date is work by Daniels and Wright (1988); however, they only provided CEC on a weight basis, which is less informative for container substrates than CEC on a volumetric basis (Biernbaum, 1992). Furthermore, the CEC values provided by Daniels and Wright (1988) are the weighted sums of CEC for several pine bark particle size fractions, which may provide inaccurate estimates of composite CEC since nesting and settling of particles was not taken into account (Nash and Pokorny, 1990).

Comparatively speaking, sphagnum moss CEC has been studied more extensively. Levesque and Dinel (1977) compared four peats of varying biological composition and chemical properties (including CEC) and reported that CEC increased with decreasing particle size. Rippy and Nelson (2007) evaluated CEC variation in 64 peatmoss samples selected from three mires across Alberta, Canada, and found CEC was positively correlated to the amount of rusty peatmoss (*Sphagnum fuscum*) present in the sample. The effects of amending sphagnum peat have been evaluated for substrate CEC and subsequent plant growth. Li et al. (2009) determined that CEC of a 60 peat:20 perlite:20 vermiculite substrate did not change by replacing portions of the peat with composted dairy manure. Others have noted correlations between CEC in peat-based substrates (with numerous amendments) and

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
0.3048	ft	m	3.2808
0.0283	ft^{3}	m^{3}	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
16.3871	inch^{3}	cm^{3}	0.0610
0.0160	lb/ft^{3}	g·cm^{-3}	62.4274
0.5933	lb/yard^{3}	kg·m^{-3}	1.6856
1	meq/100 g	cmol·kg^{-1}	1
1	meq/L	mmol·L^{-1}	1
1	mmho/cm	mS·cm^{-1}	1
28.3495	oz	g	0.0353
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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plant growth (Broschat, 2011; Johnson et al., 1981; Li et al., 2009), nutrient retention (Biernbaum, 1992; Bigelow et al., 2001), and substrate buffering (Argo and Biernbaum, 1997). The objective of our research was to develop a better understanding of pine bark CEC as it is used in northeastern U.S. container nursery substrates to improve nursery fertilization management. Specifically, our goals were to determine if CEC varies by pine bark batch, and the influence of pine bark particle size, substrate pH, and combinations of pine bark and sphagnum moss on CEC.

Materials and methods

Four batches of pine bark were collected from two nurseries in northern Ohio. Three of the four batches originated from a single nursery that purposefully obtains the three distinct batches for their perceived differences in texture and age. In all batches, none of the pine bark was amended with other components or fertilizers. From each batch, three 1-ft^3 subsamples were taken from 6 inches below the surface and ≈4 ft above the base of the ≈12-ft-tall bark piles. The three subsamples were combined and placed into 30-gal plastic containers with lids and stored in a climate-controlled storage barn before analysis. It was not possible to determine the precise region of the United States these batches originated, but it was verified that all were derived from pine in the southern United States. The peatmoss was a nursery-grade sphagnum moss (Conrad Fafard, Agawam, MA).

Particle size distribution was determined by passing ≈45 g of oven dried (131 °F) substrate through 2.8-, 2.0-, 1.4-, 1.0-, 0.71-, 0.50-, 0.35-, 0.25-, 0.18-, and 0.11-mm soil sieves. Particles ≤ 0.11 mm were collected in a pan. The sieves and pan were shaken for 3 min with a test sieve shaker [278 oscillations/min, 150 taps/min (RX-29/30 Ro-Tap®; W.S. Tyler, Mentor, OH)]. Following measurement, this material was discarded and not used in later experiments.

Bulk density of substrates was determined with aluminum cores attached to North Carolina State University Porometers™ (Horticultural Substrates Laboratory, North Carolina State University, Raleigh). Substrates were packed in a 347-cm^3 aluminum core (3 inches tall by 3 inches i.d.) according to methods described by Fonteno and Bilderback (1993) using three replications for each substrate. Bulk density (D_b) was determined as the weight of oven dried (162 °F) substrate in the 347-cm^3 cores.

Cation exchange capacity was determined using a modified method first described by Thorpe (1973). Subsamples from each substrate were oven dried at 200 °F in a forced air drying oven for 3 d. An approximate 2-g sample of dried substrate was placed in a 250-mL glass bottle and weighed. To this, 100 mL of 0.5-N hydrochloric acid (HCl) was added and placed on a mechanical shaker at 350 rpm for 16 h. The sample was then poured into a filter paper-lined funnel [11-cm G6 glass microfiber filter paper (Thermo Fisher Scientific, Pittsburg, PA)], which emptied into a 500-mL erlenmeyer flask. While in the funnel, the substrate sample was flushed twice with 100 mL deionized (DI) water. The filtrate was discarded after each washing. Next, the substrate was flushed with 10 mL of DI water, with 3 mL of 1% silver nitrate ($AgNO_3$) solution added to the filtrate to observe the formation of precipitates. The substrate was repeatedly flushed with 10 mL of DI water until no precipitates were observed in the filtrate. The moist substrate sample retained in the filter paper was then transferred to a clean 250-mL glass flask. To this, 100 mL of 0.5-N barium acetate [$Ba(C_2H_3O_2)_2$] was added and the mixture was shaken at 350 rpm for 15 min. This substrate slurry was filtered, using similar filter paper described above, into a clean 500-mL erlenmeyer flask with three successive 100-mL flushes of DI water. After stirring, a 40-mL subsample of the filtrate was titrated using a compact titrator (G20; Mettler Toledo, Columbus, OH) equipped with a pH electrode probe (DGi115-SC, Mettler Toledo). Sample numbers for each of the subsequent experiments were based on experience with this procedure in method development.

CEC of bark batches. Three samples from each of the four bark batches were collected for CEC analysis. Three separate samples were collected and measured for D_b. Data were subjected to analysis of variance (ANOVA) and means were separated with Fisher's protected least significant difference (LSD) test where α = 0.05.

CEC of bark batch by particle size distribution. Each bark batch and peatmoss was oven dried and ≈100 g of each material separated into six groups according to the following particle size ranges: group 1 (≥4 mm), group 2 (2 to 4 mm), group 3 (1 to 2 mm), group 4 (0.5 to 1 mm), group 5 (0.25 to 0.5 mm), and group 6 (<0.25 mm). These particle size groupings were based on the initial particle size distribution and our ability to separate the bark into six groups with enough weight for CEC determination. Barks were separated using the sieve shaker described previously. Once the peatmoss and each bark batch were separated into the six groups, two subsamples from each group were analyzed for CEC. Regression analysis was used to determine the relationship between median particle size and CEC for the peatmoss and each bark batch. Specifically, we tested the hypothesis that CEC varies by particle size (all the lines have a slope that do not equal 0), and we tested the hypothesis that CEC for each material varies by particle size differently (the parameters of the fitted functions differ). Fitted parameters for linear and nonlinear equations describing the relationship between particle size and CEC were compared using the sums of squares reduction test (Schabenberger and Pierce, 2002), where probability values were generated to test the hypothesis that parameters were similar.

This experiment was repeated with a single bark batch (batch 3) and peatmoss. About 400 g of each material was separated into three groups: group 1 (≥2.8 mm), group 2 (0.71 to 2.8 mm), and group 3 (<0.71 mm). Similar to the previous experiment, particle size groupings were chosen based on our ability to separate the bark into three different groups with sufficient weight to conduct the necessary analyses. In addition to CEC analysis, a sufficiently large sample was sieved to allow D_b analysis. Cation exchange capacity and D_b were determined for four samples per particle size class and substrate.

CEC of bark with varying substrate pH. A single bark batch (batch 3) was amended with either 1 or 2 lb/yard^3 elemental sulfur [S (Tiger 90CR Sulfur; Tiger-Sul Products, Atmore, AL)], or 4, 8, or 16 lb/yard^3 pulverized dolomitic lime (Dolomitic Limestone Pellets; Tyler's Grain and Fertilizer Co., Smithville, OH). A nonamended control sample was also prepared. Each amendment and rate was prepared by measuring 1 ft^3 of pine bark and hand-mixing the amendment in a plastic tub. Following 8 weeks of incubation, three 350-cm^3 subsamples of each treatment were placed in a glass jar, saturated with water, and measured for pH and electrical conductivity (EC) using the method described by Warncke (1998). Four separate samples per substrate treatment were subjected to CEC analysis. Data were subjected to ANOVA and mean separation using Fisher's LSD test. Contrast statements were used to test for linear or quadratic rate responses between CEC, lime rate, and S rate.

CEC OF PINE BARK AND PEAT COMBINATIONS. Pine bark (batch 3) and sphagnum moss were mixed in 1-ft^3 batches with the following pine bark:peat ratios: 0:100, 20: 80, 40:60, 60:40, 80:20, and 100:0 (by volume). Once mixed, each substrate treatment was placed in a plastic tub and allowed to homogenize with respect to moisture content. Three subsamples of each substrate were measured for D_b and two subsamples were subjected to CEC analysis. Data were subjected to regression analysis to determine the change in CEC and D_b with respect to peat and bark ratio. Means were separated with Fisher's protected LSD for treatment comparison.

Table 1. Cation exchange capacity (CEC), expressed in terms of weight and volume, and bulk density of four pine bark batches.

Pine bark batch	CEC (meq/100 g)^z	Bulk density (g·cm^{-3})^z	CEC (meq/L)^z
Batch 1	25.0	0.17	42.5
Batch 2	29.5	0.16	47.2
Batch 3	46.5	0.16	74.4
Batch 4	21.3	0.14	29.9
LSD$_{0.05}$^{y}	5.6	0.001	8.7

^{z}1 meq/100 g = 1 cmol·kg^{-1}, 1 g·cm^{-3} = 62.4274 lb/ft^3, 1 meq/L = 1 mmol·L^{-1}.

^{y}Fisher's least significant difference, when α = 0.05.

Table 2. Particle size distribution of four pine bark batches used in container nursery production (n = 3).

Class^z	Sieve (mm)^y	Particle size distribution (%)				LSD$_{0.05}$^{x}
		Batch 1	Batch 2	Batch 3	Batch 4	
Fine	0.00	1.0	0.5	3.8	1.6	0.4
	0.11	1.7	0.8	4.5	1.8	0.2
	0.18	2.0	1.0	3.6	1.5	0.2
	0.25	4.0	2.1	5.2	2.0	0.4
	0.35	4.7	2.9	5.1	2.2	0.6
	$\sum^w$	13.4	7.3	22.2	9.1	1.4
Medium	0.50	7.0	5.8	6.8	3.3	1.1
	0.71	6.9	7.2	6.8	4.0	1.1
	1.00	6.7	8.7	7.0	4.6	0.6
	1.40	8.8	12.5	9.0	8.2	0.9
	$\sum$	29.5	34.2	29.5	20.1	3.3
Coarse	2.00	9.5	11.6	9.5	10.8	0.9
	2.80	13.1	13.5	12.0	17.5	1.1
	4.00	19.9	16.3	15.0	23.2	3.1
	6.30	14.5	14.6	11.7	18.7	4.2
	12.50	0.0	2.4	0.0	0.6	1.1
	$\sum$	57.1	58.5	48.3	70.8	4.4

^{z}The class category represents three arbitrary and relative groupings of pine bark particle size.

^{y}1 mm = 0.0394 inch.

^{x}Fisher's least significant difference, when α = 0.05.

$^w\sum$ = the sum of values within a batch and class.

Results and discussion

Cation exchange capacity of the four pine bark batches differed and ranged from 29.9 to 74.4 meq/L (Table 1). Nash and Pokorny (1990) reported a value of 96.6 meq/L for a milled pine bark, which is higher than all batches analyzed here. Batch 3 had the highest CEC, expressed on a weight basis, while batch 4 had the lowest CEC value (although not different from batch 1). Differences in CEC of bark batches expressed in terms of volume followed a similar pattern due to the relatively uniform (although significantly different) D_b of the four bark batches. Differences in CEC among bark batches could be explained partly by differences in particle size of the bark. Batch 3 had the lowest percent of coarse particles (Table 2) and the highest CEC. Batches 1 and 2 had similar and intermediary percentages of coarse particles and likewise similar and intermediate CEC values, while batch 4 had the greatest percent of coarse particles and the lowest CEC. The fraction of coarse particles in a pine bark substrate, or conversely, the sum of fine and medium particles, has been shown to be strongly correlated to other physical and chemical properties (Richards et al., 1986).

When divided into six particle size fractions and analyzed, pine bark and peatmoss CEC decreased with increasing particle size (Fig. 1). However, the relationship between particle size and CEC was not consistent across the four pine bark batches or peatmoss ($P < 0.0001$). Peatmoss had the highest CEC, on a weight basis, across all particle size fractions, and decreased linearly with increasing particle size. Levesque and Dinel (1977) also reported decreased CEC with increasing particle size in four different peatmoss types. The CEC of pine bark from batch 2 also decreased linearly with increasing particle size, although the slope in this relationship was more negative than that for peatmoss (a decrease of 6 vs. 1.19 meq/100 g per millimeter increase in particle size). The relationship between CEC and particle size for the other three pine bark batches was best fit with an exponential function. Batch 3 had the highest CEC across all particle sizes and batch 1 had the lowest CEC across all particle sizes. Because only small samples from the sieves were available for CEC analysis, D_b could not be measured to determine volumetric CEC.

Pine bark from batch 3 and peatmoss were separated into three particle size classes so that there was enough substrate for analysis of CEC and D_b, allowing CEC to be calculated on both a weight and volumetric basis. Cation exchange capacity of pine bark on a weight basis decreased as particle size increased (Table 3). Bulk density also decreased with increasing particle size, further exacerbating the differences in volumetric CEC between the three particle size classes. Daniels and Wright (1988) reported that particle size of pine bark had little effect on weight-based CEC over the range of 0.05 to 2.38 mm, although they provided no statistical analysis to support their findings. However, they did report a "significant drop" in CEC among particles greater than 2.38 mm (Daniels and Wright, 1988), which is in general agreement with our data. Cation exchange capacity of peatmoss was similar among the two finer particle size classes (<0.71 mm and 0.71 to 2.8 mm), both of which were greater than the coarsest particle size (>2.8 mm). Levesque and Dinel (1977) found that particle size and peatmoss CEC were inversely related, but the relationship varied by peat type. Bulk densities of the two finest peatmoss particle size classes were different, resulting in differences in volumetric CEC across all three peatmoss particle size classes.

Amending pine bark (batch 3) with S or dolomitic lime had no effect on CEC (Table 4). EC increased linearly with increasing S and lime rate, although changes were relatively small compared with EC levels from typical fertilizer programs (LeBude and Bilderback, 2009). Substrate pH differed for each treatment; it decreased linearly with increasing S amendment but increased linearly with increasing lime amendment. Despite a range in pH of 2.35 units from the lowest to the highest measured pH, there were no differences in CEC across treatments. However, Daniels and Wright (1988) reported increased CEC in pine bark with increasing pH, but this discrepancy can be explained by differences in method. Cation exchange capacity is known to increase with increasing pH, resulting from the liberation of H^+ ions from exchange sites as pH increases (Argo and Biernbaum, 1997; Helling et al., 1964). Because of this, our method calls for CEC to be determined with pH of the buffering solutions set at neutral (Thorpe, 1973). We adjusted substrate pH but kept the pH of the buffering solutions and methodology for CEC determination constant. Our data show that changes in substrate pH, across a typical range (5.0 to 6.5) normally observed in nursery crop production (personal observation), have no effect on substrate CEC. Daniels and Wright (1988), in contrast, adjusted the pH of the buffering solutions, which ranged from 4 to 7, thus their observation of increasing CEC with increasing pH.

Pine bark to peat ratio affected CEC on a weight, but not volumetric, basis (Table 5). On a weight basis, CEC of 100% sphagnum peat is more than twice the value of 100% pine bark. Incrementally adding pine bark to peatmoss reduced CEC from 105.8 meq/100 g down to 48.0 meq/100 g. Nash and Pokorny (1990) demonstrated that CEC for combinations of two materials can be predicted by using the weighted sum of milliequivalents contributed by each component with corrections for shrinkage. Bulk density of the mixed substrates increased linearly with increasing additions of pine bark, from 0.073 $g \cdot cm^{-3}$ for 100% peatmoss to more than double that value (0.156 $g \cdot cm^{-3}$) for 100% pine bark. Because of the inverse relationship between CEC on a weight basis and D_b, volumetric CEC did not change with increasing pine bark ratio. Others have shown that adding peatmoss to pine bark substrates has either no effect or a negative effect on

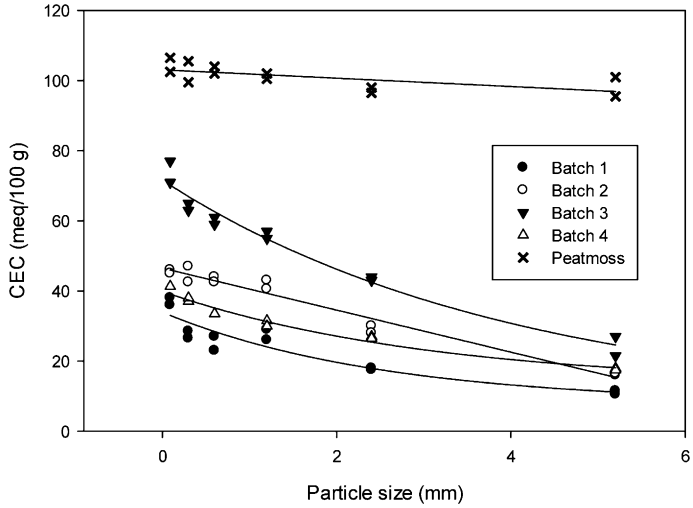

Fig. 1. The relationship between particle size and cation exchange capacity (CEC) of four bark batches. Each bark batch was fit to the following function: batch 1: $y = 7.9 + 26.0e^{-0.4x}$, $R^2 = 0.8533$; batch 2: $y = 46.5–6.0x$, $R^2 = 0.9636$; batch 3: $y = 7.0 + 64.6e^{-0.25x}$, $R^2 = 0.663$; batch 4: $y = 13.2 + 26.6e^{-0.33x}$, $R^2 = 0.9718$; and peatmoss: $y = 103.1–1.19x$, $R^2 = 0.4215$; 1 mm = 0.0394 inch, 1 meq/100 g = 1 cmol·kg^{-1}.

Table 3. Cation exchange capacity (CEC) on a weight and volume basis of pine bark and sphagnum moss separated into three particle size classes.

	Pine bark			Peatmoss		
Particle size range (mm)^z	CEC (meq/100 g)^z	Bulk density ($g \cdot cm^{-3}$)^z	CEC (meq/L)^z	CEC (meq/100 g)	Bulk density ($g \cdot cm^{-3}$)	CEC (meq/L)
<0.71	73.5	0.295	216.8	99.6	0.083	82.7
0.71 to 2.8	54.8	0.155	84.9	96.0	0.079	75.8
>2.8	24.3	0.136	33.0	77.6	0.080	62.1
$LSD_{0.05}$^{y}	3.9	0.022	6.0	5.0	0.004	4.0

^{z}1 mm = 0.0394 inch, 1 meq/100 g = 1 cmol·kg^{-1}, 1 g·cm^{-3} = 62.4274 lb/ft^3, 1 meq/L = 1 mmol·L^{-1}.

^{y}Fisher's least significant difference, when $\alpha = 0.05$.

Table 4. The effect of sulfur and pelletized dolomitic lime additions to pine bark on substrate pH, EC (EC), and cation exchange capacity (CEC).

Amendment	Rate (lb/yard^3)^z	EC (mS·cm^{-1})^z	pH	CEC (meq/100 g)^z
Sulfur	1	0.26	4.08	51.3
Sulfur	2	0.31	4.02	50.0
None	0	0.22	4.10	58.6
Dolomitic lime	4	0.20	4.71	56.4
Dolomitic lime	8	0.24	5.78	58.3
Dolomitic lime	16	0.27	6.37	58.9
Rate response: Sulfur^y		L**	L*	NS
Rate response: Lime		L*	L***	NS
$\text{LSD}_{0.05}$^{x}		0.062	0.063	NS

^{z}1 lb/yd^3 = 0.5933 kg·m^{-3}, 1 mS·cm^{-1} = 1 mmho/cm, 1 meq/100 g = 1 cmol·kg^{-1}.

^{y}NS or L represent nonsignificant or linear rate response in the measured parameter, with * and ** representing a significant response with $P < 0.05$ and 0.01, respectively.

^{x}Fisher's least significant difference, when $\alpha = 0.05$.

Table 5. Cation exchange capacity (CEC) of various combinations of pine bark and sphagnum moss, expressed in terms of weight and volume.

Pine bark (%)	Peat (%)	CEC (meq/100 g)^z	Bulk density (g·cm^{-3})^z	CEC (meq/L)^z
0	100	105.8	0.073	77.2
20	80	82.8	0.086	71.2
40	60	70.5	0.103	72.6
60	40	63.0	0.118	74.3
80	20	50.3	0.138	69.3
100	0	48.0	0.156	74.9
Rate response^y		L***Q*	L***Q**	NS
$\text{LSD}_{0.05}$^{x}		12.7	0.004	NS

^{z}1 meq/100 g = 1 cmol·kg^{-1}, 1 g·cm^{-3} = 62.4274 lb/ft^3, 1 meq/L = 1 mmol·L^{-1}.

^{y}NS, L, and Q represent nonsignificant, linear, and quadratic rate response in the measured parameter, with *, **, and *** representing a significant response with $P < 0.05$, 0.01, and 0.001, respectively.

^{x}Fisher's least significant difference, when $\alpha = 0.05$.

CEC. Johnson et al. (1981) showed that increasing the sphagnum peat ratio from 0.5 sphagnum peat:1 pine bark:1 sand to 4:1:1, respectively, increased CEC on a weight basis, but decreased CEC on a volumetric basis. Greater nutrient leaching and reduced growth of japanese privet (*Ligustrum japonicum*) in substrates with increasing ratios of peatmoss was attributed to the lower CEC levels (Johnson et al., 1981). In our study, CEC of pine bark, sphagnum moss, and all combinations thereof were similar when expressed in volumetric terms. The pine bark used was from batch 3, which had the highest CEC of the four pine bark batches (Table 1). Combinations of sphagnum peat with one of the other pine bark batches with lower CEC would likely have resulted in an increase of CEC with increasing sphagnum moss content.

In summary, these data demonstrate several key points about CEC of nursery substrates comprised primarily of pine bark. Cation exchange capacity varies by pine bark batch, and in this study, it ranged from 29.9 to 74.4 meq/L (Table 1). Variation within a batch, neither within a pile nor over time, was determined. These factors could influence CEC of pine bark substrates and are currently being studied. Variation observed in this study from batch to batch can be explained, in part, by differences in particle size distribution. Cation exchange capacity increased with decreasing particle size for all bark batches (Fig. 1); however, the four pine bark batches also had different CEC within each narrowly defined particle size range (Fig. 1). This may have been influenced by the degree of aging, composting, or decomposition. Reis et al. (1998) showed that CEC of pine bark increased slightly (without statistical analysis), from 44.2 to 49.1 meq/100 g, over a 28-month composting period. The level of aging or composting could not be documented or determined for the pine bark batches in our experiments. The impact of pine bark aging, a more common practice in the United States than composting, on CEC should be studied in the future. Second, substrate pH over the range of 4.02 to 6.37 did not affect CEC. The range of pH observed in our experiment is representative of the range of pH values typically observed in nursery crop production (LeBude and Bilderback, 2009). Finally, pine bark substrate CEC does not necessarily increase when amended with sphagnum peat. Cation exchange capacities vary for sphagnum peat (Levesque and Dinel, 1977; Rippy and Nelson, 2007) and pine bark (Table 1). The resultant CEC of any combination between sphagnum peat and pine bark will depend on the CEC of the parent components. Cation exchange capacity affects nutrient leaching from pine bark substrates, most importantly for ammonium and potassium (Broschat, 2011). Cation exchange capacity also affects pH buffering and drift over the course of crop production (Argo and Biernbaum, 1997). Growers wishing to improve nutrient retention and pH stability should have their substrates, as well as the parent components, analyzed for CEC so that more informed decisions can be made with regard to the need for amendments and ideal amendment rates. The methods used in this article could be easily adopted by most commercial or research-based substrate analysis laboratories. Because D_b of pine bark substrates can vary due to pine bark batch, as well as selection and rate of amendments, CEC should be considered on a volumetric basis when comparing two or more substrate blends.

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