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Establishing Growing Substrate pH with Compost and Limestone and the Impact on pH Buffering Capacity

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***Abstract*. The pH of peatmoss generally ranges from 3.0 to 4.0 and limestone is typically added to raise pH to a suitable range. Compost is also used as a substrate component and typically has a high pH of 6.0 to 8.0. When using compost, lime rates must be reduced or eliminated. The two objectives of this study were to determine the resulting pH of substrates created with varying amounts of limestone and compost and assess the impact of the various amounts of limestone and compost on pH buffering capacity. Compost was created from a 1:1:1 weight ratio of a mixture of green plant material and restaurant food waste:horse manure:wood chips. The first experiment was a factorial design with five compost rates (0%, 10%, 20%, 30%, and 40% by volume), four limestone rates (0, 1.2, 2.4, and 3.6 g·L^{-1} substrate) with five replications. The experiment was conducted three times, each with a different batch of compost. With 0 lime, initial substrate pH increased from 4.5 to 6.7 as compost rate increased. This trend occurred at all other lime rates, which had pH ranges of 5.2–6.9, 5.6–7.0, and 6.1–7.1 for rates of 1.2, 2.4, and 3.6 g·L^{-1} substrate, respectively. Substrate pH increased significantly as either compost or lime rates increased. The second experiment was a factorial design with four compost rates by volume (0%, 10%, 20%, and 30%), the same four limestone rates as Expt. 1, and five replications. Each substrate treatment was titrated through incubations with six sulfuric acid rates (0, 0.1, 0.2, 0.4, or 0.7 mol of H$^+$ per gram of dry substrate). Substrates with a similar initial pH had very similar buffering capacities regardless of the compost or limestone rate. These results indicate compost can be used to establish growing substrate pH similar to limestone, and this change will have little to no effect on pH buffering capacity.**

Peatmoss is one of the most commonly used substrate components in the greenhouse and nursery industry and has been used since the 1960s (Li et al., 2009; Shober et al., 2010). Currently, the environmental impacts of harvesting peatmoss are a concern since draining peatlands accelerates the decomposition process and results in the release of stored carbon to the atmosphere as carbon dioxide (Li et al., 2009). Wetlands, including peatlands, contain a vast pool of organic carbon, and currently hold about one-third of the global soil carbon stock (Freeman et al., 2004). Because of these environmental concerns, the restricted use of peat in some countries, rising cost (Sterrett, 2001), and peat scarcity issues during years of excessive precipitation (Jackson and Fonteno, 2013), a number of alternatives have been tested that include: coconut coir (Evans and Stamps, 1996), rice hulls (Buck and Evans, 2010), corn tassels (Vaughn et al., 2011), poultry feather fiber (Evans, 2004), tree-based products (Fain et al., 2008; Jackson et al., 2009), and different types of compost.

Compost has been used as a horticultural substrate additive since the 1970s and is a viable replacement for some components used in commercial substrates, specifically peatmoss (Benson, 1996; Bugbee, 1996). However, compost has not become a staple component of horticultural substrates used in the industry due to problems such as phytotoxicity, high concentration of heavy metals, chemical carry over, high salts, high pH, and inconsistency between batches (Hummel et al., 2014; Stoffella and Kahn, 2001). Since there are endless ingredients for making compost, the efficacy and rates for using each of these in greenhouse production are not well-understood (Murray and Anderson, 2004). Many of these problems can be avoided by using appropriate, high-quality, and consistent feed stocks, uniform production methods, followed by quality control testing. There are many positive impacts of using compost since it is created from recycled materials and places them back into the production stream; compost is typically locally produced, can provide supplemental nutrition, may suppress disease causing organisms, and can be used as a limestone substitute for pH establishment (Carrión et al., 2008; López-Lópeza and López-Fabal, 2013; Taylor, 2011; Wong et al., 1998).

Peatmoss has a low pH of 3.0–5.0 (Martinez et al., 1988) and typically needs 8 to 20 kg of lime per m^3 to raise the pH to an acceptable level for most crops (Nelson, 2012). Compost pH, however, can range from 5.0 (Hue, 1992) to over 8.0 (Carrión et al., 2008), but is typically 7.0 or above. Because of the high pH of most composts, limestone rates can be reduced or even eliminated when compost is used as a component of substrate or as a peatmoss replacement (Bugbee, 2002; Taylor and Nelson, 2007). Many studies have shown that when compost is added to a peat-based substrate, the resulting pH is greater (Bugbee, 2002; DeKalb et al., 2014; Dolores Perez-Murcia et al., 2005; Jeong et al., 2011; Lopez et al., 1998; Taylor and Nelson, 2007; Wilson et al., 2001).

The pH buffering capacity of growing substrates may be affected when different materials, such as lime and/or compost, are used to establish substrate pH. Titration studies have been performed on pure compost with elemental sulfur and sulfuric acid to lower the high pH of the composts to make them more suitable for containerized crops and field-grown blueberries (Carrión et al., 2008; Costello and Sullivan, 2011b). However, these studies evaluated acidification of the compost directly, rather than after it was incorporated into a final blend. The direct impact on pH buffering capacity when compost is used to establish pH compared with limestone in horticulture substrates has not been determined. Determining the pH buffering capacity of substrates produced with compost is important for pH control and high-quality crop production. The objectives of this study were to: 1) determine the resulting substrate pH when using a range of compost and limestone rates and 2) compare the pH buffing capacity of substrates that had the pH established by the addition of compost, limestone, or a combination of both.

Materials and Methods

The compost used in all experiments was created through a thermophilic composting process on an outdoor compacted soil wharf

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at Longwood Gardens in Kennett Square, PA. The compost feed stocks were a 1:1:1 ratio by weight of horse manure and bedding:wood chips:and a variable mixture of green plant material and restaurant food waste. 1800 kg of each feed stock was loaded into a running power take-off (PTO) driven dual auger mixer (5156 Vertical Maxx Mixer; Kuhn North America, Brodhead, WI). After mixing the three feed stocks for ≈5 to 10 min, a single windrow was created consisting of 11 to 13 mixed loads. This was typically created in a single day and windrows were generally 3.4 m wide, 1.5 m tall, and 50 m in length. Windrows were monitored for temperature and oxygen. Once the average internal temperature of a windrow reached 60 to 65 °C, it was turned using a PTO-driven compost turner (CMC ST 300; Compost Systems GMBH, Wels, Austria). Windrows would reach these temperatures and be turned ≈4 to 10 times during the composting process depending on the time of year, rainfall, and outside temperatures. As the feed stocks broke down, windrows were shortened in length to maintain the same width and height.

Once the average internal temperature of each windrow stayed below 60 °C the compost was considered mature and was left on the wharf for at least 30 d longer. The compost was then passed through a 0.95-cm mesh drum screen (512 A/R Trommel Screener; McCloskey International Limited, Ontario, Canada) to remove large particles. Before use in experiments, compost pH, electrical conductivity (EC), and elemental composition were determined (JR Peters Laboratory, Allentown, PA).

Expt. 1. The experiment was a factorial design with five compost rates (0%, 10%, 20%, 30%, and 40% by volume), four limestone (fine-soft white calcitic lime; Oldcastle stone products, Thomasville, PA) rates (0, 1.19, 2.37, and 3.56 g·L^{-1} substrate), and five replications, giving a total of 100 experimental units (plastic containers) per run. This experiment was run three times, each with a different batch of compost. The substrates in the first, second, and third runs were created with compost whose feedstocks were mixed on 19 May 2009 (Batch 1), 22 July 2009 (Batch 2), and 8 June 2009 (Batch 3). The experimental runs were initiated chronologically on 4 Sept. 2009, 21 Jan. 2010, and 5 May 2010. Each run lasted 22 d. The substrate treatments consisted of 25% pine bark (Harvest Garden Pro, Woodbine, MD), 5% montmorillonite clay (Red Infield Conditioner; Pro's Choice, Chicago, IL), 15% vermiculite (A4 course; Whitmore Inc. Lawrence, MA), and 15% perlite (super course; Whitmore Inc. Lawrence, MA) by volume. The remaining 40% consisted of Canadian sphagnum peatmoss (Ferti-loam, Boham, TX), compost, or a combination of both depending on the treatment. The base mix is a modified version of the general substrate used for greenhouse and nursery production at Longwood Gardens.

Each substrate treatment with various compost rates was hand mixed and then divided into four equal parts with each having different rates of limestone incorporated. Substrates were then placed into green circular plastic containers with an upper diameter of 11.75 cm of and a volume of 833 mL (5 AZ Short COEX; Dillen Product, Middlefield, OH). Containers were then placed on a bench in a randomized complete block design in a glass covered greenhouse with heating and cooling set points of 12.8 and 18.3 °C, respectively. Containers were immediately watered until water was running out of the bottom. Soil extracts were collected via the pour-through technique to be analyzed for pH and EC on the same day and 8, 15, and 22 d following (Wright, 1986). Containers were also watered on days 12 and 19 to simulate normal growing conditions as if a plant was in the container.

Expt. 2. Expt. 2 was a factorial design of four compost rates (0%, 10%, 20%, and 30% by volume) and four limestone rates (0, 1.19, 2.37, and 3.56 g·l^{-1} substrate). The base substrate ingredients were identical to Expt. 1 and the feedstocks for the compost used in this experiment were mixed on 2 Aug. 2011. The respective pH and EC of organic ingredients were 7.67 and 1591 μS, 4.63 and 91 μS, and 3.73 and 152 μS for compost, pine bark, and peat. Expt. 2 tested substrate pH buffering capacity through titration based on substrate dry weight. In preliminary experiments, oven-dried substrate was extremely hydrophobic and wettability was nearly impossible. Therefore, the moisture content of each substrate was determined and used to calculate the correct amount of substrate to use on a per weight basis for the experiment.

Table 1. pH and EC of organic materials used in Expt. 1 with compost Batches 1, 2, and 3.

	Compost		Peatmoss		Pine bark	
	pH	EC (μS)	pH	EC (μS)	pH	EC (μS)
Batch 1 experiment	7.07 a	1105 b	3.97 a	513 a	5.10 a	345 b
Batch 2 experiment	7.01 a	3320 a	2.85 b	534 a	4.78 b	780 a
Batch 3 experiment	6.90 a	3187 a	2.65 b	482 a	4.80 b	377 b

EC = electrical conductivity.

*Mean separation by least significant difference within columns at $P \leq 0.05$.

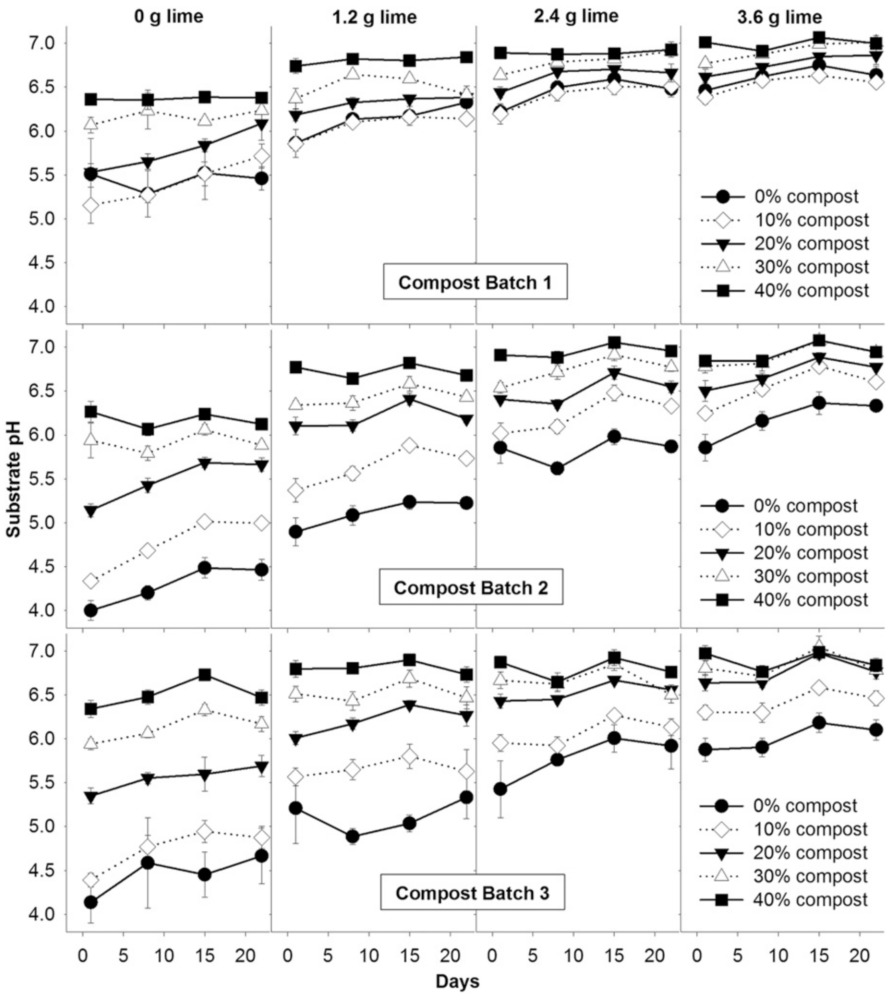

Fig. 1. pH of substrates created with 0%, 10%, 20,% 30%, or 40% compost in combination with 0, 1.2, 2.4, or 3.6 g or lime per L of substrate over 22 d in Expt. 1. Error bars represent SE (n = 5).

Substrates were mixed on 2 Aug. 2012 and placed into garbage bags for 24 h to allow the moisture to become equally distributed. Following, five replicate 120-cm^3 samples were taken of each substrate type and weighed. Samples were then placed in a drying oven at 60 °C for a minimum of 48 h and each sample was weighed to determine water content. Each treatment substrate was then equally divided into five bags and placed in a freezer and stored at –40 °C. Each of the five bags represented a replicate as this experiment was replicated over time. Substrates were frozen to prevent any physical or chemical changes to these substrates over time.

Titrations. At the beginning of each replicate titration, treatment substrates were removed from the freezer and allowed to thaw for 24 h. Each substrate was weighed to give 10 g equivalent dry substrate based on earlier water content determination. The weighed substrates were then placed into 237-mL plastic snap top vials (SKS Science Company, Watervliet, NY). Titrations were performed with different concentration of acid rather than acid applied over time. Therefore, there were six vials of each of the 16 test substrates giving a total of 96 vials per replicate. For the titrations, each of the six vials of each substrate received a specific amount of distilled water followed by 0, 2, 4, 8, or 14 mL 0.25 M H_2SO_4. The amount of distilled water added to each vial varied based on substrate water content and the amount of acid being added. The final weight ratio of the substrate to acid solution was 1:10, which resulted in 0, 0.1, 0.2, 0.4, or 0.7 mM of H^+ per gram of substrate. After the acid was added, pH readings were taken at intervals of 24, 48, 96, and 168 h. EC readings were also taken but were only performed at the 24 h test time. Before pH and EC readings, vials were stirred for 3 s and readings were taken by placing probes into the supernatant. Before and between readings vial caps remained closed to minimize reactions with ambient CO_2. pH buffering capacity was determined by taking the negative reciprocal of the linear regression slope of pH vs. mM H^+ added from the H_2SO_4

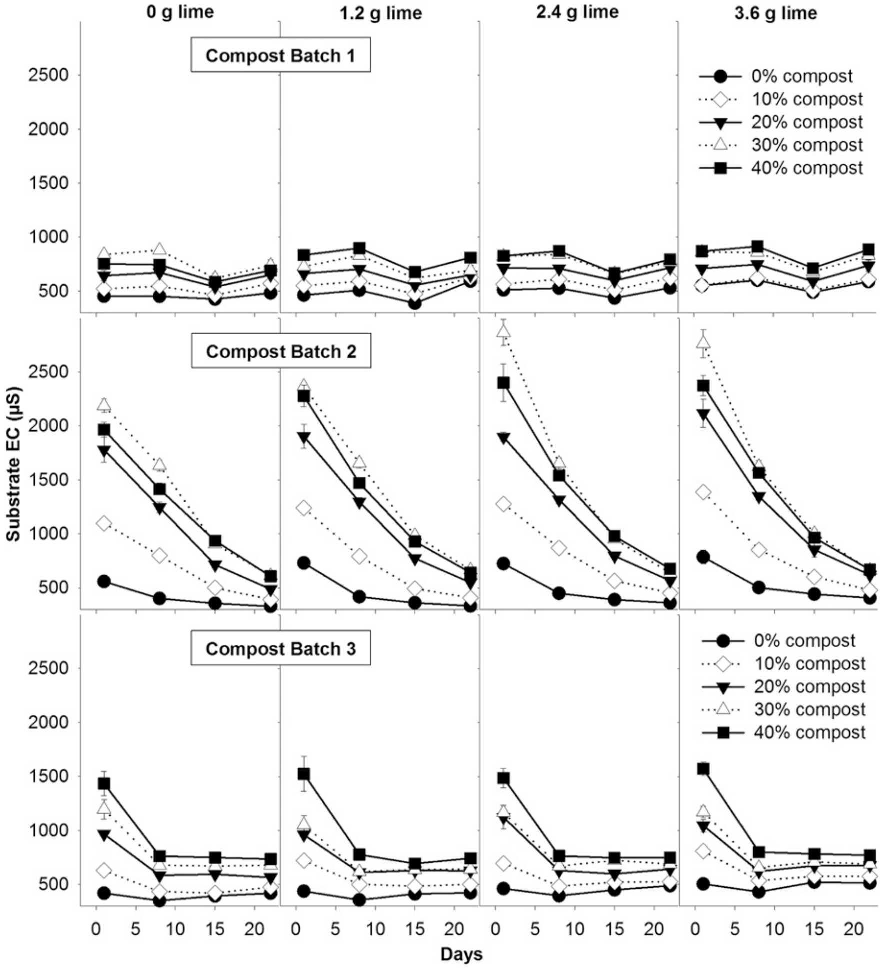

Fig. 2. Electrical conductivity of substrates created with 0%, 10%, 20%, 30%, or 40% compost in combination with 0, 1.2, 2.4, or 3.6 g or lime per L of substrate over 22 d in Expt. 1. Error bars represent SE (n = 5).

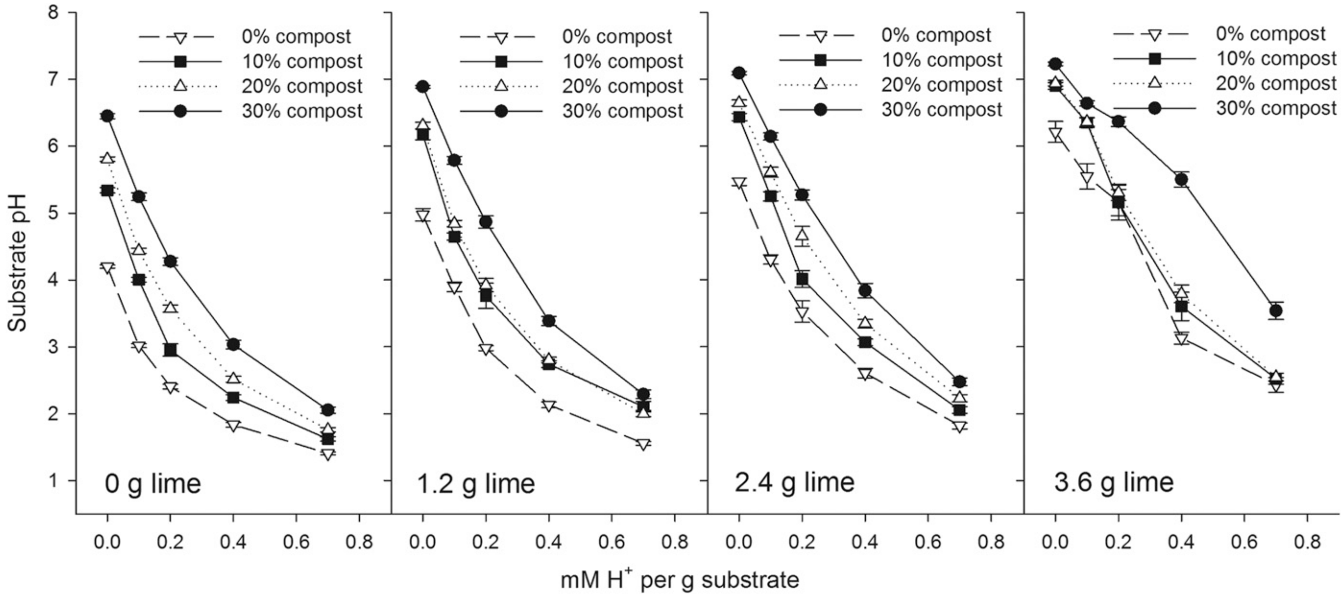

Fig. 3. Titration curves of substrates created with 0%, 10%, 20%, or 30% compost in combination with 0, 1.2, 2.4, or 3.6 g or lime per L of substrate using 0, 0.1, 0.2, 0.4, or 0.7 mM H^+ per gram of substrate in Expt. 2. Error bars represent SE (n = 5).

incubations and expressed as mM·g^{-1}·pH^{-1}, a method previously described by Costello and Sullivan (2011a), Liu et al. (2005) and McBride (1994).

Probes for pH and EC measurements for both experiments were Accumet capillary junction pH combination electrodes, gel filled with a glass body and Accumet two cell conductivity probe, respectively (Fisher Scientific, Pittsburgh, PA). Probes were attached to an Accumet Excel XL25 benchtop meter (Fisher Scientific). All experimental data were statistically analyzed as a complete block design with all interactions considered significant at $P = 0.05$ and mean separation by least significant difference test at $P = 0.05$ (SAS Institute, 2012, Cary, NC). Error bars in figures were determined using the SE function of SigmaPlot (SPSS Inc., Chicago, IL).

Results

Expt. 1. The four-way, all three-way, and most two-way interactions with batch, lime rate, compost rate, and time for pH and EC were significant. Because of interactions, pH and EC data for each batch are presented at each lime and compost rate over time. A potential source of these interactions could have been differences in inherent pH and EC of the organic ingredients used in each experiment (Table 1). There was not a significant difference in the pH of the compost batches. However, the pH of the peat and pine bark used in the Batch 1 experiment was significantly higher than the experiments with Batches 2 and 3. For EC, there were significant differences between the compost batches and pine bark used. These differences are apparent in the experimental data for pH and EC and are likely the primary source of the significant interactions.

In general, with all three batches, the substrate pH increased with lime or compost (Fig. 1). The lowest substrate pH of 4.0 and 4.1 occurred at day 1 with no lime or compost with Batches 2 and 3, respectively. The compost and lime treatments had an additive effect as both caused substrate pH to increase. In most cases, pH was level or increased slightly over time. The highest pH (at or near 7.0) was consistently observed with 40% compost and a minimum of lime rate of 1.2 g·L^{-1} substrate.

With each batch, substrate EC was near 500 µS with 0% compost at all lime rates throughout the experiment (Fig. 2). As compost percentage increased, substrate EC increased. This increase was minimal for the Batch 1 experiment and did not exceed 1000 µS at any compost rate, lime rate, or time. In the Batch 2 experiment, the greatest differences in substrate EC occurred. On day 1, substrate EC increased as compost rate increased at all lime rates and substrate EC was greater than 2100 µS with 40% compost. EC decreased significantly with time and all EC values were below 700 µS by the end of the experiment. There were similar results and trends with the Batch 3 experiment except initial EC values were not as high.

Expt. 2. With the full five fixed variable model (replications, compost rate, lime rate, acid concentration, and time), many interactions were significant for substrate pH. At each acid rate, the compost by lime interaction was significant but the compost rate by time and lime rate by time interactions were not significant. Therefore, substrate pH data are presented as a titration curve at each lime rate, comparing compost rates with combined data from the four measurement times (Fig. 3). Initial pH of substrates ranged from 4.20 to 7.23 and increased with both lime rates and compost rates, similarly to Expt. 1. With every treatment, substrate pH decreased significantly as acid concentration increased. At the highest acid concentration, substrate pH ranged from 1.41 for the zero lime and zero compost treatment to 3.54 with the highest lime and highest compost treatment. These results indicate when titrating horticultural substrates in a similar manner, using a range of acid concentrations from 0 to 0.7 mM of H$^+$ per gram of substrate, should provide a sufficient amount of acid to fully titrate the substrate though the entire pH range for nearly all horticultural crops.

The main effects of time at each acid rate on substrate pH are shown in Fig. 4. As expected, increasing acid concentration significantly lowered substrate pH. Substrate pH increased slightly or was stable over time, which indicates incubation times of 24 to 48 h may be sufficient for similar experiments. However, compost used in Expt. 2 was frozen before titrations. Wu and Ma (2001) indicate that compost samples that were previously frozen have reduced rates of CO_2 evolution compared with fresh compost. If microbial activity has a strong effect on this pH buffering system, incubation times may need to be adjusted when using fresh compost.

Increasing acid concentrations greatly increased substrate EC values of treatments and the range was from 189 to 20,360 µS with some of the highest acid concentrations (data not shown). The high substrate EC that resulted from the high acid concentrations is well above a suitable range for horticultural crops. Furthermore, the resulting EC from acid titrations is not applicable in this study. Only substrates that received 0 mol H$^+$ were analyzed statistically. The compost rate by lime rate interaction was significant and at each lime rate, substrate EC increased as compost rate increased (Table 2).

To directly compare buffering capacities, titration curves of substrates with differing compost and lime rates but similar initial pH values (difference ≤0.34 pH units) were overlaid (Fig. 5). Additionally, a single value for buffering capacity was determined for each titration curve. In each of the four graphs, there are few occasions where the substrate pH is significantly different. Buffering capacities of substrates ranged from 0.15 to 0.28 mM·g^{-1}·pH^{-1} (all data not shown). Figure 5 not only shows that the titration curves are akin but also indicates the buffering capacities are the same or within 0.01 mM·g^{-1}·pH^{-1}, regardless of lime or compost rate.

Discussion

Substrate EC. The salt content of most composts is high and therefore the EC is often greater than 3000 µS (Jeong et al., 2011; Li et al., 2009; Stoffella and Kahn, 2001). The results of Expts. 1 and 2 both showed that increasing the percentage of compost in substrate significantly increased the substrate EC and the magnitude of this effect was a function of the inherent EC of the compost. Bugbee (2002) indicated when using compost with an EC of 3300 µS, substrate EC of a peat and pine bark based substrate increased over four times from 600 to 2500 µS when compost percentage increased from 0% to 50%, respectively. The EC of compost used

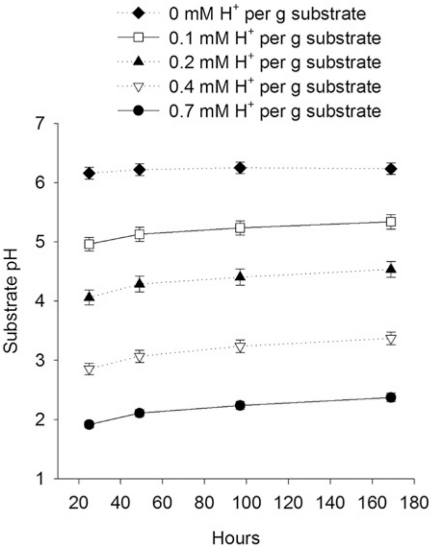

Fig. 4. The main effect of acid concentration (0, 0.1, 0.2, 0.4, or 0.7 mM H$^+$ per gram of substrate) from 24 to 168 h on pH of substrates created with 0%, 10%, 20%, 30%, or 40% compost in combination with 0, 1.2, 2.4, or 3.6 g or lime per L of substrate in Expt. 2. Error bars represent SE (n = 5).

Table 2. Effect of compost rate on electrical conductivity of treatment substrates at each lime rate in Expt. 1.

	Lime rate			
	0	2	4	6
Compost rate	µS			
0	254 d*	244 c	278 d	329 d
10	356 c	408 b	384 c	440 c
20	458 b	462 b	595 b	593 b
30	646 a	695 a	701 a	822 a

*Mean separation by least significant difference within columns at $P \leq 0.05$.

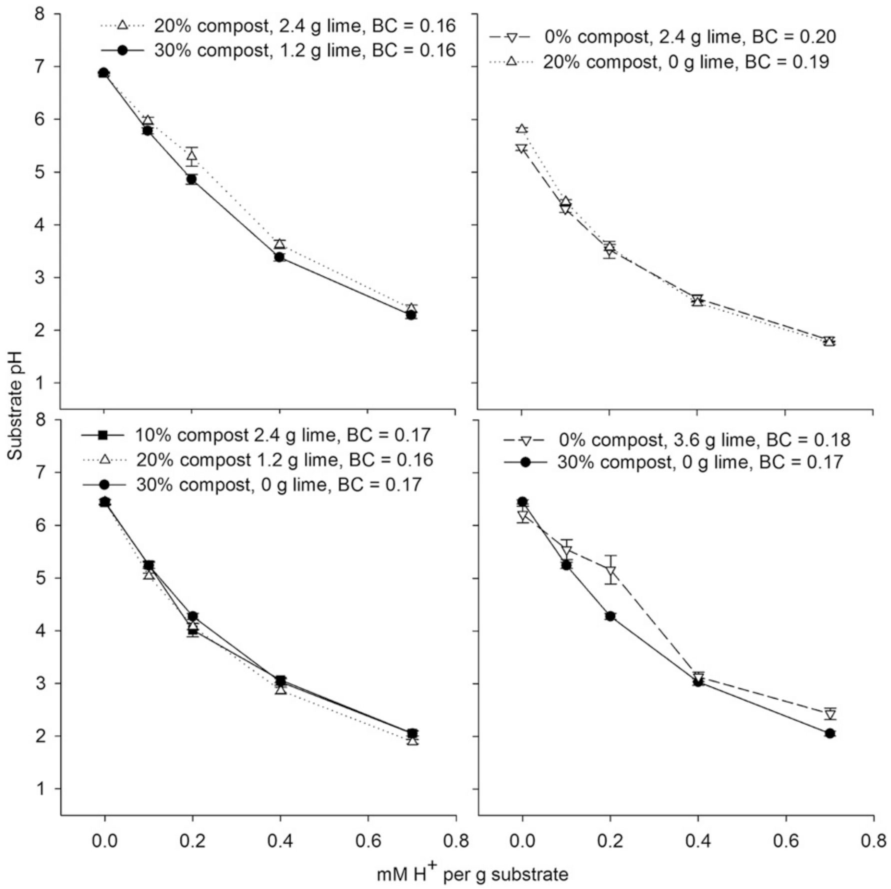

Fig. 5. Four graphs showing select titration curves of substrates created with 0%, 10%, 20%, or 30% compost in combination with 0, 1.2, 2.4, or 3.6 g or lime per L of substrate in Expt. 2. In each of the four graphs, the pH of selected substrates at 0 mM H^+ is within 0.34 units. Calculated buffering capacity ($mM \cdot g^{-1} \cdot pH^{-1}$) for each curve is also presented. Error bars represent SE (n = 5).

in Batches 2 and 3 in Expt. 1 was just above 3000 µS and when the compost percentage increased from 0% to 40% the substrate EC increased between three and four times at each lime rate. Over time, this effect was greatly reduced and with both Batches 2 and 3 in Expt. 1, the substrate EC dropped below 1000 µS at 15 d after the start of the experiment. At this point, the treatment substrate would have been irrigated four times. This indicates that the majority of the salts in high-EC compost may be leached out with only a few irrigations.

In Batch 1 of Expt. 1 and in Expt. 2, the compost EC was 1105 and 1591 µS, respectively, and all substrate EC values were below 1000 µS. This further confirms that the resulting substrate EC of peat- or pine-bark-based substrates with compost added will be a function of the compost EC. Typically, the EC of peat and pine bark is low as was also observed in this study.

Substrate pH. In horticulture, the most widely used amendment to increase the pH of substrates is limestone (Martinez et al., 1988). The results from Expts. 1 and 2 clearly indicate that compost can also be used to increase the pH of horticultural substrates, which has been shown in numerous other studies (DeKalb et al., 2014; Dolores Perez-Murcia et al., 2005; Hue, 1992; Jeong et al., 2011; Wilson et al., 2001). Results also show compost can serve as a complete or partial replacement for limestone to raise substrate pH. The amount of added compost required to achieve a desired pH is heavily dependent on the parent substrate ingredients and their pH along with the type and pH of the compost.

In Expt. 1, the pH of the three batches of compost was similar. However, the pH of both the peat and pine bark used in the Batch 1 experiment was significantly higher than what was used with Batches 2 and 3. The effect of this difference is observable when looking across all three compost batch experiments. Initial substrate pH values were consistent across all three batches with the higher compost rates (30% and 40%). At lower compost rates (0% and 10%), initial substrate pH values were much higher in the Batch 1 experiment. The variation in pH of the peat and pine bark was unexpected as they were from commercial sources. These results further emphasized the final pH of a substrate created with compost is dependent on the inherent pH of the parent substrate materials and the need for quality control when producing horticultural substrates with or without compost.

pH buffering capacity. Substrates in Expt. 2 with pH established by compost, limestone, or a combination of both, had very similar pH buffering capacities. In a study with composted dairy manure, the limestone control, and the 20% to 30% compost treatments were fairly parallel as substrate pH declined (Jeong et al., 2011). The authors indicated that the pH buffering capacity of the compost was similar to the agricultural limestone. They also suggested compost could be used in place of limestone to set the initial pH and would buffer as well as limestone, which the current study confirms.

The two most likely mechanisms involved in buffering substrate pH in this experiment are carbonate mineral buffering (limestone) and exchangeable base cation buffering (compost) (McBride, 1994). Limestone buffering pH change is a well-known process. It is also common knowledge among soil scientists that soils high in organic matter possess many base cation exchange sites on humic materials (McBride, 1994). Wong et al. (1998) indicated that the major mechanism of acid amelioration by compost is proton exchange between the soil and organic matter exchange sites. These sites exist in high amounts in compost, which is directly proportional to the cation exchange capacity and pH buffering capacity. Carrión et al. (2008) indicated that composts are alkaline because they contain few hydrogen ions on exchange sites as they are occupied by a great deal of exchangeable base cations.

Conclusion

One of the most significant impediments to using composts for container substrates is the variation in physical and chemical characteristics between different types of compost, different sources of compost, and even between different batches of the same compost from the same source. Regular testing of all substrate ingredients, particularly compost, is critical to produce a consistent and reliable growing substrate. Nevertheless, compost is a highly sustainable product made from waste materials and is regularly used in horticulture and agriculture. Although there is variability in the properties of compost, this research elucidates the effects of compost utilization in container substrates.

Higher amounts of compost can result in high substrate EC levels and therefore salt-sensitive crops should not be grown in these mixes. Expt. 1 indicated these high salts may be leached easily with just a few irrigations. Growers using higher compost rates should avoid high fertilization rates during the early stages of a crop and allow the compost to provide the majority of the nutrition. The length of the low or no fertilizer period will be dependent on the type of compost used and the particular crop.

Limestone is incorporated into peat-based substrates to raise the pH and increase pH buffering capacity (Huang et al., 2006). This research demonstrates that compost, with properties similar to the material used in this study, can be used in the same fashion as lime. When compost is used in this fashion, lime will need to be applied at lower rates or eliminated to achieve the target pH, and growers can anticipate a similar pH buffering capacity. However, growers still need to consider that not only will pH buffering be influenced by the substrate composition, but also by the type of fertilizer, specific crop, and water alkalinity (Taylor and Nelson, 2007).

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