Influence of Lime and Micronutrient Amendments on Growth of Containerized Landscape Trees Grown in Pine Bark

by

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INFLUENCE OF LIME AND MICRONUTRIENT AMENDMENTS ON GROWTH OF CONTAINERIZED LANDSCAPE TREES GROWN IN PINE BARK

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(ABSTRACT)

Growing landscape trees in containers is a common practice in the nursery industry. In the southeastern United States, pine bark is often used as a container substrate, and two common amendments to pine bark are lime and micronutrients. In this study, three experiments were conducted to determine the effect of these amendments on the growth of a wide range of landscape tree species grown in pine bark. In the first experiment, nine species of landscape trees [*Acer palmatum* (Japanese maple), *Acer saccharum* (sugar maple), *Cercis canadensis* (redbud), *Cornus florida* (flowering dogwood), *Cornus kousa* (kousa dogwood), *Koelreuteria paniculata* (golden-rain tree), *Magnolia* x *soulangiana* (magnolia), *Nyssa sylvatica* (blackgum), and *Quercus palustris* (pin oak)] were grown from seed in two pine barks: pH 4.7 (low) and 5.1 (high). Preplant amendment treatments to each pine bark (*Pinus taeda*) were: with or without dolomitic limestone (3.57 $kg \cdot m^{-3}$) and with or without micronutrients (0.9 $kg \cdot m^{-3}$, Micromax™). The same experiment was repeated using *Koelreuteria paniculata* and *Quercus palustris*, the same lime and micronutrient treatments, and two pine barks: pH 5.1 (low) and 5.8 (high). In both experiments, micronutrients increased shoot dry mass and height for all species, while lime decreased shoot dry mass and height for all species. Effect of bark type in the first experiment was variable, while shoot dry mass and height were highest in the low pH bark when the experiment was repeated. Substrate solution element concentrations increased when micronutrients were added, decreased when lime

was added, and in general, concentrations were higher in low pH bark than in high pH bark. In the third experiment, *Koelreuteria paniculata* was grown from seed in pine bark amended with 0, 1.2, 2.4, or 3.6 kg·m^{-3} dolomitic limestone and 0 or 0.9 kg·m^{-3} micronutrients (Micromax™). Initial pH for each lime rate was 4.0, 4.5, 5.0, and 5.5, respectively. Adding micronutrients increased shoot dry mass and height. Lime increased growth only at the 1.2 kg·m^{-3} rate. In general, substrate solution element concentrations increased when micronutrients were added and decreased when lime was added. In all three experiments, adding micronutrients was necessary regardless of pine bark pH, while adding lime was not necessary.

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Chapter One

Literature Review

Substrate Amendments

I. Lime

In the southeastern United States, pine bark is a frequently used container substrate, and within the nursery industry, growers often preplant amend pine bark with lime and micronutrients. The effects of lime on the chemical properties of pine bark are numerous. Substrate solution pH increases with increasing lime rate (Chrustic and Wright, 1983; Starr and Wright, 1984; Wiedenfeld and Cox, 1988). This pH increase results from neutralization of H^+ in solution by the supply of either HCO_3^- or OH^-, depending on liming material (Tisdale et al., 1993). Changes in pH subsequently affect cation exchange capacity (CEC) (Brady, 1990). Daniels and Wright (1988) showed that CEC of pine bark increased with increasing lime rate. Changes in CEC affect a substrate's capacity for binding nutrient cations, with an increase in CEC allowing more cations to adsorb to the substrate particle (Brady, 1990). Increases in pH decrease nutrient availability by increasing CEC and increasing precipitation and adsorption of nutrient cations (Brady, 1990). As a result, an increase in pH associated with lime additions often results in decreased micronutrient concentrations in pine bark solution (Niemiera and Wright, 1984) and amount of extractable micronutrients (Haynes and Swift, 1985). Peterson (1982) listed pH 4.0 to 5.2 as the optimal pH range for micronutrient availability in soilless substrates.

In the case of dolomitic limestone [$Ca\ Mg(CO_3)_2$], Ca and Mg concentrations in solution often increase with lime additions (Crockett et al., 1984; Gillman et al., 1998), hence a common justification for adding lime (Wright and Niemiera, 1987). However, Ca and Mg can be supplied in adequate amounts by either Ca or Mg sulfates (Fuller and Meadows, 1983), by the irrigation water (Whitcomb, 1984), or the substrate itself (Ogden et al., 1987).

Nitrification, the conversion of NH_4-N to NO_3-N by bacteria, is also affected by lime rate. Niemiera and Wright (1986) found that nitrification rate in pine bark

increased with increasing lime rate. This response is due to the pH-dependence of nitrification, with optimum pH being 7 to 8 (Focht and Verstraete, 1977).

Because of the numerous chemical properties that lime additions may affect, plant growth is often affected when a container substrate is preplant amended with lime. Plant growth response to lime may be related to any of these chemical factors and results vary depending on author, substrate, and plant species. *Abies fraseri* (Pursh) Poir. seedlings in a sphagnum peat substrate were found to grow best in a pH range of 4.2 to 4.5 obtained via lime additions at rates of 1 and 2 kg·m^{-3}, respectively (Bryan et al. 1989). In the same study, substrate pH of 5.0 and 7.6 (lime rates of 4 and 8 kg·m^{-3}, respectively) decreased seedling growth and resulted in chlorotic plants with blackened roots. *Carya illinoensis* (Wangenh.) C. Koch seedlings, in a pine bark-sand substrate, grew best at pH 4.3 (3 kg·m^{-3} lime) (Keever et al., 1991), while pH 4.7 to 4.9 (lime rates of 5.9 to 11.9 kg·m^{-3}) decreased growth of these seedlings. In both cases, growth was greatest at the low lime rate, indicating that high rates of lime were not necessary, and often decreased growth (due to decreased nutrient availability at higher pH; Niemiera and Wright, 1984). This result was also seen by several other authors. In work by Chrustic and Wright (1983), as lime rate increased (0, 1, 2, 4, 8 kg·m^{-3}) *Ilex crenata* Thunb. 'Helleri' and *Rhododendron obtusum* Planch. 'Rosebud' shoot dry weight decreased in a pine bark substrate. The authors attributed the negative growth response to increased NH_4 adsorption to the pine bark and increased nitrification rate at higher pH. Work with *Ilex crenata* 'Helleri' and *Juniperus horizontalis* Moench 'Plumosa' (Yeager and Ingram, 1983) in a pine bark-peat-sand substrate showed that growth was greatest with no lime additions. Sartain and Ingram (1984) showed that lime additions decreased *Juniperus horizontalis* 'Andorra Compacta' growth in a pine bark-peat-sand substrate. In each case, lime additions increased pH and therefore decreased nutrient availability. Lime has even been shown to effect seedling propagation. Diver and Whitcomb (1981) found that *Pyracantha coccinea* M. J. Roem. and *Juniperus procumbens* Endl. rooted better in the absence of lime additions.

In some cases, Ca and Mg supply are responsible for growth results. *Buddleia davidii* Franch. 'Royal Red' growth in pine bark was greatest when the substrate pH was

5.6 (2.4 kg·m^{-3} lime) (Gillman et al., 1998). Wright and Hinesley (1991) showed that *Juniperus virginiana* L. growth in a pine bark-sand substrate was greatest in a pH range of 5.5 to 6.1 (3 kg·m^{-3} lime). In both cases, growth responses were not due to substrate pH but instead to the Ca and Mg supplied by dolomitic limestone. Growth of *Photinia* x *fraseri* Dress in a pine bark-sand substrate was greatest in the presence of lime addition (4.2 kg·m^{-3}) compared to no lime addition, even though the pH ranges for unamended substrate and substrate with lime additions were similar (4.2 to 5.1 and 4.4 to 5.2, respectively) (Nash et al., 1983). The authors attributed the growth response not to a change in pH, but instead to the Mg supplied by dolomitic limestone.

II. Lime and Micronutrients

Another common amendment to pine bark is micronutrient fertilizer. Pine bark inherently contains micronutrients (Ogden et al., 1987), however individual concentrations may vary or be deficient, so micronutrient fertilizers are often added. As with lime, micronutrient additions also affect substrate chemistry. In the case of a water-soluble micronutrient fertilizer such as Micromax™, micronutrients are released over time, increasing the amount in solution, and thus increasing availability for plant uptake (Whitcomb, 1983). Micronutrient solution concentrations resulting from micronutrient additions have been shown to remain relatively constant over an 18 month period (Broschat and Donselman, 1985). The form of micronutrients applied can also affect substrate solution pH. In the case of sulfate forms of micronutrients, pH can decrease due to release of H^+ from hydrolysis involving micronutrient cations. Displacement of adsorbed cations by added micronutrient cations can also occur, affecting solution element concentrations.

As with lime, micronutrient additions have the potential to affect growth. In most cases, micronutrients are added in conjunction with lime, so most work has been done to determine plant growth response when a substrate is amended with both micronutrients and lime. There was no growth response of *Juniperus virginiana* to micronutrients when added in conjunction with lime and a negative growth response to micronutrient only additions (Wright and Hinesley, 1991). In this case, the pH of the unamended substrate

was 3.7 to 4.0. Because micronutrient cation availability increases as pH decreases (Brady, 1990; Niemiera and Wright, 1984), in cases of low pH, micronutrients inherently present in the substrate may be adequate to support plant growth (Niemiera, 1992), and for some species, micronutrient additions may induce toxicity. The lime additions used in work by Wright and Hinesley (1991) may have prevented micronutrient toxicity which possibly occurred in the micronutrient only treatment. Interactions between lime and micronutrients were also observed by Cline et al. (1986), working with *Prosopis alba* Griseb. and *Prosopis glandulosa* Torr. in a peat-perlite-vermiculite substrate. Micronutrient additions had no effect on growth in the pH range of 6.0 to 8.3 (0 and 1.2 $kg \cdot m^{-3}$ lime, respectively), but increased growth in the pH range of 8.5 to 9.0 (3.6 and 6.0 $kg \cdot m^{-3}$ lime, respectively). Hathaway and Whitcomb (1977) showed that *Quercus shumardi* Buckl., *Betula nigra* L., *Pinus thunbergii* Franco, and *Carya illinoensis* growth was greatest when the pine bark-peat-sand substrate was preplant amended with micronutrients, and that lime amendments decreased growth of these species. Benefits of micronutrient additions to soilless substrates have also been documented with *Pistacia chinensis* Bunge. and *Pinus thunbergi* in a peat-perlite substrate (Whitcomb, 1979) and *Pinus nigra* Arnold. in a pine bark-peat-perlite substrate (Field and Whitcomb, 1981).

III. Summary

Because of substrate type, species-specific responses, and experimental methodology, the responses to lime and micronutrient amendments are variable. In some cases lime has been beneficial, while in other cases it has decreased growth. Some species have responded positively to micronutrient additions, while others have not. Chemical properties such as optimal pH also vary depending on species. Most research in this area has focused on shrub species, and no work has been done to determine optimal substrate conditions for container production of a wide range of common landscape trees. Because the container production of common landscape trees is so widespread and pine bark is a common container substrate in the southeastern United States, this is an extremely important area of research for the nursery industry. This

work was undertaken to determine the lime and micronutrient preferences for a wide range of container-grown landscape trees grown in pine bark.

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Chapter Two

Preplant Lime and Micronutrient Amendments to Pine Bark Affect Growth of Nine Landscape Tree Species

Abstract

The objective of this study was to determine the lime and micronutrient amendment requirements for a wide range of container-grown landscape trees grown in pine bark substrates of different pH. Nine species of landscape trees were grown from seed in two different pH pine barks (pH 4.7 and 5.1) (Expt. 1). Species were *Acer palmatum* Thunb. (Japanese maple), *Acer saccharum* Marsh. (sugar maple), *Cercis canadensis* L. (redbud), *Cornus florida* L. (flowering dogwood), *Cornus kousa* Hance. (kousa dogwood), *Koelreuteria paniculata* Laxm. (golden-rain tree), *Magnolia* x *soulangiana* Soul.-Bod. 'Lennei' (magnolia), *Nyssa sylvatica* Marsh. (blackgum), and *Quercus palustris* Muenchh. (pin oak). Preplant amendment treatments for each of two pine bark (*Pinus taeda* L.) sources were: with and without dolomitic limestone (3.57 $kg \cdot m^{-3}$) and with and without micronutrients (0.89 $kg \cdot m^{-3}$), supplied as Micromax™. Seedlings were harvested 12 and 19 weeks after planting, and shoot dry mass and height were determined. The same experiment was repeated using *Koelreuteria paniculata* and *Quercus palustris* and pine barks of pH 5.1 and 5.8 (Expt. 2). Seedling shoot dry mass and height were measured 11 weeks after planting. For both experiments, pine bark solutions were extracted using the pour through method and analyzed for Ca, Mg, Fe, Mn, Cu, and Zn. Shoot dry mass and height of all species in both experiments were higher for micronutrient-amended bark and lower for lime-amended bark. In general, adding micronutrients increased nutrient concentrations in the pine bark solution, while lime additions decreased these concentrations. Effect of bark type in Expt. 1 was variable; however, in Expt. 2 growth was greater in the low pH bark than in the high pH bark. In general, nutrient concentrations were higher in low pH bark than in high pH bark for both experiments. Under the pH conditions of this experiment, micronutrient additions were necessary for optimal growth, and a lime amendment was not necessary.

Introduction

Pine bark is a common container substrate used by nurseries in the Southeastern United States and is often pre-plant amended with lime and micronutrients. The rationale for liming pine bark is linked to the practice of liming mineral soils to supply Ca and Mg and to raise the pH and thereby avoid heavy metal toxicity. To date, most research on the effects of lime and micronutrient amendments on soilless substrates and plant growth has been variable and mainly confined to shrub species. Sartain and Ingram (1984) showed that lime additions decreased *Juniperus horizontalis* Moench 'Andorra Compacta' growth in a pine bark-peat-sand substrate. Yeager and Ingram (1983) found that growth of *Ilex crenata* Thunb. 'Helleri' and *Juniperus horizontalis* 'Plumosa' in a pine bark-peat-sand substrate was best when grown without lime, while lime had no effect on *Rhododendron obtusum* (Lindl.) Planch. 'Hino-Crimson' growth. Chrustic and Wright (1983) showed that *Ilex crenata* 'Helleri' and *Rhododendron obtusum* 'Rosebud' growth in pine bark was not increased by liming, and that growth was even decreased at high lime rates.

Wright and Hinesley (1991), showed that the growth response of *Juniperus virginiana* L. in a pine bark-sand substrate was positive to lime additions, unaffected by micronutrients in the presence of lime additions, and negative to micronutrient-only additions. Leda (1986) found that no growth response due to micronutrient additions to pine bark occurred for *Ilex crenata* 'Helleri', *Juniperus chinensis procumbens* (Endl.) Miq. 'Nana', and *Ligustrum lucidum* Ait.

Due to the advent of the pot-in-pot tree production system as well as recent favorable market forces, the number of landscape trees being produced in containers is rapidly increasing (personal observation). However, very little information exists on the chemical substrate requirements for container-grown tree species. Research is therefore needed to determine the effects of lime and micronutrient amendments on tree growth. Since pine bark pH varies with source, the recommendation for substrate amendments may be dependent on pH. The purpose of this work was to determine the lime and

micronutrient amendment requirements for a wide range of landscape tree species grown in pine bark substrates of different pH.

Materials and Methods

Experiment 1

Nine species of landscape trees were grown in each of two pine bark (*Pinus taeda* L.) substrates (pH 4.7 and 5.1). Species were *Acer palmatum* (Japanese maple), *Acer saccharum* (sugar maple), *Cercis canadensis* (redbud), *Cornus florida* (flowering dogwood), *Cornus kousa* (kousa dogwood), *Koelreuteria paniculata* (golden-rain tree), *Magnolia* x *soulangiana* 'Lennei' (saucer magnolia), *Nyssa sylvatica* (blackgum), and *Quercus palustris* (pin oak). Amendment treatments for the two pine bark types were: with or without lime and with or without micronutrients, in a 2 (pine bark) x 2 (lime) x 2 (micronutrients) factorial arrangement. Ground dolomitic limestone (18% Ca, 10% Mg; James River Limestone Co., Inc., Buchanon, Va.) with a calcium carbonate equivalence of 100% was applied at a rate of 3.6 kg•m^{-3}. Proportions of lime passing though indicated mesh size (number of holes per 2.5 cm) were: size 8, 100%; size 10, 100%; size 20, 90%; size 50, 55%; size 60, 50%; and size 100, 35%. Micronutrients (Micromax™, Scotts-Sierra, Marysville, Ohio), had the following composition: 12% sulfur, 0.1% boron (Na_2 B_4O_7), 0.5% copper ($CuSO_4$), 12% iron ($FeSO_4$), 2.5% manganese ($MnSO_4$), 0.05% molybdenum (Na_2MoO_4), and 1% zinc ($ZnSO_4$), and was applied at a rate of 0.9 kg•m^{-3}. Micronutrients and lime were preplant incorporated using a substrate mixing apparatus. Initial pine bark pH was 4.7 (low) (Summit Bark Plant, Waverly, Va.) and 5.1 (high) (Summit Bark Plant, Lewisburg, N.C.). Bark physical properties (Fonteno et al.) for low and high pH bark, respectively, were: air space = 25.9% and 24.3%; bulk density = 213 and 200 kg•m^{-3}; total porosity = 71.2% and 79.8%;container (water holding) capacity = 45.4% and 55.5%.

Treatments were assigned in a completely randomized design with three single-container replications per treatment. Plastic 11.3 liter containers (26.7-cm diameter, 24-cm height) were filled with bark of each lime-micronutrient-bark combination. Each species was a separate experiment, and all experiments were conducted concurrently.

Approximately 30 seeds (Sheffield's Seed Company, Inc., Locke, N.Y.) per container were sown just below the substrate surface on 17 January 1997 (week 0). Seeds of all species germinated in one to two weeks and were thinned at week six to approximately 15 seedlings of uniform size per container. All seedlings were irrigated as needed with a 500-ml fertilizer solution of 300 mg•liter^{-1} N (as ammonium nitrate), 45 mg•liter^{-1}P (as phosphoric acid), and 100 mg•liter^{-1} K (as potassium chloride). Calcium and magnesium concentrations in the irrigation water were 10.2 and 4.2 mg•liter^{-1}, respectively, and micronutrient concentrations were (in mg•liter^{-1}) 0 Fe, 0 Mn, 0.04 Zn, and 0.002 Cu. Irrigation water alkalinity was 36 mg•liter^{-1}. All plants were greenhouse-grown on raised benches.

Pine bark solutions were extracted at weeks 2, 7, and 18 using the pour-through method (Yeager, et al., 1983). At each date, solution was extracted from six containers (three containers per species) per lime-micronutrient-bark treatment combination, by applying 500-ml water to the substrate surface 1 h after irrigation and collecting the substrate leachate. Leachate pH was measured, and filtered solutions were analyzed for Ca, Mg, Fe, Mn, Zn, and Cu using inductively coupled plasma analysis. Week 18 pour-through solutions were also analyzed for NO_3-N and NH_4-N using ion-specific electrodes.

At week 12, all plants except one (randomly selected) per container for *A. palmatum, A. saccharum, C. canadensis, C. florida,* and *Q. palustris* were harvested, and shoot dry mass and height were determined. For other species, all seedlings were harvested at week 12, and the same measurements were taken. At week 19, the remaining seedling for each of the above listed species was harvested, and shoot dry mass and height were determined. Samples of most recently matured leaves of *Q. palustris, K. paniculata, and C. florida* were collected and analyzed as follows. For each sample, 250 mg of dried and ground leaf tissue was ashed (approximately 4 h) at 450°C, dissolved in 20-ml 0.3 N HNO_3, filtered, and brought up to 50- ml volume with 0.3 N HNO_3. These solutions were analyzed for Ca, Mg, Fe, Mn, Zn, and Cu as described above. All data were analyzed using SAS (version 6.12) PROC GLM (SAS, 1985).

Experiment 2

The above experiment was repeated beginning on 17 July 1997 using *Koelreuteria paniculata* and *Quercus palustris*. Both pine barks were from the same sources listed previously, and the initial pH of the low and high pH barks were 5.1 and 5.8, respectively. Seedlings were thinned at week six to five seedlings of uniform size per container. All plants were harvested at week 11 for shoot dry mass and height. Pine bark solutions were extracted using the pour-through method at weeks 3 and 10 and analyzed as described above. All data were analyzed using SAS (version 6.12) PROC GLM (SAS, 1985).

Results

Micronutrient effect

Shoot dry mass and height of all species were greater for micronutrient amended bark than in bark without micronutrient additions (Expt. 1 and 2) (Tables 1, 2, 3). Depending on species, shoot dry mass increases due to micronutrient additions ranged from 15% for *Q. palustris* to 247% for *A. palmatum*. Similar patterns were seen at week 19 in Expt. 1 (data not shown). In addition to the significant main effect for micronutrients, there were also two significant growth interactions involving micronutrients. The micronutrient main effect was considered important despite the interactions, because the interactions did not change the basic growth response to micronutrients, but instead changed only the magnitude of the response (see appendix for complete ANOVA). For *K. paniculata*, *M.* x *soulangiana*, *Q. palustris*, *N. sylvatica*, *C. kousa*, (Expt. 1) and *K. paniculata* and *Q. palustris* (Expt. 2) there was a micronutrient x bark interaction, and for both species in Expt. 2 there was a micronutrient x lime interaction. Data for *K. paniculata*, Expt. 2, are shown as representative growth data for those species exhibiting micronutrient interactions. The interactions indicated that micronutrients increased dry mass or height (depending on species) more in high pH bark than in low pH bark, and more in the presence of lime than with no lime additions (Fig. 1, 2).

In both experiments, pine bark solution Fe, Mn, Cu, and Zn concentrations in micronutrient-amended bark were higher than in bark without micronutrient additions (Tables 4, 5), with increases ranging from 38% (Fe) to over 1500% (Mn). Solution Ca and Mg concentrations were higher with micronutrient additions than without. Ca concentrations in micronutrient amended bark increased 135% in Expt. 1 and 200% in Expt. 2 compared to bark without micronutrient additions. Likewise, Mg concentrations in the plus micronutrient treatments increased 147% in Expt. 1 and 224% in Expt. 2. Solution NO_3-N concentration (Expt. 1) was lower in the plus micronutrient treatments than in treatments without added micronutrients (Table 4). In both experiments, pH was 0.2 units lower in micronutrient amended bark compared to bark without a micronutrient addition. Foliage of plants grown without added micronutrients appeared chlorotic compared with those plants grown with added micronutrients. In general, adding micronutrients increased leaf micronutrient concentrations, while Ca and Mg leaf concentrations were variable (data for *Q. palustris* are shown as a representative treatment response, since the responses for *K. paniculata* and *C. florida* were generally similar) (Table 6).

Lime effect

Either shoot dry mass or height for all species at week 12 in Expt. 1 (except Japanese maple) and for both species in Expt. 2 were lower in the plus lime treatments than the minus lime treatments (Tables 1, 2, 3). However, by week 19 in Expt. 1, either height or dry mass for all species was lower in the presence of lime additions (data not shown). In addition to significant main effect for lime, there was also a significant micronutrient x lime interaction (previously explained). The main effect was addressed despite the interaction for the same reason given in the previous micronutrient section. In Expt. 1 and 2 (week 7 and week 3, respectively), pine bark solution pH was 0.6 units higher in lime-amended bark than in bark without lime additions (Tables 4, 5). This is consistent with pH values determined throughout both experiments (data not shown). Solution Mg concentration increased with lime additions in both Expt. 1 (84%) and Expt. 2 (39%) (Tables 4, 5). Solution Ca concentration was 17% lower with lime

additions compared to without lime additions in Expt. 1, and was the same in Expt. 2 (Tables 4, 5). Solution Fe, Mn, Cu, and Zn concentrations were lower in the presence of lime additions compared with no lime additions in Expt. 1 and 2 (Tables 4, 5). Solution NO_3-N concentration was 23% higher, while solution NH_4-N concentration was 99% lower with lime additions compared to without lime additions (Expt. 1) (Table 4). There were no clear trends across species for leaf element concentrations relative to lime treatments. Exceptions to this were for Mg, which was increased in the presence of lime additions compared with no lime additions, and Ca which was unaffected by lime additions (Table 6).

Bark effect

In Expt. 1, the main effect of bark type was more variable compared to lime and micronutrient effects. In Expt. 2 both shoot dry mass and height for both species was highest in low pH bark (Table 3). In addition, plants grown in high pH bark in Expt. 2 appeared chlorotic, whereas those grown in the lower pH bark did not. Solution element concentrations were lower in the high pH bark (Tables 4, 5). Decreases ranged from 37% (Ca) to 1536% (Mn) in Expt. 1 and 16% (Ca) to 149,000% (Mn) in Expt. 2. In addition to those elements supplied by micronutrient and lime additions, the unamended bark in both experiments supplied some nutrient elements, resulting from elements inherently present in the pine bark. Initial solution element concentrations (Expt. 1) for unamended low pH bark and high pH bark, respectively, were (in $mg \bullet liter^{-1}$): 37 and 32 Ca, 8.2 and 4.3 Mg, 0.90 and 0.23 Fe, 0.58 and 0.13 Mn, 0.40 and 0.30 Cu, and 0.20 and 0.17 Zn. In Expt. 2, the same elements were supplied in similar relative initial concentrations, with Expt. 2 concentrations being slightly lower than those of Expt. 1 (data not shown). Leaf element concentrations were generally higher in plants grown in low pH bark (Table 6).

Discussion

The overall positive growth response to micronutrient additions (Tables 1, 2, 3) was likely due to increased micronutrient concentrations in the pine bark solution

(Tables 4, 5). Increased leaf micronutrient concentration was also evidence of a micronutrient response (Table 6). However, few elements were present in tissue in adequate concentrations (Mengel and Kirkby, 1987). This is thought to be a result of the dilution effect often observed for tissue element concentrations in fast-growing tissue (Mengel and Kirkby, 1987). The relatively small (Tables 1, 2, 3) and usually chlorotic plants of treatments without added micronutrients was most likely due to a micronutrient deficiency, which was supported by the relatively low substrate solution micronutrient concentrations (Tables 4, 5) and corresponding leaf tissue micronutrient concentrations (Table 6). Pine bark solution Ca concentrations were higher when micronutrients were added for both bark types. The micronutrient source (Micromax™) was analyzed and did not contain sufficient Ca levels that would contribute to this effect (data not shown). There are a few probable reasons for this increase in Ca concentration. Micronutrient additions may have displaced some of the Ca adsorbed to the bark particles, resulting in the increased Ca solution concentration. The increase in Ca solution concentration may also have been due to the decrease in pH associated with micronutrient additions (Tables 4, 5). Such a decrease in pH lowers the cation exchange capacity (Daniels and Wright, 1988) and results in Ca dissociation from the bark particle. This decrease in pH was likely due to release of H^+ during hydrolysis reaction of the sulfate forms of Fe, Mn, Cu, and Zn present in Micromax™. However, the increased calcium levels are not thought be the reason for the increase in plant growth. In both experiments, Ca solution concentration for unamended bark was at least 28 mg•liter^{-1} (with ~10 mg•liter^{-1} Ca supplied by the irrigation water), and Starr and Wright (1984) found no increase in dry mass for *Ilex crenata* 'Helleri' above 5 to 10 mg•liter^{-1} Ca.

Amending pine bark with lime did not increase growth at any time, and suppressed growth for most species in Expt. 1 by week 12 (Tables 1, 2) and for all species in Expt. 1 by the final harvest date (data not shown). Both species in Expt. 2 had reduced growth when pine bark was amended with lime (Table 3). Plants in the lime only treatment appeared particularly chlorotic and had lower leaf micronutrient concentrations compared with other treatments (data not shown). This effect of lime additions on shoot concentrations most likely resulted from the lower pine bark solution

micronutrient concentration associated with plus lime treatments (Tables 4, 5), which is often referred to as lime-induce chlorosis (Mengel and Kirkby, 1987). The decrease in pine bark solution micronutrient concentrations associated with lime addition was likely due to the increase in substrate pH (Tables 4, 5). An increase in pH can reduce nutrient availability by precipitating micronutrient cations, as well as increasing adsorption of cations to the substrate particle due to higher cation exchange capacity (Brady, 1990, Daniels and Wright, 1988). The micronutrient x lime interaction in Expt. 2 (Fig. 2) indicated that micronutrients had a greater effect on growth in the presence of lime. This effect was also seen in work done by Cline et al. (1986) with *Prosopis* sp. and a peat-perlite-vermiculite substrate, in which micronutrient additions had a greater effect on growth in the presence of high (3.6 and 6.0 $kg \cdot m^{-3}$) lime rates than in low (0 and 1.2 $kg \cdot m^{-3}$) lime rates. Thus, if pine bark contains lime or if bark pH is relatively high, then a micronutrient amendment may be necessary to supply extra micronutrients for improved growth.

Amending pine bark with lime impacted other pine bark solution chemical components in addition to pH and micronutrient, Ca, and Mg concentrations. With lime additions, NO_3 -N concentrations were greater, and NH_4-N levels were lower compared to treatments without lime additions (Table 4). This response to lime additions was expected because of the increase in nitrification rates (conversion of NH_4-N to NO_3-N) associated with lime additions and the subsequent increase in substrate pH (Niemiera and Wright, 1986). Argo and Biernbaum (1997) showed that substrate pH did not affect N uptake by *Impatiens wallerana* Hook. F., and that these plants showed no growth response to NH_4-N : NO_3-N ratio. This would further support the probability that the growth differences between plus lime and plus micronutrient treatments of our work were due to a micronutrient effect and the amount of available nutrient elements present in solution.

Compared to the high pH bark, low pH bark had higher substrate solution element concentrations in Expts. 1 and 2 (Table 4, 5) and higher leaf tissue element concentrations in Expt. 1 (Table 6). The effect of bark type on growth was not as evident in Expt. 1 as it was in Expt. 2. This result is perhaps due to the lower initial pH of both

bark types of Expt. 1 (4.7 and 5.1) compared to the initial pH of the two bark types of Expt. 2 (5.1 and 5.8). Final bark pH (for both bark types) in Expt. 1 was 5.1, while in Expt. 2 it was 6.1 In spite of the drift upward in pH, Expt. 1 still had an overall lower pH range than Expt. 2. The lower bark pH values of Expt. 1 would result in more available micronutrients in both bark types in Expt. 1 than in Expt. 2 due to decreased precipitation and decreased adsorption of the nutrients to the bark particle. We saw a greater difference in growth due to bark type in Expt. 2 than in Expt. 1, because at the higher pH the micronutrients inherently present in the bark were less available (based on solution element concentrations for unamended bark). This suggests that at a relatively low pH, the inherent micronutrient supply may be sufficient to produce marketable plants. In fact, we found no growth response to micronutrient additions using a pine bark with a pH of 4.0 (unpublished data).

Bark type interaction was also important. A micronutrient x bark interaction, the most common interaction for growth data in both experiments (Fig. 1), indicated that the increase in growth due to micronutrient additions was greater for high pH bark than low pH bark. The high pH bark provided lower solution micronutrient concentrations than low pH bark. This was the case for the bark solutions of the control for each bark type (results section). Once again, the higher pH was likely responsible for decreased nutrient availability resulting either from precipitation or adsorption to bark particles. The micronutrient x lime interaction was similar in its effect, supporting the fact that micronutrient additions were particularly important in cases of elevated pH. We feel that the growth response to bark type was not due to the difference in physical properties (materials and methods), because differences were relatively small. Instead, bark pH and the resultant bark solution nutrient concentrations were the primary factors affecting growth.

The species used in this experiment represent a wide range of landscape trees from seven plant families. The main results of this experiment show that the common practice of amending pine bark with lime is unnecessary for container-grown landscape trees (grown in the pH range of these experiments) and can even be detrimental to the growth of these trees by raising the pH and making nutrients present in the substrate

unavailable for plant uptake. We make this recommendation noting that our irrigation water had Ca and Mg concentrations of 10.2 and 4.2 mg•liter^{-1}, respectively. The dramatic response to micronutrients indicates that the inherent micronutrient supply of pine bark in the pH range of these experiments limits growth, thereby necessitating a micronutrient amendment. Although plants consistently responded positively to micronutrient additions, the importance of this amendment may depend on substrate pH. The effect of micronutrients on growth was greatest under conditions of high pH and a lime addition. Under conditions of a relatively low bark pH (4.0 - 4.2), a micronutrient amendment may be unnecessary, or the rate of additions may be lower than commonly recommended. Lime additions increased substrate solution pH which resulted in decreased substrate solution and shoot tissue concentrations of nutrients which ultimately decreased growth. Whether growth results noted in these experiments are a response to a single micronutrient element or more than one is not known. This is perhaps an area for future research.

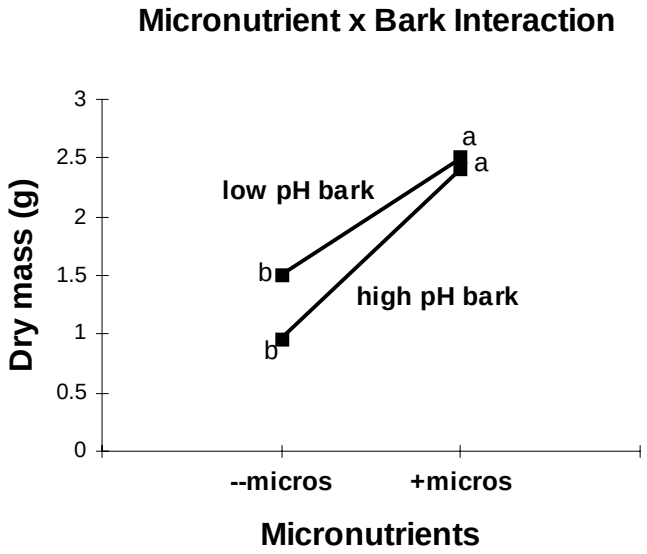

Fig. 1. Micronutrient x bark interaction showing the effect of micronutrient additions on shoot dry mass of *K. paniculata*, Expt. 2, in both low pH bark and high pH bark. Each point is the mean of 12 observations, and pairs of means within bark type are not significantly different when followed by the same letter (Tukey, HSD, α=0.05). Interaction is significant at $p \leq 0.05$.

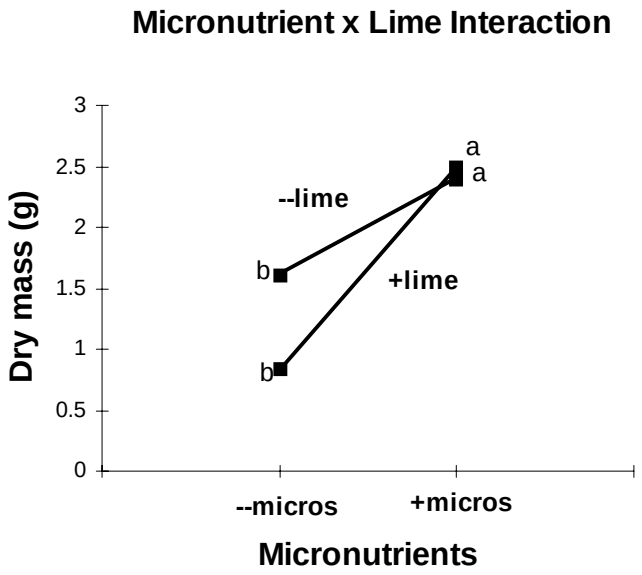

Figure 2. Micronutrient x lime interaction showing the effect of micronutrient additions on shoot dry mass of *K. paniculata*, Expt. 2, both with and without lime additions. Each point is the mean of 12 observations, and pairs of mean within lime treatment are not significantly different when followed by the same letter (Tukey HSD, α=0.05). Interaction is significant at $p \leq 0.001$.

Table 1. Main effects of micronutrients, lime, and bark type on shoot dry mass (week 12) for nine tree species, Expt. 1.

	Shoot dry mass (g)					
	Micronutrients		Lime		Bark	
Species	+	–	+	–	low pH	high pH
A. palmatum	0.66a[zy]	0.19b	0.38a	0.46a	0.44a	0.40a
A. saccharum	0.55a	0.30b	0.39b	0.46a	0.42a	0.44a
C. canadensis	0.77a	0.38b	0.50b	0.64a	0.60a	0.55a
C. kousa	0.67a	0.34b	0.37b	0.63a	0.34b	0.66a
C. florida	0.80a	0.34b	0.50b	0.63a	0.48b	0.66a
Q. palustris	1.44a	1.27b	1.34a	1.38a	1.34a	1.38a
K. paniculata	1.2a	0.52b	0.80a	0.91a	0.85a	0.86a
M. x *soulangiana*	0.30a	0.22b	0.24b	0.28a	0.23b	0.29a
N. sylvatica	0.22a	0.13b	0.16b	0.20a	0.17a	0.18a

[z] Means reported are for n = 12 observations.

[y] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

Table 2. Main effects of micronutrients, lime, and bark type on shoot height (week 12) for nine tree species, Expt. 1.

	Shoot height (cm)					
	Micronutrients		Lime		Bark	
Species	+	–	+	–	low pH	high pH
A. palmatum	25.8a[zy]	10.1b	16.7a	19.2a	19.4a	16.5b
A. saccharum	15.2a	11.1b	12.6a	13.7a	13.0a	13.3a
C. canadensis	20.2a	13.3b	15.4b	18.1a	17.7a	15.8a
C. kousa	12.7a	7.6b	9.0b	11.4a	8.8b	11.6a
C. florida	15.6a	9.9b	12.0b	13.5a	12.5a	13.0a
Q. palustris	24.3a	22.2b	22.4b	24.2a	23.5a	23.1a
K. paniculata	10.4a	6.4b	7.8b	9.0a	8.2a	8.6a
M. x *soulangiana*	6.5a	5.2b	5.6a	6.1a	5.3b	6.3a
N. sylvatica	6.1a	4.9b	5.3b	5.8a	5.2b	5.8a

[z] Means reported are for n = 12 observations.

[y] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

Table 3. Main effects of micronutrients, lime, and bark type on shoot dry mass and height (week 11) for *Q. palustris and K. paniculata*, Expt. 2.

Species	Shoot dry mass (g)						Shoot height (cm)					
	Micronutrient		Lime		Bark type		Micronutrients		Lime		Bark type	
	+	–	+	–	low pH	high pH	+	–	+	–	low pH	high pH
Q. palustris	3.1a[zy]	2.5b	2.7a	2.9a	3.1a	2.5b	32.3a	27.2b	28.9b	30.6a	32.0a	24.7b
K. paniculata	2.4a	1.2b	1.7b	2.0a	2.0a	1.7b	11.4a	7.4b	8.4b	10.4a	10.5a	8.3b

[z] Means reported are for n = 12 observations.

[y] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

Table 4. Pine bark solution pH and element concentrations at week 7, Expt. 1[z].

	Micronutrients		Lime		Bark Type	
	+	–	+	–	low pH	high pH
pH	5.1a[yx]	5.3a	5.5a	4.9b	5.1b	5.3a
Ca	73.9a[w]	31.5b	47.8b	57.6a	60.9a	44.5b
Mg	27.2a	11.0b	24.7a	13.4b	25.0a	13.1b
Fe	0.08a	0.05b	0.05b	0.08a	0.08a	0.05b
Mn	1.80a	0.15b	0.46b	1.49a	1.8a	0.11b
Cu	0.02a	0.01b	0.01b	0.02a	0.02a	0.01b
Zn	0.31a	0.09b	0.09b	0.30a	0.28a	0.12b
NO_3-N	88.1b	104.0a	106.1a	86.0b	84.0b	108.0a
NH_4-N	2.3a	5.6a	0.04b	7.9a	4.4a	3.5a

[z]Data shown here are representative of pour-through data taken weeks 2 and 18 in Expt. 1.

[y] Means reported are for n = 24 observations.

[x] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

[w]Elemental concentration expressed in mg•liter^{-1}.

Table 5. Pine bark solution pH and element concentrations at week 3, Expt. 2[z].

	Micronutrients		Lime		Bark Type	
	+	–	+	–	low pH	high pH
pH	5.6b[yx]	5.8a	6.0a	5.4b	5.4b	6.0a
Ca	175.3a[w]	58.3b	118.9a	114.8a	125.7a	107.9b
Mg	47.0a	14.5b	35.8a	25.8b	37.5a	24.0b
Fe	0.11a	0.08b	0.07b	0.12a	0.11a	0.08b
Mn	2.9a	0.17b	0.64b	2.4a	3.0a	0.02b
Cu	0.02a	0.008b	0.01b	0.02a	0.02a	0.01b
Zn	0.47a	0.08b	0.11b	0.44a	0.46a	0.12b

[z]Data shown here are representative of pour-through data taken weeks 2 and 18 in Expt. 1.

[y] Means reported are for n = 24 observations.

[x] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

[w]Elemental concentration expressed in mg•liter^{-1}

Table 6: Elemental concentrations for *Q. palustris* leaf tissue at week 19 harvest, Expt. 1.

	Tissue concentration					
	Micronutrients		Lime		Bark type	
Element	+	-	+	-	low pH	high pH
Ca (%)	0.55a	0.49b[zy]	0.51a	0.54a	0.54a	0.50b
Mg (%)	0.15b	0.19a	0.22a	0.12b	0.18a	0.16b
Fe (μg/g)	41.8a	36.5b	41.4a	36.9b	43.6a	34.7b
Mn (μg/g)	221.8a	150.5b	167.4b	204.8a	127b	245a
Cu (μg/g)	5.53a	3.83b	4.93a	4.40b	5.5a	3.9b
Zn (μg/g)	38.4a	31.7b	40.2a	29.9b	39.2a	31.0b

[y] Means reported are for n=12 observations.

[z] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, α=0.05).

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Chapter Three

Micronutrient Fertilization Essential Regardless of Pine Bark pH

Abstract

The purpose of this work was to determine the growth effects of micronutrient amendments to pine bark with a wide pH range. *Koelreuteria paniculata* seedlings were container-grown in pine bark amended (preplant) with 0, 1.2, 2.4 or 3.6 kg·m^{-3} dolomitic limestone and 0 or 0.9 kg·m^{-3} micronutrients (Micromax™). Initial pine bark pH for each lime rate was 4.0, 4.5, 5.0, and 5.5, respectively. Final pH (week 10) ranged from 4.7 to 6.4. Seedlings were harvested at week 10, and shoot dry mass and height were determined. Pine bark solution was extracted using the pour-through method at weeks 3, 7, and 10 and analyzed for pH, Ca, Mg, Fe, Mn, Cu, and Zn. Shoot dry mass and height were higher in micronutrient-amended bark than in bark without micronutrient amendments. Lime increased growth only in the absence of micronutrient additions. In general, adding micronutrients increased pine bark solution Ca, Mg, and micronutrient concentrations. Adding lime increased pine bark solution pH and Mg concentration and either had no effect on or decreased solution Ca and micronutrient concentrations. Regardless of pine bark pH, micronutrient additions were necessary for optimal growth, while adding lime was not.

Introduction

Soilless substrates are commonly amended with dolomitic limestone to increase pH and supply Ca and Mg. Plant growth response to lime may be related to one or both of these factors. Increasing pH due to lime additions decreases micronutrient availability, increases cation exchange (Brady, 1990), and alters the NH_4-N : NO_3-N ratio by increasing nitrification rate (Niemiera and Wright, 1986). Recommendations for lime incorporation and substrate pH varies according to author, substrate, and species. *Abies fraseri* (Pursh) Poir. seedlings in a sphagnum peat substrate were found to grow best in a pH range of 4.2 to 4.5 obtained via lime additions of 1 and 2 kg·m^{-3}, respectively (Bryan et al., 1989). In the same study, substrate pH of 5.0 and 7.6 (lime

rates of 4 and 8 kg·m^{-3}, respectively) decreased seedling growth and resulted in chlorotic plants with blackened roots. *Carya illinoensis* (Wangenh.) C. Koch seedlings, in a pine bark-sand substrate, grew best at pH 4.3 (3 kg·m^{-3} lime), while a pH 4.7 to 4.9 (lime rates of 5.9 to 11.9 kg·m^{-3}) decreased seedling growth (Keever et al., 1991). *Buddleia davidii* Franch. 'Royal Red' shoot and root dry weights in pine bark were highest when the substrate pH was 5.6 (2.4 kg·m^{-3} lime) (Gillman et al., 1998). Wright and Hinesley (1991) showed that *Juniperus virginiana* L. growth in a pine bark-sand substrate was greatest in a pH range of 5.5 to 6.1 (3 kg·m^{-3} lime). In all three of the above instances, the authors attributed the positive growth responses to the Ca and Mg supplied by dolomitic limestone and not to substrate pH. In work by Keever et al. (1991) and Gillman et al. (1998), high lime rates resulted in decreased growth. In contrast, fresh weight of *Photinia* x *fraseri* Dress in a pine bark-sand substrate was highest in the presence of lime addition (4.2 kg·m^{-3}), even though the pH ranges for unamended substrate and substrate with lime were similar (4.2 to 5.1 and 4.4 to 5.2, respectively) (Nash et al., 1983).

Growth response to substrate amendment of both lime and micronutrients has also been reported. There was no growth response of *Juniperus virginiana* to micronutrients when added in conjunction with lime, and a negative growth response to micronutrient only additions was reported (Wright and Hinesley, 1991). In this case, the pH of the unamended pine bark-sand substrate was 3.7 to 4.0. Because micronutrient cation availability increases as pH decreases (Brady, 1990), micronutrients present in a low pH substrate may be adequate to support plant growth (Niemiera, 1992), and for some species, micronutrient additions may induce toxicity. Cline et al. (1986), working with *Prosopis alba* Griseb. and *Prosopis glandulosa* Torr. in a peat-perlite-vermiculite substrate, found that micronutrient additions had no effect on growth in the pH range of 6.0 to 8.3 (0 and 1.2 kg·m^{-3} lime, respectively), but increased growth in the pH range of 8.5 to 9.0 (3.6 and 6.0 kg·m^{-3} lime, respectively). Hathaway and Whitcomb (1977) showed that *Quercus shumardi* Buckl., *Betula nigra* L., *Pinus thunbergii* Franco, and *Carya illinoensis* shoot height was highest when the pine bark-peat-sand substrate was preplant amended with micronutrients, and that lime decreased growth of these species.

Benefits of micronutrient additions to soilless substrates have also been documented with *Pistacia chinensis* Bunge. and *Pinus thunbergi* in a peat-perlite substrate (Whitcomb, 1979) and *Pinus nigra* Arnold. in a pine bark-peat-perlite substrate (Field and Whitcomb, 1981). In Chapter Two, adding lime to pine bark decreased growth, whereas adding micronutrients increased growth for pine bark with initial pH values of 4.7 to 5.8. However, this information on the effect of micronutrient additions on the growth of common containerized landscape trees did not characterize responses for a wide pH range, particularly at pH below 4.7. Since micronutrient cation availability increases as substrate pH decreases, the possibility exists that micronutrient amendments may not be necessary at relatively low pH. The purpose of this experiment was to determine the effect of preplant micronutrient amendments to pine bark on growth of *Koelreuteria paniculata* seedlings in pine bark substrates of different pH. *Koelreuteria paniculata* was selected since the growth response of this species to micronutrient and lime treatments was representative of several common landscape tree species (Chapter Two).

Materials and Methods

Preplant amendment treatments to pine bark (*Pinus taeda* L.; Summit Bark Plant, Waverly, Va.) were four lime rates (0, 1.2, 2.4, or 3.6 $kg \cdot m^{-3}$, resulting in initial bark pH values of 4.0, 4.5, 5.0, and 5.5, respectively) each with micronutrients (0.9 $kg \cdot m^{-3}$) or without. This resulted in a 4 (lime) x 2 (micronutrients) factorial experiment. Ground dolomitic limestone (18% Ca, 10% Mg; James River Limestone Co., Inc., Buchanon, Va.) had a calcium carbonate equivalence of 100%. Proportions of lime passing though indicated mesh size (number of holes per 2.5 cm) were: size 8, 100%; size 10, 100%; size 20, 90%; size 50, 55%; size 60, 50%; and size 100, 35%. Micronutrients were supplied by Micromax™ (Scotts-Sierra, Marysville, Ohio), which had the following composition: 12% sulfur, 0.1% boron (sodium borate), 0.5% copper (copper sulfate), 12% iron (ferrous sulfate), 2.5% manganese (manganese sulfate), 0.05% molybdenum (sodium molybdate), and 1% zinc (zinc sulfate). Micronutrients and lime were preplant incorporated using a substrate mixing apparatus.

Treatments were assigned in a completely randomized design with six single-container replications per treatment. Plastic 3.8 containers (19-cm diameter, 18-cm height) were filled with bark of each lime-micronutrient combination. Approximately 20 *Koelreuteria paniculata* seeds (Sheffield's Seed Co., Inc., Locke, N.Y.) per container were sown just below the substrate surface on 24 March 1998 (week 0). Seeds germinated in two to three weeks and were thinned at week 8 to five seedlings of uniform size per container. Seedlings were irrigated as needed with 300-ml fertilizer solution of 300 mg•liter^{-1} N (as ammonium nitrate), 45 mg•liter^{-1}P (as phosphoric acid), and 100 mg•liter^{-1} K (as potassium chloride). Calcium, Mg, and alkalinity concentrations in the irrigation water were 10.2, 4.2, and 36 mg•liter^{-1}, respectively, and micronutrient concentrations (in mg•liter^{-1}) were 0 Fe, 0 Mn, 0.04 Zn, and 0.002 Cu. Plants were greenhouse-grown on raised benches.

Pine bark solutions were extracted from three containers per lime-micronutrient treatment combination at weeks 3, 7 and 10, using the pour-through method (Yeager et al., 1983), by applying 300 ml water to the substrate surface and collecting the leachate. Leachate pH was measured, and filtered solutions were analyzed for Ca, Mg, Fe, Mn, Zn, and Cu using inductively coupled plasma analysis. Seedlings were harvested at week 10 and shoot dry mass and height were determined.

Results

Shoot dry mass and height were higher, 74% and 56%, respectively, when seedlings were grown in pine bark amended with micronutrients compared to plants grown without micronutrient additions (Table 1). Lime additions had no effect on shoot dry mass or height (Table 1), with the exception of a slight growth increase at the 1.2 kg•m^{-3} lime rate in the absence of micronutrients. In this case, shoot dry mass increased from 0.7 g at the zero lime rate to 1.1 g at the 1.2 kg•m^{-3} (single degree of freedom contrast, analysis not shown), and above the 1.2 kg•m^{-3} rate there was no effect of lime rate on growth.

Only week 3 pour-through data (Tables 2, 3) are presented since these data were similar to those for weeks 7 and 10. Magnesium solution concentration was highest at

the 3.6 kg·m^{-3} lime rate and 173% higher with micronutrient additions compared to without micronutrient additions (Table 2). Iron solution concentration was highest without lime additions compared to the three plus-lime rates and 165% higher with micronutrient additions compared to treatments without micronutrient additions (Table 2). Copper solution concentration was 400% higher with micronutrient additions than without (Table 2).

There was a significant lime x micronutrient interaction for pH and Ca, Mn, and Zn pine bark solution concentrations (Table 3). Single degree of freedom contrasts were used to compare the effect of micronutrient additions on pH, and Ca, Mn, and Zn concentrations at each lime rate. At each lime rate, micronutrient additions significantly increased Ca, Mn, and Zn solution concentrations compared to corresponding values for bark without added micronutrients (analysis not shown). The interaction indicated that lime had no effect on Ca, Mn, and Zn concentrations without micronutrient additions, but with micronutrient additions concentrations were highest at the zero lime rate compared to the three plus-lime rates (Table 3).

Pine bark solution pH increased approximately one unit from week 0 to week 10 at each lime rate. Initial and week 10 pH values for the 0, 1.2, 2.4, and 3.6 kg·m^{-3} lime treatments were 4.0 to 4.7, 4.5 to 5.8, 5.0 to 6.0, and 5.5 to 6.4, respectively. In bark both with and without micronutrient additions, pH increased due to lime additions (Table 3). However, the lime x micronutrient interaction for pH indicated that lime increased pH more in the plus micronutrient treatments (pH 4.0 to 5.9) than when no micronutrients were added (pH 4.5 to 6.0; data pooled over lime rate; Table 3). Without lime, bark pH was 0.5 units lower with micronutrient additions, than without (contrast analysis not shown, Table 3).

Discussion

Preplant micronutrient additions to pine bark increased shoot dry mass and height (Table 1), which may be explained by the increased solution Fe, Mn, Zn, and Cu concentrations due to preplant micronutrient additions (Tables 2, 3). At the zero lime rate, substrate solution pH values of the with and without micronutrients were 4.0 and

4.5, respectively (Table 3). The reason for the lower pH of pine bark with added micronutrients compared to bark without added micronutrients was likely due to release of H^+ during hydrolysis reaction of the sulfate forms of Fe, Mn, Cu, and Zn present in the micronutrient fertilizer (Micromax™). The decrease in pH may have resulted in the micronutrients inherent in the bark becoming more soluble, also contributing to increased solution concentration. Also in plus micronutrient treatments, Ca and Mg concentrations were higher (Tables 2, 3) than without micronutrient additions. Because the micronutrient fertilizer contained only trace amounts of Ca or Mg (data not shown), the increase in concentrations of these elements is attributed to an increase in dolomitic lime solubility (Berner and Morse, 1974) as a result of the decrease in pH that accompanied micronutrient additions.

Lime additions had no main effect on shoot dry mass or height (Table 1). In Chapter Two, pine bark amended with 3.6 kg·m^{-3} lime decreased shoot dry mass and height of *Koelreuteria paniculata*. Current solution micronutrient concentrations in the 3.6 kg·m^{-3} lime treatment (Tables 2, 3) were as much as six times higher than those in Chapter Two for the 3.6 kg·m^{-3} lime treatment. Even though lime additions decreased solution micronutrient concentrations in both experiments, the possibility exists that concentrations in the current work were above threshold levels that would inhibit growth.

Contrast analysis for the effect of lime rate on growth (no micronutrient amendment) showed that dry mass increased 57% from 0 kg·m^{-3} lime to 1.2 kg·m^{-3} lime, but was not increased at higher rates. In addition, plants in the 1.2 kg·m^{-3} lime only treatment appeared less chlorotic than those of the control (0 kg·m^{-3} lime). The positive growth response to the low lime rate in the absence of micronutrient additions was not associated with an increase in substrate solution micronutrient concentration (Fe and Cu, data not shown; Mn and Zn, Table 3). In addition, the dolomitic limestone contained only trace amounts of micronutrients (<2 ug·g^{-1}), so this growth response was likely not due to micronutrient impurities in the lime. We also do not attribute this growth response to Ca solution concentration, because for all treatments, Ca solution concentration was at least 20 mg·liter^{-1} (data not shown). Starr and Wright (1984) found no increase in growth of *Ilex crenata* Thunb. 'Helleri' for pine bark solution Ca and Mg

concentrations higher than 5 to 10 mg·liter^{-1}. Instead, we attribute the growth response to the low lime rate (no micronutrients added) to Mg supply. In unamended bark, Mg solution concentration was 5 mg·liter^{-1} and increased to 10 and 18 mg·liter^{-1} at 1.2 and 2.4 kg·m^{-3} lime (without micronutrient additions), respectively. So, at lime rates above 1.2 kg·m^{-3}, the critical minimum value for Mg solution concentration of 5 to 10 mg·liter^{-1} (Starr and Wright, 1984) was exceeded, and the effect of lime was not significant.

The reason for the overall one unit increase in pH for each lime rate from week 0 to week 10 may be due to the alkalinity of the irrigation water (36 mg·liter^{-1}). Williams et al. (1988) found that even moderately alkaline irrigation water (38 mg·liter^{-1}) may raise the substrate solution pH in some cases more than a lime amendment.

Results of this experiment illustrated that micronutrient amendments to pine bark are necessary regardless of substrate pH. Initial bark pH ranged from 4.0 to 5.5, values commonly encountered by nurseries. In addition, the need for micronutrient additions was consistent for all lime rates used in this experiment. Because *Koelreuteria paniculata* performed similarly to other common landscape tree species in Chapter Two, results of this experiment suggest that optimal growth of containerized landscape trees requires a micronutrient amendment. In addition, we found no positive influence of lime on growth and question the routine use of this amendment if the irrigation water or substrate supplies ample Ca and Mg.

Table 1. Main effect of lime and micronutrients on shoot dry mass and height of *K. paniculata*, week 10.

Main effect		Shoot dry mass (g)	Height (cm)
Lime rate	($kg \cdot m^{-3}$)		
	0	1.1a[zy]	10.7a
	1.2	1.4a	10.9a
	2.4	1.3a	10.7a
	3.6	1.2a	10.8a
Micronutrients	($kg \cdot m^{-3}$)		
	0	0.90b	8.4b
	0.89	1.57a	13.1a
Significance[x]	Lime	NS	NS
	Micronutrients	***	***
	Lime x Micros	NS	NS

[z] Means reported are for n = 12 observations.

[y] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

[x] NS, *** nonsignificant or significant at $p \leq 0.001$, respectively.

Table 2. Main effects of lime and micronutrients on pine bark solution Mg, Fe, and Cu concentrations at week 3.

Main effect		Substrate solution concentration (mg·liter^{-1})		
		Mg	Fe	Cu
Lime rate	(kg·m^{-3})			
	0	21.5b[zy]	0.64a	0.03a
	1.2	22.5b	0.50ab	0.03a
	2.4	25.6b	0.31b	0.03a
	3.6	35.6a	0.22b	0.04a
Micronutrients	(kg·m^{-3})			
	0	14.1b	0.23b	0.01b
	0.89	38.5a	0.61a	0.05a
Significance[x]	Lime	**	**	NS
	Micronutrients	***	***	***
	Lime x Micros	NS	NS	NS

[z] Means reported are for n = 6 observations.

[y] Pairs of means within main effect are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

[x] NS, **, ***, nonsignificant or significant at $p \leq 0.01$, 0.001, respectively.

Table 3. Pine bark solution pH and Ca, Mn, and Zn concentrations at week 3.

Treatment		pH	Substrate solution concentration (mg·liter^{-1}) Ca	Mn	Zn
+ *Micros*					
Lime rate	(kg·m^{-3})				
	0	4.0d[zy]	118a	6.9a	1.2a
	1.2	5.1c	57b	2.1b	0.32b
	2.4	5.5b	45b	0.98b	0.18b
	3.6	5.9a	55b	1.1b	0.17b
- *Micros*					
Lime rate	(kg·m^{-3})				
	0	4.5d	21a	0.41a	0.16a
	1.2	5.0c	22a	0.34a	0.11a
	2.4	5.4b	27a	0.27a	0.07a
	3.6	6.0a	29a	0.22a	0.05a
Significance[x]	Lime	***	***	***	***
	Micros	*	***	***	***
	Lime x Micros	***	***	***	***

[z]Means reported are for n = 3 observations.

[y] Column means within micronutrient treatment are not significantly different when followed by the same letter (Tukey HSD, $\alpha = 0.05$).

[x] NS, *, **, ***, nonsignificant or significant at $p \leq 0.05, 0.01, 0.001$, respectively.

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Significance to Industry

Results of this thesis indicate that lime additions to pine bark are not necessary to improve growth of containerized landscape trees and in many cases produced detrimental results. Lime additions were also not necessary to supply Ca and Mg, since the irrigation water supplied sufficient concentrations of these nutrients. Instead, micronutrient amendments are necessary and greatly improved seedling growth and quality, regardless of substrate pH. Because the species used here represent seven different plant families, these results may be applied to container landscape tree production for a wide range of tree species.

Appendix A

ANOVA Tables, Chapter Two

Table 1. Interaction significance for shoot dry mass (week 12) for nine tree species, Expt. 1.

	Main effect and interaction significance (p-value)						
Species	Micronutrients	Lime	Bark	Lime x Micro	Lime x Bark	Micros x Bark	Lime x Micros x Bark
A. palmatum	0.0001	0.1076	0.3736	0.1860	0.2087	0.3054	0.8737
A. saccharum	0.0001	0.0116	0.4720	0.5108	0.1874	0.1518	0.0685
C. canadensis	0.0001	0.0066	0.3299	0.2028	0.2271	0.1042	0.5503
C. kousa	0.0018	0.0091	0.0024	0.4862	0.0876	0.0518	0.8972
C. florida	0.0001	0.0685	0.200	0.5926	0.2962	0.3289	0.9905
K. paniculata	0.0001	0.0696	0.8096	0.7661	0.1649	0.0150	0.9209
M. x *soulangiana*	0.0001	0.0245	0.0003	0.3582	0.0615	0.0027	0.0767
N. sylvatica	0.0001	0.179	0.2504	0.1047	0.0080	0.0303	0.6029
Q. palustris	0.0038	0.4304	0.4880	0.9611	0.5714	0.0184	0.7092

Table 2. Interaction significance for height (week 12) for nine tree species, Expt. 1.

	Main effect and interaction significance (p-value)						
Species	Micronutrients	Lime	Bark	Lime x Micro	Lime x Bark	Micros x Bark	Lime x Micros x Bark
A. palmatum	0.0001	0.0792	0.0412	0.1492	0.1185	0.5238	0.9327
A. saccharum	0.0001	0.0925	0.6514	0.7619	0.1576	0.3009	0.2987
C. canadensis	0.0001	0.0179	0.0880	0.3896	0.6073	0.1275	0.8582
C. kousa	0.0001	0.0164	0.0063	0.6088	0.7672	0.2172	0.2065
C. florida	0.0001	0.0613	0.4374	0.6936	0.9555	0.3089	0.6671
K. paniculata	0.0002	0.0002	0.2339	0.0709	0.6856	0.0005	0.2339
M. x *soulangiana*	0.0002	0.1031	0.0019	0.4673	0.5543	0.0008	0.4598
N. sylvatica	0.0001	0.2018	0.0085	0.1773	0.0754	0.2164	0.0402
Q. palustris	0.0207	0.0368	0.5839	0.7913	0.4669	0.9027	0.6992

Table 3. Interaction significance for shoot dry mass and height (week 11) for *K. paniculata* and *Q. palustris*, Expt. 2.

	Main effect and interaction significance (p-value)			
	K. paniculata		*Q. palustris*	
Interaction	Dry mass	height	Dry mass	height
Micronutrients	0.0001	0.0001	0.0001	0.0001
Lime	0.0008	0.0001	0.1091	0.0305
Bark	0.0007	0.0001	0.0001	0.0001
Lime x Micro	0.0001	0.0433	0.0192	0.0043
Lime x Bark	0.1423	0.4537	0.1126	0.0807
Micros x Bark	0.0705	0.4537	0.0417	0.0212
Lime x Micros x Bark	0.0005	0.0287	0.6940	0.3706

Appendix B

Three-Way Interaction Means, Chapter Two

Table 1. Three-way interaction means for *K. paniculata* shoot dry mass and height, Expt. 1.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	0.56	0.20
0	0	low pH	0.61	0.92
0	0.9	high pH	1.4	0.53
0	0.9	low pH	1.1	1.0
3.6	0	high pH	0.34	0.20
3.6	0	low pH	0.57	0.25
3.6	0.9	high pH	1.2	0.84
3.6	0.9	low pH	1.1	0.55

Table 2. Three-way interaction means for *M.* x *soulangiana* shoot dry mass and height, Expt. 1.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	0.28	5.6
0	0	low pH	0.21	5.4
0	0.9	high pH	0.37	7.6
0	0.9	low pH	0.258	5.6
3.6	0	high pH	0.17	4.6
3.6	0	low pH	0.22	5.1
3.6	0.9	high pH	0.34	7.4
3.6	0.9	low pH	0.23	5.3

Table 3. Three-way interaction means for *Q. palustris* shoot dry mass and height, Expt. 1.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	1.3	23
0	0	low pH	1.3	23
0	0.9	high pH	1.6	25
0	0.9	low pH	1.4	25
3.6	0	high pH	1.2	21
3.6	0	low pH	1.3	22
3.6	0.9	high pH	1.5	23
3.6	0.9	low pH	1.4	24

Table 4. Three-way interaction means for *N. sylvatica* shoot dry mass and height, Expt. 1.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	0.02	5.2
0	0	low pH	0.13	4.9
0	0.9	high pH	0.30	7.3
0	0.9	low pH	0.20	5.6
3.6	0	high pH	0.10	5.0
3.6	0	low pH	0.15	4.6
3.6	0.9	high pH	0.19	5.7
3.6	0.9	low pH	0.19	5.7

Table 5. Three-way interaction means for *C. kousa* shoot dry mass and height, Expt. 1.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	0.6	10.1
0	0	low pH	0.3	7.0
0	0.9	high pH	1.2	15.7
0	0.9	low pH	0.5	12.7
3.6	0	high pH	0.2	6.8
3.6	0	low pH	0.2	6.6
3.6	0.9	high pH	0.7	13.7
3.6	0.9	low pH	0.3	8.9

Table 6. Three-way interaction means for *K. paniculata* shoot dry mass and height, Expt. 2.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	1.2	7.2
0	0	low pH	1.9	11
0	0.9	high pH	2.6	11
0	0.9	low pH	2.2	12
3.6	0	high pH	0.7	5.7
3.6	0	low pH	1.0	6.2
3.6	0.9	high pH	2.2	9.3
3.6	0.9	low pH	2.8	13

Table 7. Three-way interaction means for *Q. palustris* shoot dry mass and height, Expt. 2.

Lime ($kg \cdot m^{-3}$)	Micronutrients ($kg \cdot m^{-3}$)	Bark Type	Dry mass (g)	Height (cm)
0	0	high pH	2.4	26
0	0	low pH	3.1	32
0	0.9	high pH	3.1	32
0	0.9	low pH	3.1	32
3.6	0	high pH	1.7	22
3.6	0	low pH	2.7	29
3.6	0.9	high pH	2.9	30
3.6	0.9	low pH	3.5	35

Amy Noelle Wright

Vita

Amy was born in and grew up in Blacksburg, Virginia and graduated from Blacksburg High School in June 1992. She entered Virginia Tech in August 1992 and graduated in December 1996 with a Bachelor of Science degree in Chemistry. During her undergraduate program, she obtained a minor in Biochemistry and conducted undergraduate research in the Department of Food Science and Technology. She also worked as a laboratory assistant for three and a half years in the Virginia Tech Pesticide Residue Research Laboratory from July 1993 through December 1996. She began work on her Master of Science degree in Horticulture in January 1997. During her graduate work, she taught two semesters of Indoor Plants and presented papers at both SNA and ASHS annual meetings. Amy completed her Master of Science in August 1998, and in the same month moved to Raleigh, North Carolina and began work on her Doctor of Philosophy degree at North Carolina State University in the Department of Horticultural Science.