Amending a Gravel Based Growing Medium with Calcined Clay Improves Physical Properties and Seedling Growth[1]

Catherine A. Bohnert[2], Christopher Starbuck[2] and Stephen Anderson[3]
Division of Plant Sciences and
Department of Soil, Environmental and Atmospheric Sciences
University of Missouri, Columbia, MO 65211

Abstract

The Missouri Gravel Bed (MGB) is a system that uses pea gravel with 10% sand (v/v) as a root growth medium, allowing plants to be removed from the gravel and planted, bare root, during the growing season. However, the low water holding capacity of the medium necessitates frequent irrigation. This study was conducted to determine the effects of amending pea gravel with calcined clay (Terra-Green®) on the physical properties of the medium and on growth of *Gymnocladus dioicus* (L.) K. Koch seedlings. Adding 10% sand (v/v) increased water holding capacity of the medium slightly at water tensions above 1 kPa. Gravel amended with 40% calcined clay had 16% air-filled porosity and had 3.5 times more plant available water than gravel with sand only. Dry weights of seedlings grown in gravel amended with 40% calcined clay and no sand were over twice as great as those of seedlings grown in the standard MGB medium.

Index words: calcined clay, soilless growth medium, gravel bed, water retention, bare root, *Gymnocladus dioicus* (L.) K. Koch, nursery stock.

Significance to the Nursery Industry

More nurseries and landscapers can take advantage of the savings in cost and labor associated with bare root handling if the survival rate and length of planting season of bare root nursery stock can be increased. The Missouri gravel bed (MGB) is a system in which field grown, bare root plants are placed with their roots in river rock to promote root regeneration, improve transplanting survival and extend the bare root planting season (18). While survival of plants held in the MGB has been excellent, maintaining a moist, nutrient rich root zone environment in a gravel medium requires frequent fertilization and irrigation.

Results of this research showed that amending a pea gravel medium with calcined clay significantly increased water holding capacity while maintaining over 16% air-filled pore space. Shoot dry weight of *Gymnocladus dioicus* (L.) K. Koch seedlings grown in gravel amended with 40% (v/v) Terra-Green® (calcined clay) with no sand was over twice that of seedlings grown in the standard MGB medium containing only 10% sand. Thus, amending a gravel medium with calcined clay shows promise as a means to maintain plants in good condition and increase plant growth in a gravel bed with less irrigation and fertilization than required using the standard MGB medium. With this improvement, installation and management of a gravel bed as a tool to facilitate bare root handling of nursery stock will be greatly simplified.

Introduction

Balled-and-burlapped (B&B) trees and shrubs are generally considered to have a higher transplanting survival rate and a greater initial growth rate than bare root plants, but are more costly to harvest, transport and transplant. (13, 15). Additionally, B&B harvesting depletes topsoil over time (7).

Bare root plants are lighter and easier to handle than B&B plants of comparable size. However, with current nursery practices, harvesting and planting of bare root stock is limited to its dormancy period. Bare root plants have a higher risk of desiccation after harvesting and may take longer to become established in the landscape than B&B plants (17).

The Missouri gravel bed (MGB) is a system in which dormant bare root plants are placed in frequently irrigated pea gravel amended with sand. The method was developed to simplify the handling of bare root nursery stock and to extend the planting season, while still ensuring a high survival rate after transplanting (17). Macropores created by the pea gravel provide an ideal environment for root regeneration of field grown bare root plants, increasing survival after transplanting relative to conventionally handled bare root plants. Also, bare rooted trees from the MGB system can be transplanted during the summer months without detrimental effects (16).

Since pea gravel and sand have low water holding and cation exchange capacities, it is difficult to maintain a moist and nutrient rich root zone environment (12). The majority of the nutrients in the pea gravel medium remain in solution in a limited volume of water, making frequent applications of fertilizer necessary.

Due to lack of buffering capacity of the pea gravel, over time the pH in the root zone environment may increase, especially if irrigation water is alkaline (12). This can lead to precipitation of micronutrients, and with the increase of calcium, a reduction in manganese and iron uptake can occur (20). Chlorosis was a common problem for *Syringa patula* (Palib.) Nak. 'Miss Kim' and *Nyssa sylvatica* L. when they were grown in the MGB system at a pH of 7.8 or higher (12).

Addition of calcined clay was found to improve the physical and chemical properties of a pine bark medium and a perlite-peat moss medium compared to pine bark or perlite-peat alone (18). Kirk et al. (12) found that *G. dioicus* (L.) K. Koch seedlings grown in pea gravel with 10% sand (v/v) and containing at least 60% calcined clay had greater

[1]Received for publication June 15, 2007; in revised form April 4, 2008. This research was funded through the University of Missouri Center for Agroforestry under cooperative agreement 58-6227-5-029 with the USDA ARS Dale Bumpers Small Farm Research Center, Booneville, AR and CR 826704-01-0 with the US EPA.

[2]Graduate Research Assistant and Associate Professor, respectively.

[3]Professor, Department of Soil, Environmental and Atmospheric Sciences.

heights and dry weights than those grown in an unamended medium (12). Additionally, gravel amended with calcined clay had a lower pH by the end of the experiment than gravel containing only sand, indicating that exchange sites on the clay particles had a buffering effect.

In previous experiments, it was determined that adding approximately 10% fine sand to gravel improved the water holding ability of the gravel and facilitated lateral movement of irrigation water (17). However, experiments have not been performed to characterize the effects of amending pea gravel with calcined clay on the physical properties of the medium as well as the subsequent water availability. Such research would facilitate development of a mixture utilizing the minimum amount of calcined clay required to provide an ideal root growth medium for woody plants with minimal irrigation. This study was performed to determine the effects of mixing selected levels of calcined clay into a pea gravel growing medium with and without sand on particle size range, water retention, saturated hydraulic conductivity, porosity, and bulk density of the medium and on growth of Kentucky coffee tree seedlings.

Materials and Methods

Particle size distribution, hydraulic conductivity, and moisture release characteristics of a pea gravel growing medium with and without 10% sand (v/v) amended with selected levels of calcined clay were determined in the Soil Physics Laboratory at the University of Missouri-Columbia. In March 2006, an experiment was conducted in the University of Missouri-Columbia Horticulture greenhouse to determine the effects of mixing calcined clay at selected levels into a pea gravel growing medium with and without 10% sand (v/v) on growth of *G. dioicus* (L.) K. Koch seedlings.

Physical properties. The growing media treatments (Table 1) were hand mixed on a volume basis and contained pea gravel with and without 10% sand (v/v) amended with 0, 10, 20, 30, or 40% calcined clay. Pea gravel from the Osage River (85% of the particles are 4.75 to 11 mm in effective diameter), sand dredged from the Missouri River (96% of particles are 0.05 to 2 mm), and Terra-Green® (a calcined clay product with particles ranging from 0.84 to 4.00 mm) were used. Each treatment mixture was poured into a 35.6 × 35.6 × 12.7 cm (14 × 14 × 5 in) tray lined with polypropylene weed fabric and then watered 3 times a day for 3 days to encourage natural settling. Trays were watered until ponding was visible.

Four core samples were taken from each treatment about 2 weeks after irrigation events ended by driving a cylindrical ring (diameter = 7.62 cm, height = 7.62 cm) straight down into the mix. The medium sample was leveled off and a piece of gauze was secured on top of the core so that it could be inverted.

Cores were placed in a plastic tub with a water level maintained at 7 cm for 24 hours to ensure saturation. The constant head method was used to measure saturated hydraulic conductivity, K_{sat}, (14). After K_{sat} measurements were taken, the cores were re-saturated, and water retention measurements were performed. The water desorption method was used with water pressures of –1, –2, –3, –4, –5, and –6 kPa in glass Büchner funnels with porous ceramic plates (4). Cores were dried at 105 C for one week and those samples were used to determine bulk density (1). Water retention at –1500 kPa water pressure (permanent wilting point) was determined using a pressure chamber with four replications of each treatment according to Klute (13).

Table 1. Composition of the different growing media treatments used to evaluate growth of Kentucky coffee tree seedlings, expressed as a percent of the volume of the mixture.

Treatments[z]	% Pea gravel	% Calcined clay	% Sand
0% cc + 10% s	90	0	10
10% cc + 10% s	80	10	10
20% cc + 10% s	70	20	10
30% cc + 10% s	60	30	10
40% cc + 10% s	50	40	10
0% cc + 0% s	100	0	0
10% cc + 0% s	90	10	0
20% cc + 0% s	80	20	0
30% cc + 0% s	70	30	0
40% cc + 0% s	60	40	0

[z]s denotes sand.

Particle size distributions were determined for each component (pea gravel, river sand and calcined clay) and the ten media treatments. Five 20 g equivalent air-dried samples were shaken through a nest of sieves (4.75, 2, 1, 0.5, 0.25, 0.1, and 0.05 mm). Samples were shaken in the sieves for 3 minutes before the size fractions were weighed (Table 2).

Plant growth. Components and mixtures in the greenhouse study were the same as those used to formulate the media used for physical property determinations. However, the growing media were used two times in preliminary experiments before use in the current greenhouse study. At the end of the first experiment in 2004, the media were not analyzed for mineral content; however, leachate electrical conductivity measurements indicated that the fertilizer applied the previous April had been reduced to suboptimal (EC <0.2 $mS \cdot cm^{-1}$) levels by leaching and plant removal.

When conductivity of the leachate was measured near the end of the second preliminary experiment in 2005, the highest reading was 0.97 $mS \cdot cm^{-1}$ which was 0.28 $mS \cdot cm^{-1}$ higher than that of the irrigation water

In March 2006, *G. dioicus* (L.) K. Koch seeds were acid scarified according to the method described in Dirr and Heuser (6), then rinsed and soaked in water overnight. Seeds were germinated in perlite. Once seedlings had radicals 1 cm in length, they were transplanted into 15.2 cm (6 in) pots containing 1 liter of the ten experimental mixtures. The experiment had 10 replications of the 10 treatments, arranged in a randomized complete block design. The experimental design was factorial with 5 levels of clay and 2 levels of sand. Each pot was fertilized with 5.6 g of Scott's Topdress Special (N–P–K) (17–3–6 Plus Minors fertilizer; Marysville, OH). Supplemental liquid fertilizer was added in the form of Peter's N–P–K (20–10–20; Scott's Company) at 100 ppm nitrogen applied weekly beginning April 27, 2006 (about four weeks after planting). The greenhouse air temperature ranged from 13.8 to 38.3C (57–101F). A 55% shade cloth covered the greenhouse from May 1 through the end of the experiment on July 11. All pots were watered by hand with a hose breaker with approximately 200 ml per pot when the control plants (growing in pure gravel) showed signs of wilting. Irrigation frequency varied with seedling size and greenhouse environment from once per day to once every third day.

Table 2. Particle size distributions of the individual components and the ten growth media treatments.

Treatments	MG[z]	FG[y]	VCS[x]	CS[w]	MS[v]	FS[u]	VFS[t]	Silt + Clay
	Particle size, mm diameter							
	>4.75	2.0–4.75	1.0–2.0	0.5–1.0	0.25–0.5	0.1–0.25	0.05–0.1	<0.05
	%							
Components of mixes								
Pea gravel	85.3	14.7	0.0	0.0	0.0	0.0	0.0	0.0
River sand (s)	0.0	3.7	17.5	41.8	23.9	12.4	0.7	0.0
Calcined clay (cc)	0.0	36.1	44.8	17.0	1.2	0.5	0.4	0.0
Container mixes[s]								
0% cc + 10% s	74.0	16.1	4.6	3.7	1.2	0.4	0.0	0.0
10% cc + 10% s	65.4	14.0	7.9	7.7	3.2	1.3	0.5	0.0
20% cc + 10% s	56.0	15.1	11.6	11.0	3.9	1.8	0.6	0.0
30% cc + 10% s	49.8	12.8	14.5	14.6	5.4	2.3	0.6	0.0
40% cc + 10% s	44.8	15.5	17.9	14.8	4.5	1.9	0.6	0.0
10% cc	76.7	17.0	4.3	1.3	0.3	0.2	0.2	0.0
20% cc	69.1	17.0	9.1	3.3	0.7	0.5	0.3	0.0
30% cc	73.6	11.8	7.8	4.7	0.9	0.8	0.4	0.0
40% cc	55.1	15.9	16.4	8.1	1.7	1.7	1.1	0.0

[z]MG, medium gravel.
[y]FG, fine gravel.
[x]VCS, very coarse sand.
[w]CS, coarse sand.
[v]MS, medium sand.
[u]FS, fine sand.
[t]VFS, very fine sand.
[s]Container mixes: cc = calcined clay (v/v), s = sand (v/v), main component of mixes was pea gravel.

The experiment was terminated after sixteen weeks. Plant height was measured from the top of the root flare to the topmost branching point on the central leader of the seedlings. Stem diameter measurements were taken with a digital caliper at the top of the root flare. Plants were then removed from the growing media, roots were rinsed, the aerial portions were separated from roots, and all tissues were dried at 60C for 48 hours prior to weighing.

All data were subjected to analysis of variance (ANOVA) using the GLM procedure in the SAS program. Means were separated using the LSD t-test with the $\alpha = 0.05$ level of significance. Since calcined clay amendments were equally spaced, a statistical evaluation of the linear, quadratic, cubic and quartic regression relationships for calcined clay was performed. Since most of the cubic and quartic terms were found to be non-significant ($P > 0.05$), only the linear and quadratic terms are presented.

Results and Discussion

Physical properties. The relationship between percent water retention of the media and the moisture tension is presented in Table 3 and Fig. 1. Table 3 gives the average water contents of the media at measured water pressures as well as the ANOVA summary. The shapes of the water release curves for all of the treatments were similar. Between saturation and –1 kPa water pressure, a substantial decrease in water content was observed in all of the treatments, with the highest decrease observed in the 0% calcined clay. This can be attributed to the major component of the treatments, pea gravel. Its relatively large particle size (up to 11 mm in diameter), creates macropores which drain quickly under high water pressures. With larger pores, more water drains at low moisture tension (–1 kPa water pressure) allowing more air infiltration, thus creating an adequate root/atmosphere interface for the exchange of gases (22).

The treatments with sand retained slightly more water than those without at –1 kPa, but at –2 kPa pressure and lower, the difference decreased until media with and without sand had similar water retentions at the lower pressures (–5 kPa and –6 kPa). Sand significantly increased water retention for mixtures containing 10 to 30% calcined clay at –1 kPa (Table 3). The release of water from the treatments slowed dramatically with pressures lower than –3 kPa with almost no change in water content between –5 and –6 kPa water pressure.

A clear pattern emerged among the treatments. As calcined clay content increased, water content increased relative to the control treatments (0% calcined clay with and without sand; Fig. 1). Treatments with 40% calcined clay retained nearly 4 times more water than the control at –1 kPa and that difference was maintained over the range of water pressures applied.

As shown in Table 4, there were significant differences in mean K_{sat}, total porosity (TP), air-filled porosity (AP), available water (AW), unavailable water (UW), and bulk density (BD) among the ten different growing media treatments. Calcined clay had a significant effect ($P < 0.001$) on all of the measured physical properties. Due to the stable internal pore spaces within the fired clay particles, they reduce bulk density and increase total and water filled pore volume when mixed with gravel and sand. Sand had a significant effect ($P < 0.05$) on TP, AP, AW, and BD.

Table 3. **Average water content as a function of water pressure (0 to –6 kPa) and the ANOVA summary of water content as a function of water pressure for the ten gravel based growing media treatments.**

Treatments		Water pressure, kPa						
		0	–1	–2	–3	–4	–5	–6
		m³·m⁻³						
0% cc + 10% s		0.42ef	0.10g	0.07g	0.07e	0.07e	0.07e	0.07e
10% cc + 10% s		0.41f	0.20f	0.17f	0.15d	0.14d	0.14d	0.14d
20% cc + 10% s		0.46d	0.27de	0.23de	0.21c	0.20c	0.20c	0.19c
30% cc + 10% s		0.49bc	0.33bc	0.29bc	0.26b	0.25b	0.25b	0.24b
40% cc + 10% s		0.52a	0.38a	0.33a	0.31a	0.30a	0.29a	0.28a
0% cc		0.44e	0.08g	0.06g	0.06e	0.06e	0.06e	0.06e
10% cc		0.43e	0.17f	0.14f	0.14d	0.14d	0.13d	0.13d
20% cc		0.47cd	0.25e	0.22e	0.20c	0.20c	0.19c	0.19c
30% cc		0.50b	0.29cd	0.26cd	0.25b	0.24b	0.24b	0.23b
40% cc		0.52a	0.36ab	0.32ab	0.30a	0.29a	0.29a	0.28a
		Water pressure, kPa						
		0	–1	–2	–3	–4	–5	–6
Source of Variation	d.f.	ANOVA *Pr* > *F*						
Treatment	9	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sand	1	0.028	0.006	0.13	0.64	0.81	0.90	0.99
Clay linear	1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Clay quadratic	1	0.010	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sand × clay linear	1	0.12	0.99	0.92	0.90	0.87	0.87	0.97
Sand × clay quadratic	1	0.58	0.69	0.56	0.37	0.36	0.42	0.31
Error	30							
Total	39							

Saturated hydraulic conductivity. The addition of 10% sand by volume reduced the K_{sat} from 53.6 to 14.2 m·h^{-1} for the gravel medium. This was due to the sand particles filling in the large pores created by the pea gravel, thus obstructing the flow of water through the system. When pea gravel was amended with only 10% calcined clay, K_{sat} dropped from 53.6 to 3.48 m·h^{-1}. The fine calcined clay particles acted in the same way as sand particles by inhibiting water flow through the system. When the medium had 20 to 40% calcined clay, the addition of sand changed the K_{sat} slightly, although it was only significantly different at the 20% calcined clay level. Furuta (1974) suggested that the K_{sat} for container mixes should be at least 5 cm·hr^{-1}. In all of the treatments, K_{sat} levels were above the recommended minimum value with the most limiting being the medium amended with only 40% calcined clay (32 cm·hr^{-1}). K_{sat} was related to calcined clay with significant linear and quadratic relationships. There were also significant linear and quadratic sand × clay interactions (Table 4). These were the results of changes in effects of sand with increasing percentage of calcined clay.

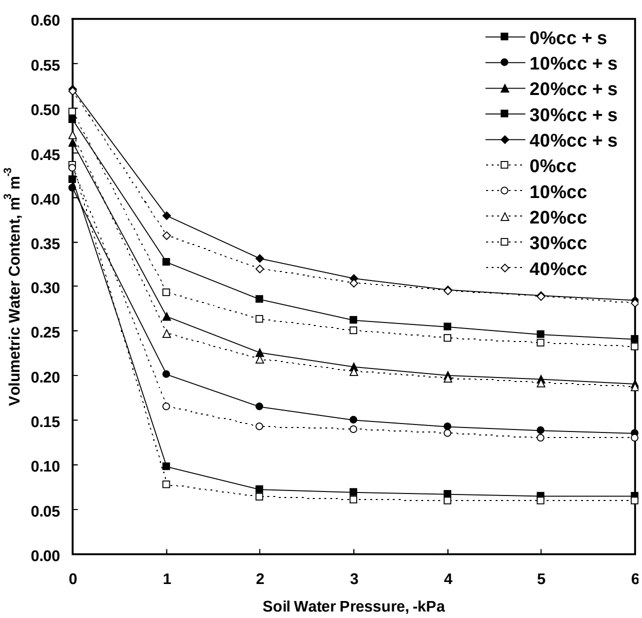

Fig. 1. **Water retention measured in cores at selected water pressures for the media treatments composed of pea gravel and calcined clay (cc) with (s) or without 10% sand after settling of material.**

Total porosity (TP). TP refers to the total porosity of the growing media, which is equivalent to the water content at 0 kPa when all of the pores are full of water. Treatments with sand had lower TP than those without sand. Media containing 10% calcined clay with and without sand did not have significantly different TP values from the pea gravel amended with 10% sand only. Addition of calcined clay had significant linear and quadratic effects (also significant cubic and quartic effects, data not shown) on TP with the strongest being linear (Table 4). As increments of calcined clay were added to the medium, TP increased. The largest increase was between 10 and 20% calcined clay levels. Bulk density values, inversely related to total porosity, are also shown in Table 4. These values show similar patterns to porosity.

Air-filled porosity (AP). AP is the volume of air in the medium after it is left to drain under atmospheric pressure (5). We estimated this using TP minus the water content at –1 kPa. Since the pea gravel media had a height of about 10

Table 4. Physical properties of the gravel based growing media amended with calcined clay and the ANOVA summary of physical properties.

Treatments[z]		K_{sat}[y]	Total porosity[x] (TP)	Air-filled porosity[w] (AP)	Available water[v] (AW)	Unavailable water[u] (UW)	Bulk density (BD)
		$m \cdot h^{-1}$	v/v, %				$(g \cdot cm^{-3})$
0% cc + 10% s		14.22b	42.0ef	32.2b	5.1f	4.7e	1.51ef
10% cc + 10% s		2.26cd	41.0f	20.9d	13.6de	6.6de	1.53f
20% cc + 10% s		1.12d	46.1d	19.4d	16.6abcd	10.1c	1.40d
30% cc + 10% s		0.54e	48.8bc	16.1e	19.2ab	13.5b	1.32bc
40% cc + 10% s		0.54e	52.1a	14.2e	20.2a	17.7a	1.23a
0% cc		53.62a	43.6e	35.8a	3.4f	4.4e	1.47e
10% cc		3.48c	43.2e	26.7c	11.2e	5.3e	1.47e
20% cc		0.58e	47.0cd	22.3d	16.0bcd	8.7cd	1.37cd
30% cc		0.62e	49.5b	20.2d	15.0cde	14.3b	1.30b
40% cc		0.32e	51.9a	16.1e	18.3abc	17.4a	1.24a
		LogK_{sat}	TP	AP	AW	UW	BD
Source of Variation	d.f.	ANOVA $Pr > F$					
Treatment	9	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sand	1	0.25	0.028	<0.001	0.025	0.39	0.027
Clay linear	1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Clay quadratic	1	<0.001	0.010	<0.001	<0.001	0.026	0.0096
Sand × clay linear	1	<0.001	0.12	0.29	0.73	0.61	0.12
Sand × clay quadratic	1	0.023	0.58	0.41	0.94	0.68	0.59
Error	30						
Total	39						

[z]Treatments: cc = calcined clay (v/v), s = sand (v/v), main component of mixes was pea gravel.
[y]K_{sat}, saturated hydraulic conductivity.
[x]TP, 1-bulk density/particle density.
[w]AP, TP – percent volume at –1 kPa.
[v]AW, percent volume at –1 kPa – percent volume at –1500 kPa.
[u]UW, percent volume at –1500 kPa.

cm while in the container, 10 cm of tension (–1 kPa) were used to determine AP. Sand had a significant effect on AP. The AP of treatments with sand was lower than that of treatments without sand. This can be explained by the fact that the water content of the media with sand was higher at –1 kPa. Due to its relatively smaller particle size, sand had fewer macropores than did pea gravel, thus the volume of water-filled pores in the mixtures increased with addition of sand and AP decreased (Furuta, 1974).

Calcined clay had significant linear and quadratic effects on AP (Table 4; Fig. 2a). The rate of decrease of AP in the medium between 0 and 10% calcined clay was high, and then the decline slowed with 20% and higher additions of calcined clay (Fig. 2a). The AP of the gravel medium was reduced by half when 40% calcined clay was added, but was still slightly above 16%. An ideal medium drains rapidly after irrigation leaving 10 to 20% AP by volume (2). Even when pea gravel with or without 10% sand was amended with 40% calcined clay, the AP was within the recommended range (14 and 16%, respectively). High AP allows for adequate gas exchange between plant roots and the atmosphere in the growing medium (10).

Plant available water (AW). Water held in the growing medium at –1500 kPa is considered unavailable to plants and is used to determine AW held within the growing media by subtracting the water content at –1500 kPa from the water content at –1 kPa (5). Sand had a significant effect on the amount of AW (Table 4). With the addition of sand, the media retained slightly more AW at each calcined clay level. The addition of calcined clay also increased AW. Media with

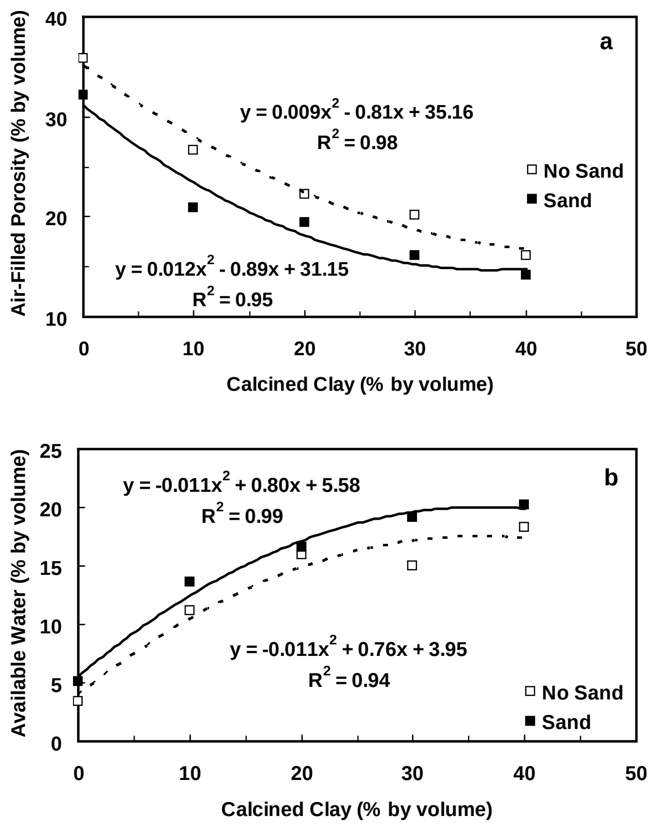

Fig. 2. Effects of calcined clay levels in a gravel based medium on air-filled porosity (a) and plant available water (b).

Table 5. Effects of incorporating selected levels of calcined clay into gravel based growing media on stem diameter, height, and dry weights of Kentucky coffee tree seedlings and the ANOVA summary for these parameters with degrees of freedom (n = 100) for the greenhouse experiment.

		Greenhouse experiment				
Treatment[z]		Stem diameter (mm)	Height (cm)	Root dry wt. (g)	Shoot dry wt. (g)	Root-to-shoot ratio
0% cc + 10% s		6.41c	12.5def	6.61ef	3.61ef	1.88bcd
10% cc + 10% s		6.39c	11.8ef	6.38f	3.31ef	2.16bc
20% cc + 10% s		7.01bc	16.4bcd	9.97cd	5.61cd	1.86bcd
30% cc + 10% s		6.95bc	16.8bc	10.66bc	5.80cd	1.99bcd
40% cc + 10% s		8.92a	20.2ab	13.22a	8.56ab	1.65d
0% cc		5.34d	9.1f	5.17f	2.05f	2.68a
10% cc		5.57d	10.8f	6.92ef	3.12ef	2.34ab
20% cc		6.54c	15.7cde	8.42de	4.86de	1.91bcd
30% cc		7.37b	17.2bc	12.26ab	7.18bc	1.77cd
40% cc		8.34a	21.7a	13.50a	9.29a	1.62d
		Stem diameter	Height	Root dry wt.	Shoot dry wt.	Root-to-shoot ratio
Source of Variation	d.f.			ANOVA $Pr > F$		
Block	9	0.33	0.63	0.33	0.31	0.51
Treatment	9	<0.001	<0.001	<0.001	<0.001	0.0014
Sand	1	0.0058	0.48	0.78	0.85	0.17
Clay linear	1	<0.001	<0.001	<0.001	<0.001	<0.001
Clay quadratic	1	0.0023	0.43	0.25	0.049	0.89
Sand × clay linear	1	0.082	0.096	0.12	0.032	0.011
Sand × clay quadratic	1	0.20	0.84	0.70	0.69	0.12
Error	81					
Total	99					

[z]Treatments: cc = calcined clay (v/v), s = sand (v/v), main component of mixes was pea gravel.

40% calcined clay held about 5.4 times more water than pea gravel alone and about 3.6 times more water than pea gravel amended with 10% sand (v/v; Table 4). Amending the gravel with 10% calcined clay with and without sand improved AW for plants when compared to the pea gravel alone with and without sand. AW was related to calcined clay with significant linear and quadratic relationships (Table 4, Fig. 2b). The increase in AW with increasing percentage of calcined clay can be attributed to the calcined clay's ability to store plant available water in the pore space within its ceramic particles (vitrified by heating to a high temperature). The firing of the montmorillonite clay fixes the internal pores giving rise to a moisture content at –33 kPa of 73% by weight (44% by volume) for 100% calcined clay reported by Wildon and O'Rourke (1964). The moisture content for the medium amended with just 40% calcined clay in the current experiment was estimated from the regression line using a log relationship at –33 kPa to be about 25% by volume.

Unavailable water (UW). Sand did not have a significant influence on the UW of the growing media (Table 4), which is the percentage of water retained in the medium at –1500 kPa. As the percentage of calcined clay increased, the amount of UW in the medium increased (Table 4), exhibiting significant linear and quadratic relationships (Table 4).

Plant growth. At the conclusion of the greenhouse study, there were no seedling mortalities. The addition of calcined clay affected all of the measured plant growth parameters (Table 5). As more calcined clay was added to the basic pea

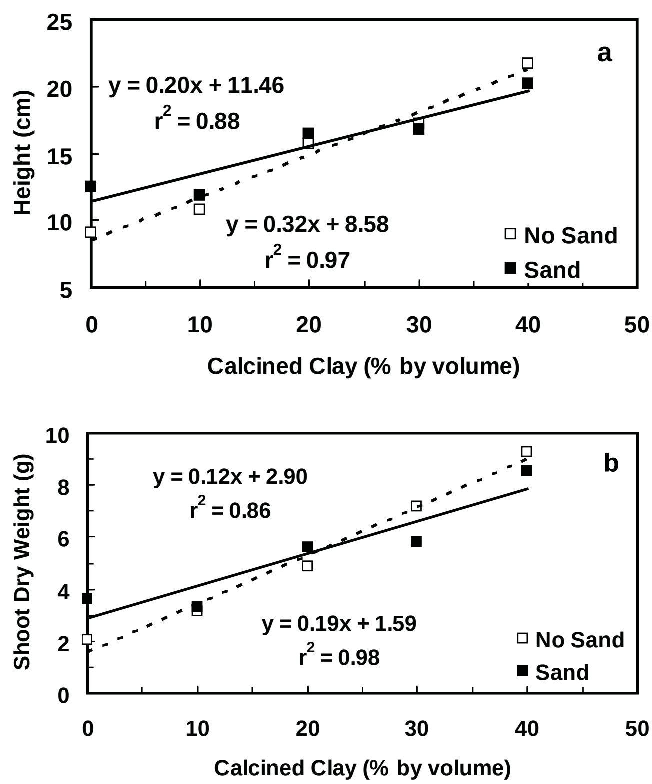

Fig. 3. Effects of calcined clay levels in a gravel based medium on Kentucky coffee tree seedling height (a) and shoot dry weight (b).

gravel medium, all of the seedling growth parameters increased linearly (Table 5, Fig. 3). Stem diameter and shoot dry weight were related to calcined clay with significant quadratic relationships ($P < 0.05$). A significant linear interaction ($P < 0.05$) between clay and sand occurred for shoot dry weight (Table 5, Fig. 3b). Seedlings grown in mixtures with at least 30% calcined clay without sand had significantly greater stem diameters, heights and dry weights than those grown in media containing 0% calcined clay without sand.

Sand only affected seedling growth in mixtures containing less than 20% calcined clay (Table 5). Plants in mixtures with less than 20% calcined clay responded favorably to the addition of sand by having slightly greater diameters, heights and dry weights, although these differences were not always statistically significant. The mean diameter of seedlings grown in sand-amended gravel containing 0 or 10% clay was greater than that of seedlings grown in the same media containing no sand. These differences could be attributed in part to the increased water retention of the media conferred by sand (Table 3).

The mean stem diameter of seedlings grown in gravel amended with 40% calcined clay (no sand) was 56% greater than that of plants grown in gravel containing no calcined clay or sand and 30% greater than that of seedlings grown in the standard MGB medium. Seedlings grown in pea gravel amended with 40% calcined clay (no sand) were 2.4 times taller than those grown in gravel alone and 1.7 times taller than those grown in the standard MGB medium.

Seedlings in the gravel media amended with 30–40% calcined clay grew taller than those grown in pure pea gravel (Table 5, Fig. 3a). In a study involving seed potatoes grown in pure arcillite (calcined montmorillonite clay), Hiller and Koller (9) found that plants exhibited more root and shoot growth than those grown in white quartz sand, which is analogous to pea gravel in terms of its low water holding and nutrient holding capacities.

After growth in the gravel based medium for 16 weeks, extensive branching from the taproot was observed, and the roots of seedlings grown in treatments containing 30–40% calcined clay had greater dry root weights than those grown in media with less than 30% calcined clay (Table 5). Mean root dry weight of seedlings grown in the medium with 40% calcined clay and no sand was 2.6 times greater than that of seedlings grown in pea gravel alone and were 2 times greater than that of plants grown in gravel containing 10% sand.

Mean shoot dry weight of plants grown in gravel amended with 40% calcined clay was 4.5 times greater than that of plants grown in gravel alone and 2.6 times greater than that of plants grown in the standard MGB medium. Jaeger et al. (11) reported that shoot dry weight was greater for tomatoes, soybeans, and marigolds grown in a 1:1:1 mixture by volume of arcillite, #2 size vermiculite and 60 mm quartz river bottom gravel than for plants grown in a 1:1 vermiculite:gravel mixture. In our experiment, the increase in dry weight of seedlings grown in treatments with 40% calcined clay content may be attributed to the calcined clay's ability to improve the water holding capacity of pea gravel (from 3.4% by volume available water for pea gravel to 18.3% by volume available water for gravel amended with 40% calcined clay; Table 4).

The root-to-shoot ratios were not significantly affected by the addition of sand to the pea gravel growing medium (Table 5). The root-to-shoot ratios showed a significant linear relationship with level of calcined clay. Generally, root-to-shoot ratios decreased, becoming closer to 1 as more calcined clay was added to the growing medium. Also, a significant interaction ($P < 0.05$) occurred between calcined clay and sand (Table 5). The plants grown in pea gravel alone had root-to-shoot ratios (2.68) 65% higher than those grown in pea gravel amended with 40% calcined clay (1.65) and no sand (1.62). Plants grown in the traditional MGB medium had 16% higher root-to-shoot ratios compared to pea gravel amended with 40% calcined clay and no sand.

The results of this research indicated that addition of calcined clay to pea gravel created media with physical properties more favorable for plant growth than pea gravel alone, with or without 10% sand. Total porosity and available water were significantly greater with 20% calcined clay and higher (with and without sand) compared to the standard MGB medium. Treatments with 40% calcined clay had the greatest total porosity and available water and the lowest K_{sat}, air-filled porosity and bulk density among treatments. This combination of physical properties provides more water for plant growth and allows roots to penetrate more easily, due to a lower bulk density than that found in the standard MGB medium, while still allowing for sufficient drainage after irrigation events for gas exchange by roots.

The addition of calcined clay to the pea gravel medium had a linear effect on the plant growth parameters and a quadratic effect on diameter and shoot dry weight. Plants grown in a pea gravel medium with and without 10% sand (v/v) and amended with 30 or 40% calcined clay had greater stem diameters, heights and total dry weights than seedlings grown in the standard MGB medium. Even though plants grown in 40% calcined clay amended pea gravel displayed the most plant growth, the expense of the calcined clay may be a deterrent to using it as a major medium component. However, seedlings grown in pea gravel amended with 30% calcined clay grew significantly more than those grown in the traditional MGB medium; thus, the amount of calcined clay could be reduced to 30% to achieve improved plant growth with lower cost.

The effect of the sand on the plant growth measurements was neither pronounced nor consistent across the treatments. Adding 10% sand (v/v) to the pea gravel increased seedling growth slightly over seedlings grown in pure pea gravel. However, the benefits were less than those of calcined clay. The addition of 10% sand (v/v) to pea gravel is recommended when calcined clay is not available, but it could be omitted when calcined clay is used. This research demonstrated that a pea gravel based medium amended with calcined clay can support repeated plant growth. With this study, plants were grown in media that were used in two prior growing seasons. Reuse of MGB medium may offer an alternative to container production. If the efficacy of incorporating calcined clay into the MGB medium is confirmed in field scale experiments, studies comparing the cost of MGB with other growing methods should be conducted.

Literature Cited

1. Blake, G.R. and K.H. Hartge. 1986. Bulk density. p. 363–375. *In*: A. Klute (ed.) Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

2. Bowman, D.C. and J.L. Paul. March 1983. Understanding of container media vital knowledge for growing successful plants. Pacific Coast Nurseryman and Garden Supply Dealer. p. 48–50.

3. Cool, R.A. 1976. Tree spade vs. bare root planting. J. Arboriculture 2:92–95.

4. Danielson, R.E. and P.L. Sutherland. 1986. Porosity. P. 443–461. *In*: A. Klute (ed.) Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

5. DeBoodt, M. and O. Verdonck. 1972. The physical properties of the substrates in horticulture. Acta Hort. 26:37–44.

6. Dirr, M. A. and C.W. Heuser, Jr. 1979. Reference Manual of Woody Plant Propagation: from Seed to Tissue Culture. Varsity Press, Inc., Athens, GA. p.129.

7. Fare, D.C. 2004. Effect of bare root and B&B harvest on growth and establishment of landscape size trees. Proc. Southern Nurserymans Assoc. Res. Conf. 49:134–136.

8. Furuta, T. 1974. Environmental Plant Production and Marketing. Cox, Arcadia, CA.

9. Hiller, L.K. and D.C. Koller. 1979. Potato growth responses in arcillite and sand. HortScience 14:534–536.

10. Holcomb, E.J. 2000. Growing media. Penn State: College of Agriculture Sciences. http://hortweb.cas.psu.edu/courses/hort450/topics/GrowingMixFA00.html. (February 17, 2005).

11. Jaeger, C.H., H. Hellmers, and I.D. Teare. 1981. An improved medium for nutriculture incorporating arcillite. HortScience 16:176–177.

12. Kirk, S.D., C. Starbuck, and J.W. Van Sambeek. 2004. Comparing the growth of *Gymnocladus dioicus* in a pea gravel medium amended with calcined clay or expanded shale. Turfgrass 2004 Research and Information Report, University of Missouri, Columbia.

13. Klute, A. 1986. Water retention: Laboratory methods. P. 635–662. *In*: A. Klute (ed.). Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

14. Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687–734. *In*: A. Klute (ed.) Methods of Soil Analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

15. Magley, S.B. and D.K. Struve. 1983. Effects of three transplant methods on survival, growth, and root regeneration of caliper pin oaks. J. Environ. Hort. 1:59–62.

16. Starbuck, C.J. 2005. The Missouri gravel bed: A system allowing bare root trees and shrubs 12 months of the year. http://www.missouri.edu/~starbuckc/MGB/MGB_home.htm (May 22, 2006).

17. Starbuck, C., D.K. Struve, and H. Mathers. 2005 Bareroot and balled-and-burlapped red oak and green ash can be summer transplanted using the Missouri gravel bed system. HortTechnology 15:122–127.

18. Warren, S.L. and T.E. Bilderback. 1992. Arcillite: Effect on chemical and physical properties of pine bark substrate and plant growth. J. Environ. Hort. 10:63–69.

19. Wildon, C.E. and F.L.S. O'Rourke. 1964. The effect of arcillite in media for pot plants. Mich. State Univ. Res. Rpt. 16.

20. Winsor, G.W. 1990. Nutrient solutions for soilless culture. p. 95–118. *In*: W.O. Baudoin (ed.) Soilless culture for horticultural crop production. Food and Agriculture Organization of the United Nations, Rome, Italy.

21. Witty, G. July 1986. Testing pore space of container mixes. Long Island Horticulture News. 1–2. Long Island Horticultural Research and Extension Center. Riverhead, NY.