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Growth response of *Ficus benjamina* to limited soil volume and soil dilution in a skeletal soil container study

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Abstract: The interactive effects of rooting volume and nutrient availability in a skeletal soil medium designed to meet street tree and pavement needs were observed in a containerized experiment. Benjamin fig (*Ficus benjamina* L.) was grown in a stone-soil blended skeletal soil material (CU-Soil ™) and compared to a loam soil. The same topsoil used as the soil component in the skeletal soil material was used as the sole component in the comparison soil-only treatment.

Plants grown in the skeletal soil material had reduced leaf tissue N content and depressed growth compared with plants grown in non-diluted soil. No other mineral deficiencies were found. Leaf number, chlorophyll concentration, shoot weight, and root characteristics were all affected.

Reduced growth from soil dilution could be offset by the provision of an enlarged rooting volume for root development. Large containers of skeletal soil were observed to have smaller root systems compared to equivalent net volumes of loam soil at the first two harvest dates of the study. By the end of the study, the large containers of skeletal soil were observed to have developed larger root systems compared to equivalent net volumes of loam soil; resulting in comparable leaf N levels and total plant dry matter. Plants in skeletal soil had lower shoot: root ratios at the end of the study. Investing resources to further root growth in times of nutrient shortages is a probable plant reaction as evidenced by differences in specific root length between treatments. The study allowed a method for directly partitioning the containerization effect by having equivalent amounts of soil over two volumes.

Key words: root restriction, specific root length, urban trees

Introduction

Street trees are often placed in sidewalks where they are surrounded by paved surfaces. The traditional tree pit design detail calls for a "topsoil" volume surrounded by the heavily compacted pavement section detail. Small pavement openings, with the associated limited planting soil volumes, and the compacted materials used to support the surrounding pavement can cause drainage problems and immediately impact the success of a street tree planting. Moreover, as tree roots grow to the edges of the planting holes, they face restricted growing conditions due to physical

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impedance of the roots by the surrounding compacted soil.

Plant morphological and developmental responses to root restriction have been extensively documented (NeSmith et al. 1992; Richards & Rowe 1977; Robbins & Pharr 1988). Root restricted plants are poor in both shoot and root growth compared with unrestricted plants (NeSmith & Duval 1998). Negative growth responses have been linked to a possible reduced nutrient uptake (Bar-Tal & Pressman 1996; Choi et al. 1997) and root-induced hormonal change (Krizek & Dubik 1987). Thus, it has been suggested that root restriction by either compaction or containerization are alike in inducing similar plant responses (Dubik et al. 1990).

Development of viable materials to establish trees in paved situations should promote more tree planting in urban areas in situations generally not planted due to inhospitable soil conditions. The use of designed skeletal soils is one strategy to enlarge rooting volumes in a horticulturally sound manner without compromising the need for load-bearing in durable pavement design (Grabosky & Bassuk 1995; Grabosky et al. 1996; Kristoffersen 1998). The material used in this study, CU-Soil, is a recently patented growing media (US Patent No. 5,849,069) capable of supporting plant growth under compacted conditions commonly found under pavement (Grabosky & Bassuk 1998).

CU-Soil essentially consists of a 2-part mixture; a stone skeletal matrix and a suspension of soil within the pores of the matrix, often greater than 80 percent stone to 20 percent or less soil by weight. Due to the design limitations on the amount of soil used in the system, a typical CU-Soil stone skeleton occupies a substantial 60 percent of the space by volume while the soil solids occupies around 15 percent (Grabosky 1999), raising concerns that the high dilution rate of the soil fraction in skeletal soils may inadvertently affect the nutrient status of plants over time.

Increasing tree survival, quality, and life expectance, while maintaining a durable pavement, will result in a healthier and more valuable urban canopy, while increasing the frequency, profitability and value of street tree installations. Beyond survival, management strategies need to be developed to successfully care for trees in a harsh urban environment, particularly with the use of skeletal soil material profiles. This study begins to look at defining nutrient management issues in the use of skeletal soil systems wherein the soil component for tree root zones is diluted. Secondarily, this study provides an opportune system to evaluate the impact of containerization restrictions on plant growth while holding the soil resource as a constant for a short term study.

To test the effect of soil dilution and increased rooting volume, an orthogonal containerized experiment was devised to investigate plant growth responses to CU-Soil (skeletal soil material). Two container sizes provided different potential rooting space. The small container mimicked the mechanically impeded soil walls of a tree pit by adversely affecting root extension. By examining plant growth, a test of the hypothesis of growth reduction associated with soil dilution in skeletal soil material while testing for effects of an enlarged rooting volume was constructed.

Materials and Methods

The experiment was conducted in a 30 °C/25 °C greenhouse located at Cornell University, Ithaca, NY. For their importance as a pH tolerant street tree in tropical urban forests, clonal Benjamin fig (*Ficus benjamina* L.) plugs (2 × 2 × 5 cm for a total root zone volume of 20 cm^3) were allowed to acclimatize in the experiment greenhouse for 2 weeks before planting. Plants were between 14–20 cm in height, and were standardized by removing any lateral branches leaving 5–6 leaves on the terminal axis. Plants were bare-rooted and transplanted into 45 cm^3 (3 × 3 × 5 cm) chiseled openings in the media treatments on 1st Dec 1998. One application of water soluble 15–5–15 fertilizer at 200 ppm nitrate nitrogen was applied after planting. No further fertilization was applied during the length of study. All containers were watered daily as needed. To prevent overwatering which often results with soil in containers, planted "dummy replicates" were established with a series of 2 cm diameter piezometers installed across the radius of the soil-filled containers. A float gauge was placed within the pipe to detect the presence of a saturated water table. Plants were not irrigated on days where excess water was detected. Horticultural oil was sprayed monthly during summer (May-Sep 1999) to control scale insects. Supplemental lighting with high intensity lamps (additional 60 μmol quanta m^{-2} s^{-1} for a 14 hr day duration) was used during the winter months of 1999 (December 1999–March 2000).

Experimental design

Four treatments listed in Table 1 were arranged in a factorial combination of 2 rooting volumes, 0.011 m^3 and 0.054 m^3, and 2 media, skeletal soil material and the undiluted interstitial soil. The container volumes were chosen to provide an equivalent weight of soil between treatments 1 and 4 distributed over a different rooting volume while meeting design needs for the skeletal soil material after full compaction (Table 1). Standard plastic containers 55.3 cm diameter by 33 cm deep and 27.2 cm diameter by 25.4 cm deep were used. The orthogonal set allowed accurate partitioning of the degrees of freedom into the 2 separate effects (volume and media). By comparing responses between treatments 1 and 4, we would be able to detect if the soil

Table 1. Description of loam soil (loam) and skeletal soil media (ssm) treatments by total volume, density, volume of voids and comparable amount of loam soil in the treatment system

Treatment	Media volume	Dry density (S.E.)	Volume of voids	Soil weight (relative weight)
1 loam	0.011 m^3	1.37 Mg m^{-3} (0.005)	0.005 m^3	0.015 Mg (0.2)
2 ssm	0.011 m^3	1.94 Mg m^{-3} (0.02)	0.003 m^3	0.003 Mg (0.04)
3 loam	0.054 m^3	1.37 Mg m^{-3} (0.005)	0.026 m^3	0.074 Mg (1.0)
4 ssm	0.054 m^3	1.94 Mg m^{-3} (0.02)	0.015 m^3	0.015 Mg (0.2)

dilution effect in skeletal soil material affected plant response.

One hundred twenty plants were arranged in a split-split plot design with 2 blocks; one on either side of the greenhouse. Main plots were 3 harvest timings, spread approximately 5 months apart (2nd week of May 1999, 2nd week of October 1999 and 2nd week of March 2000). Subplots consisted of 5 separate rows parallel to the heating pipes of the greenhouse. The sub-plot was further split into the 4 treatments (sub-subplot).

Preparation of media treatments

The screened topsoil purchased for the study was determined to be a loam by hydrometer particle size analysis (23% clay, 29% silt and 48% sand) with a pH of 7.47 and an initial electrical specific conductivity of 0.61 mmho cm^{-1} [0.61 $m\Omega^{-1}$ cm^{-1}] (2 water: 1 soil saturation extract). Nutrient analysis to verify available P, K, Mg, Ca, Fe, Mn, Zn and N (NO_3^-) was conducted by Cornell Nutrient Analysis Laboratories, Cornell University. The skeletal soil material consisted of 84.7% crushed limestone ranging from 2–2.5 cm (Cayuga Crushed Stones, Inc., Lansing, NY), 15.3% loam soil and 0.025% stabilizing hydrogel (Gelscape, Amereq Corp. New York City, NY) by weight.

The soil treatments 1 and 3 were not compacted, whereas the skeletal soil material treatments 2 and 4 were compacted to within 3% of peak standard density as determined from standard moisture-density compaction testing (ASTM D-698-99). Depth of material in each sized container was determined to be 22.6 and 18.7 cm for the large and small containers respectively, and filled with a prescribed weight of media to ensure an equal amount of soil over the two container volumes in treatments one and four after manual compaction with a 25 cm^2 striking surface tamping hammer to the target skeletal soil material density. Compaction uniformity was assessed by randomly measuring the bulk density of 15 of 30 containers in each treatment. Wet and dry densities were then measured by high-speed neutron and gamma radiation via a Troxler 3411-B nuclear densimeter. The probe was placed at center and off-center locations of the containers at 2 depths (8 and 12 cm). There were no differences in the dry densities at these various locations, or the total density by measured inputs and volume control, indicating that our compaction was even throughout the profile. The skeletal soil material bulk density was 1.94 Mg m^{-3} (g/cm^3) and the loam was 1.37 Mg m^{-3} (g/cm^3) (Table 1).

Above ground measurements

Growth Response of *Ficus benjamina* to Limited Plant height and number of fully expanded leaves greater than 2 cm in length were measured monthly. One week prior to each harvest, 6 leaves per replicate were randomly taken to form a sample, avoiding the first and last 3 leaves from any one shoot or apex. Triplicate readings using a SPAD-502 chlorophyll meter (Minolta Corporation, Ramsey, NJ) were taken around the midpoint near the midrib of each leaf sample and averaged (Peng et al. 1992). Calibration curves of SPAD data to extractable chlorophyll yielded a high correlation (Eq. 1) within the range of values observed in this study, and to a lesser degree nitrogen concentration (Loh et al. 2002).

$$\text{Chlorophyll concentration (ppm)} = -298 + 35.6 \times \text{SPAD readout} \quad (r^2 = 0.90) \qquad \text{(Eq. 1)}$$

Mineral analyses of leaf tissue were conducted at Fruit and Vegetable Science Analytical Laboratory of Cornell University. Nitrogen content was determined using the Kjeldahl method (Wolf 1982); while other essential elements and heavy metals were analyzed using the dry ashing procedure (Greweling 1976). Plant shoots were harvested at the soil surface and dried to determine above-ground dry weight, inclusive of the 6 leaves sampled for mineral analyses.

Root measurements

Roots from all pots were hand-washed over a 3 mm × 3 mm mesh then sorted into fine (< 2 mm) and coarse (> 2 mm) diameter roots. Root volume was determined for each size class by water displacement and the roots were dried and weighed. Total root length, an indication of colonization ability, was calculated from the fine and coarse root volume data, using a median diameter of

1 mm for fine roots and a 6 mm diameter for coarse roots (the latter being the calculated mean diameter from measuring roots obtained from dummy replicates). Specific root length (SRL = root length/root mass or weight) was calculated for treatment differences in root growth adaptation. Root length density was also calculated as root length divided by media volume.

Soil pH, electrical conductivity, and available soil nutrients (specifically nitrates) were determined from random soil samples obtained during each harvest. For skeletal soil material, this refers to the soil component isolated by sieving on an ASTM #40 sieve (450 μm opening).

Data analysis

Analysis of variance was performed in SAS using General Linear Model procedures consistent with a split-split plot design (SAS Institute 1990). Multiple pairwise treatment comparisons were analyzed using Tukey-Kamer test procedures. Main effects (volume and media), and interactions, were divided into orthogonal contrasts when the analysis of variance indicated in the treatment effect was significant. Unless specified, the level of significance adopted for all tests was 0.05.

Results

Above-ground growth responses

Plant height and number of fully expanded leaves reflected similar trends (Figs. 1 and 2). Plants established in large loam containers (Treatment 3) yielded significantly greater leaf counts and greater height while plants from small skeletal soil material (Treatment 2) containers were significantly smaller by the second harvest. While the small loam (Treatment 1) plants were significantly larger than plants in large skeletal soil material (Treatment 4) containers in the first harvest, there were no differences observed by the second harvest date in September 1999 (Figs. 1 and 2).

SPAD-502 data, as an indicator of chlorophyll concentration, decreased over the term of the study. Treatment differences at each harvest followed the same relationships as the shoot and leaf count data, except the SPAD-502 data in the large skeletal soil material containers were significantly higher than in small loam containers by the final harvest (Histograms in Fig. 3a; Means in Table 2), reversing their respective early ranking in treatment response levels.

Leaf tissue nitrogen levels, when compared to nursery production standards, were found to be deficient in all treatments throughout the study falling below 1.8% of tissue weight (Table 2). All other elements were found within the minimum sufficiency levels using comparative nursery production data from standard *Ficus benjamina* plants (Mills & Jones 1996). No toxicities were reported. Leaf nitrogen levels mirrored the SPAD-502 data described above (Table 2), reenforcing the earlier reported differences in shoot growth among the various treatments. Electrical specific conductivity (less than 0.3 mmho cm^{-1} [0.3 $m\Omega^{-1}$ cm^{-1}]) and nitrate nitrogen levels in media analysis were low in all treatments (Table 2). It was presumed to be an artifact of the irrigation regime. As nitrate is easily leached, it may explain the rapid onset of deficiency symptoms recorded for our treatments since the loam was not lacking at the onset of the study.

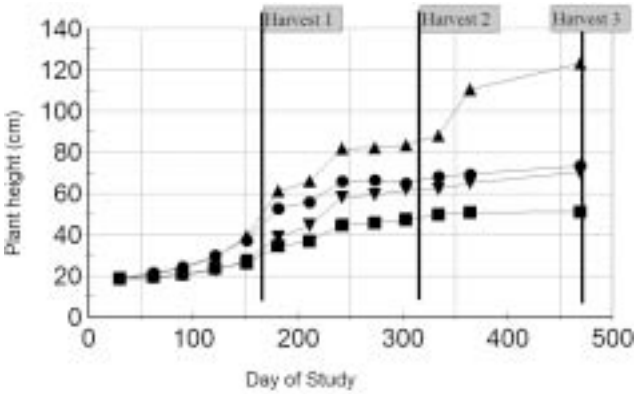

Fig. 1. Monthly tracking of plant height of Benjamin fig grown in a containerized loam and Skeletal soil material media (SSM) treatments. Harvest occurred on days 165, 318 and 470. Standard errors increased from 0.25 at the beginning to 3.36 as successive harvests reduced replicate numbers. Error bars were thus smaller than data points on graph. –●– Small loam; –■– Small SSM; –▲– Large Loam; –▼– Large SSM.

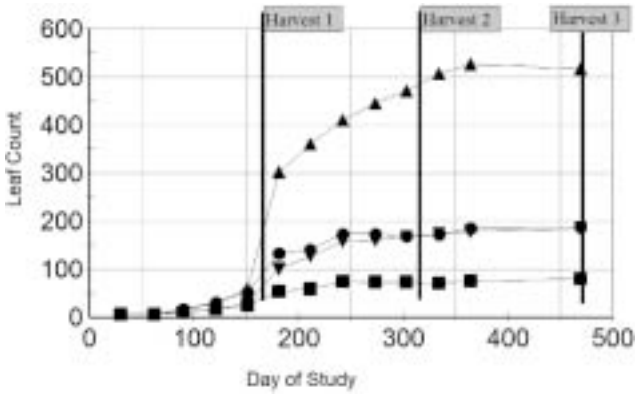

Fig. 2. Monthly tracking of leaf counts of Benjamin fig grown in a containerized loam and Skeletal soil material media (SSM) treatments. Harvest occurred on days 165, 318 and 470. Standard errors increased from 0.2 at the beginning to 8.8 as successive harvests reduced replicate numbers. Error bars were thus smaller than data points on graph. –●– Small loam; –■– Small SSM; –▲– Large Loam; –▼– Large SSM.

Table 2. Plant growth and media data from Benjamin fig grown in a containerized study with loam and skeletal soil medium (SSM) treatments over three, five month harvest intervals. Shoot data included leaf nitrogen concentration determined from Kjeldahl method, SPAD-502 data as an indicator of chlorophyll concentration and shoot dry weight. Media data included pH, nitrate levels and salinity. SSM media data was based on the loam component sieve-separated from the stone matrix. Root length, dry weight and fresh volume based on total root collection and segregation into size classes for the volume to length conversion. Derived root characteristic data for replicates calculated prior to treatment analysis. Means separation within harvest date performed using Tukey-Kamer procedure ($p = 0.05$) with significance noted by subscripts within column (within harvest date). Statistical differences in root dry weight treatments 2 and 4 in harvest 1 are masked by rounding error (*) 2.48 g versus (**) 2.9 g

	Leaf N conc. (ppm)	SPAD read-out	Shoot dry weight (g)	Soil pH (ppm)	Soil nitrate conc.	Soil electrical specific conductivity (mmho/cm) $\left(\mathrm{m}\frac{1}{\Omega}\cdot\frac{1}{\mathrm{cm}}\right)$	Root length (m)	Root dry weight (g)	Root volume (cm^3)	Shoot: root ratio (SSR)	Spec. root length (cm/g)	Root length density (m/cm^3)
Harvest 1: 5 month, May 1999												
1. Small loam soil	1.68ab	52.6b	15b	7.9a	1.68a	0.27a	44b	5b	64b	3.3a	9.7a	0.42a
2. Small SSM	1.56bc	41.7d	5d	7.8a	1.56b	0.24b	2c	*3d	19d	2.2b	9.8a	0.23a
3. Large loam Soil	1.72a	56.5a	30a	7.9a	1.72a	0.24b	82a	9a	100a	3.3a	9.4a	0.15bc
4. Large SSM	1.50c	44.9c	8c	7.8a	1.49b	0.29a	33c	**3c	26c	2.9a	11.5a	0.06c
Harvest 2: 10 month, October 1999												
1. Small loam soil	0.81c	40.0b	59b	7.4b	0.81a	0.24a	110b	42b	205b	1.4bc	2.6a	1.04a
2. Small SSM	0.80c	34.8c	16c	7.9a	0.80a	0.29a	57c	13d	90c	1.2c	4.8a	0.54b
3. Large loam Soil	1.11b	49.1a	205a	7.9a	1.10a	0.32a	288a	103a	494a	2.1a	2.9a	0.53b
4. Large SSM	1.50a	40.4b	57b	7.8a	0.96a	0.22a	121b	32c	189b	1.8ab	3.8a	0.22b
Harvest 3: 15 month, March 2000												
1. Small loam soil	0.81c	33.5c	89b	8.0a	0.81c	0.24a	110c	89c	283c	1.0a	1.3ab	1.04a
2. Small SSM	0.77d	29.4d	25c	8.0a	0.77d	0.28a	41d	44d	134d	0.6b	0.9b	0.39bc
3. Large loam Soil	1.00a	46.1a	327a	8.1a	1.00a	0.21b	316a	275a	753a	1.2a	1.1b	0.57b
4. Large SSM	0.89b	36.3b	85b	8.0a	0.89b	0.30a	187b	130b	410b	0.7b	1.6a	0.35c

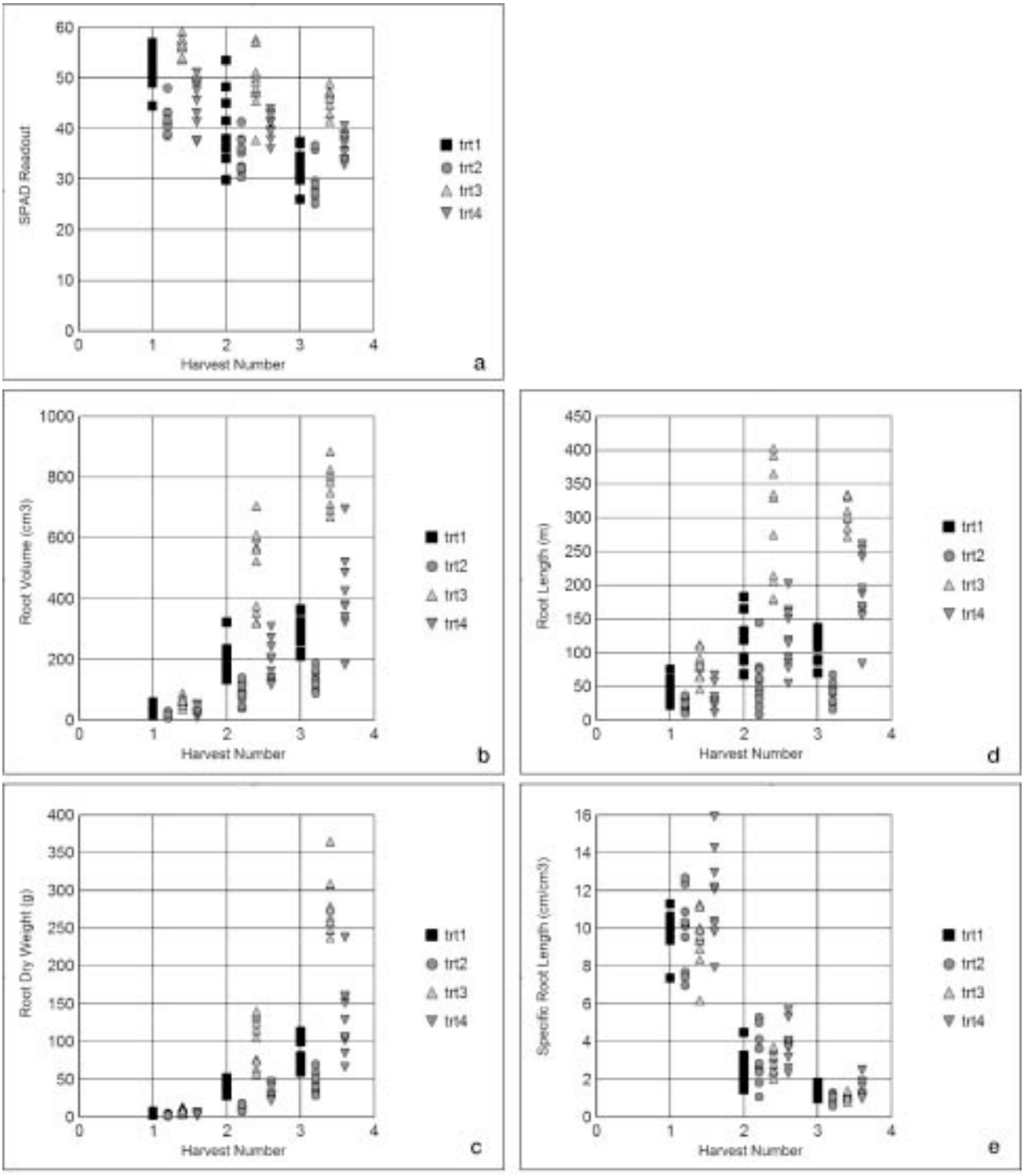

Fig. 3. Histograms of data taken on *Ficus benjamina* in loam soil and skeletal soil material (SSM) in two volumes. Treatment definitions: 1) small container loam soil 2) small container SSM 3) large container loam and 4) large container SSM. Harvest occurred on days 165, 318 and 470 of the study. SPAD readout, (histogram a) is correlated to chlorophyll concentration in leaves, and decreased over the term of the study. Total root volume and dry weight (histograms b and c) generally increased over the course of the study. Total root length (histogram d) as a parameter calculated from volume and diameter class also increased over the course of the study. Specific root length (histogram e) decreased over the course of the study. Each data cluster represents ten replicates within each treatment within each harvest. Means and significance testing on the split-split plot design are given in Table 2.

Below-ground growth

Total root volume, root dry weight and root length exhibited similar trends with that of their shoot counterparts (Histograms in Fig. 3b,c,d; Means in Table 2). The large soil volume in treatment 3 produced significantly greater root growth than all other treatments. Treatment 1 had a significantly higher degree of root growth compared with treatment 4 at the 1st harvest, but root weight, length and volume in treatment 4 was significantly greater by the end of the study (Table 2). The root length data between the second and third harvests showed a greater relative increase in root length in treatment 4 (large skeletal soil material) compared with the minor increase in root length in the large loam soil container of treatment 3 (Table 2). Root length and dry weight were positively influenced by larger container size. There was a negative influence from skeletal soil on root length and dry weight much of which was due to the small skeletal soil treatment as evidenced by the interaction significance.

Derivative plant root parameters are summarized in Table 2. Root length densities registered for both loam and skeletal soil material were within comparative range of previous literature (Bowen & Nambiar 1984; Grabosky 1999) for tree species. Root length density was significantly higher for roots in small loam soil containers ($p < 0.05$), but below 2–6 cm/cm^3 range wherein root competition occurs (De Willigen & Van Noordwijk 1987; Yamaguchi & Tanaka 1990). Specific root lengths differences were not significant between all treatments until the last harvest when the equal soil volumes of treatments 1 and 4 were comparable, and lower in the large loam soil and small skeletal soil treatments (histograms in Fig. 3e; means in Table 2).

Orthogonal contrasts revealed a positive volume impact by the end of the study, and a negative impact of skeletal soil during the first two harvests (Table 3). One can infer the effect of soil dilution in the early establishment period, but this impact was apparently decreasing in influence by the end of the study as media was no longer a significant effect, as pertaining to specific root length.

Effects of root restriction on plant growth

Orthogonal contrasts revealed that the larger soil volumes of treatments 3 and 4 resulted in significant increases on plant shoot dry weight and leaf SPAD readings (Table 3). The larger container treatments also had higher shoot to root ratios ($p < 0.05$) as compared with smaller container treatments for harvests 1 and 2 (Table 2 for actual values and Table 3 for analysis by orthogonal contrast). Root growth data followed the patterns established in shoot growth; larger containers developed larger root systems (Table 3). Compared to the small loam soil container, plants in large skeletal soil material containers (the same amount of loam soil) had developed a larger root system (Table 2, treatment 1 versus 4).

Discussion

The finding that root restriction impaired plant growth similar to compaction concurs with the results of previous studies (Hawver 1997; Kharkina et al. 1999; Ne-Smith et al. 1992; Richards & Rowe 1977). Depressed shoot and root dry matter, leaf number and SPAD-502

Table 3. Separation of soil volume and media effects using orthogonal contrasts for shoot and root measurements of Benjamin fig grown in containerized loam and skeletal soil material media treatments over three harvest periods at five month intervals. Data for each harvest and pooled results over three harvest intervals

	Volume				Media				Interaction			
Harvest interval	1	2	3	pooled	1	2	3	pooled	1	2	3	pooled
Shoot dry weight	+[1]	+	+	+	+[2]	+	+	+	S[3]	S	S	S
SPAD-502 data	+	+	+	+	+	+	+	+	N[4]	N	S	S
Shoot:Root ratio	+	+	N	+	+	+	+	+	S	N	N	N
Root dry weight	+	+	+	+	+	+	+	+	S	S	S	S
Root length	+	+	+	+	+	+	+	+	S	S	S	S
Specific root length	N	N	+	N	–[5]	–	N	–	N	N	S	N

[1] + in volume effect indicates the parameter is significantly higher for larger compared to smaller containers ($p < 0.05$).
[2] + in media effect indicates the parameter is significantly higher for loam soil compared to skeletal soil ($p < 0.05$).
[3] S = Interaction was significant
[4] N = Not significant
[5] – in media effect indicates the parameter is significantly lower for loam soil compared to skeletal soil ($p < 0.05$).

Table 4. Leaf tissue nutrient analysis data for Benjamin fig grown in a containerized study with loam and skeletal soil medium (SSM) treatments over three, five month harvest intervals. Means separation within harvest date performed using Tukey-Kamer procedure (p =0.05) with significance noted by subscripts within column (within harvest date). Statistical differences in phosphorous levels in treatments 1 and 2 in harvest 3 are masked by rounding error

Elemental designation of nutrient in leaf tissue	P %	K %	Mg %	Ca %	Mn ppm	Fe ppm	Cu ppm	B ppm	Zn ppm	Mo ppm	Ni ppm
Harvest 1: 5 month, May 1999											
1. Small loam soil	0.16a	1.49a	0.44ab	4.62a	29.2a	105.3a	10.3a	92.8a	24.6a	2.1a	2.3a
2. Small SSM	0.34a	1.89a	0.58a	5.35a	94.8a	129.9a	5.0a	102.2a	109.6a	2.0a	2.3a
3. Large loam Soil	0.14a	1.36a	0.41ab	4.85a	36.2a	113.0a	4.9a	81.9a	20.7a	2.2a	1.3a
4. Large SSM	0.21a	1.47a	0.44a	4.43a	53.1a	94.3a	4.5a	83.9a	54.2a	1.8a	1.2a
Harvest 2: 10 month, October 1999											
1. Small loam soil	0.09b	1.33b	0.44b	4.64a	35.2a	56.1a	4.7b	114.2a	26.4a	2.2b	1.0a
2. Small SSM	0.09b	1.32b	0.60a	4.51a	32.5a	28.9a	5.7ab	101.2ab	38.5a	1.7b	1.4a
3. Large loam Soil	0.13a	1.59ab	0.39b	4.46a	27.4a	149.1a	5.9a	97.1ab	31.3a	2.2b	1.3a
4. Large SSM	0.11ab	1.75a	0.50ab	4.50a	26.4a	30.5a	5.78ab	6.8b	31.4a	3.2a	1.3a
Harvest 3: 15 month, March 2000											
1. Small loam soil	0.09ab	1.49ab	0.49b	5.23a	26.9bc	53.0a	5.8a	105.9c	49.7ab	0.8a	3.2a
2. Small SSM	0.09b	1.36b	0.66a	6.46b	45.0a	71.0a	5.8a	152.8a	69.4a	0.4a	14.6a
3. Large loam Soil	0.11a	1.37b	0.39c	5.29a	25.2c	62.0a	4.8b	101.1c	33.6b	0.4a	1.5a
4. Large SSM	0.10a	1.65a	0.52b	6.20ab	33.6b	42.6a	5.8a	130.1b	50.1ab	0.9a	4.8a
Sufficiency range (Mills & Jones 1996)	0.1–0.4	1.0–3.0	0.2–1.0	0.8–3.3	25–200	30–200	4–25	25–75	15–200	0.12–0.5	0.5–5

readings within media type could be satisfactorily explained from a plant nutrition standpoint. Though we did not detect differences in leaf P, K and Ca levels (Table 4) as reported by some authors (Bar-Tal & Pressman 1996; Kharkina et al. 1999; Richards & Rowe 1977), plants in the smaller container treatments had significantly lower leaf nitrogen levels at the second and third harvests. The deleterious effects of mineral deficiency, particularly nitrogen on plant growth and crop yield had been well-documented (Bowen & Nambiar 1984; Marschner 1995). Nitrogen nutrient deficiency reduces foliage mass, leaf size, numbers and longevity and adversely affects the photosynthetic process.

Root-shoot interactions in response to root restriction are complex especially with woody perennials and conflicting reports exists (Hsu et al. 1996; Kharkina 1999; Klepper 1991; Liu & Latimer 1994; Nesmith et al. 1992; Richards & Rowe 1977). In this study, root restriction as a volume effect within media type negatively impacted root length, weight, and volume in the second and third harvests (Tables 2 and 3). A clear containerization impact with the same useable soil resource in differing volumes was not observed above ground within the time-frame of this study. In fact, the differences found in the root system were in marked contrast to the lack of difference in plant height, shoot dry weight or leaf count.

Carbon allocation to roots under conditions of nitrogen limitation is well-reviewed (Levin et al. 1989). The traditional nitrogen-carbon model by Thornley (1972) proposed that under conditions of nitrogen unavailability, the concentration of nitrogen in the shoot system will be lower than in the root, because the shoot system is further from the source of nitrogen supply. This results in a corresponding carbon concentration gradient in the opposite direction (shoot > root); causing a biomass carbon flow towards the roots. Though details of this model have been supplanted in recent years by findings of phloem reloading of nitrogen from shoot to root and the role played by root-borne phytohormones in mediating the effect of nitrogen on the shoot: root ratio, the outcome remains essentially that a low nitrogen environment modifies shoot: root ratio negatively (Ericsson 1995; Marschner et al. 1996). It should be noted that in previous reports of the influence of root restriction on shoot: root ratios, the authors either did not investigate or reported only slightly lower levels of nitrogen; not the deficient levels as observed in this study.

Plants grown in the large loam soil containers were significantly larger in shoot and root size at the second and third harvests. Plants grown in skeletal soil material exhibit morphological features markedly similar to root restricted plants. The media effect suggested that on an absolute volume basis, skeletal soil material is disadvantaged given its lower inherent soil content and corresponding nutrient pool. However, it is important to note that given an equal amount of soil matter by increasing the bulk volume of material under pavement, skeletal soil material grown plants can perform favorably. By the end of the study, large container skeletal soil material plants were comparable in shoot growth to those grown in small loam soil, but were characterized by a weak start. During the first 5 months of growth, the small loam soil container plants had a clear edge over the large skeletal soil containers in factors measured in this study. This suggests a negative skeletal soil material media effect as new roots were handicapped by the dilution of the soil component by stones. The initial media effect of the small soil container was eventually offset by a positive volume effect during subsequent harvests (2^{nd} harvest onwards); where roots were able to grow unrestricted in the larger skeletal soil material containers. As the differences in the root parameters favored the larger skeletal soil over the loam soil at the end of the study, an experiment of longer duration is needed to observe above-ground responses over time.

The higher leaf nitrogen attained by large skeletal soil material containers over the small loam soil container can be explained by the increase in rooting volume and root length. Given the assumed leaching as reflected by the low soluble salts content in the study, NO_3^- nitrogen levels were depleted rapidly as a direct result of plant uptake and irrigation. Buffer power for NO_3^- is usually low in soils and plants increasingly rely on NO_3^- transport by diffusion, rather than mass flow as the season progresses (Strebel et al. 1980). Thus the greater rooting length of large skeletal soil material plants became important as they offered greater contact opportunity with the limited NO_3^- ions. Other nutritional balance influences to increase uptake, such as calcium influences on phosphorous uptake (Mills & Jones 1996), cannot be ruled out.

Another root colonization trait that is important, especially for relatively immobile nutrients is plasticity in growth, or the ability to sense and respond to localized or temporary changes in mineral availability (Grime et al. 1991). Root plasticity in response to nutrient levels had been documented for many plant forage species (Hutchings & De Kroon 1994). Root diameter does not usually change with nutrient availability, but the ability of plants to regulate SRL (root length per unit mass) is common (Fitter 1985). SRL is always higher under nutrient poor environments. Thus, when nutrients are scarce, thinner and less dense roots are formed, which explore the soil more efficiently (Nye 1973) at lower cost. While different sized containers did not affect specific root length, roots grown in skeletal soil material containers tended to have longer roots per unit weight ($p < 0.05$). Investing resources to further root growth in times of nutrient shortages is a probable plant reaction.

The extent of nitrogen limitation in working systems needs to be further clarified with field data as the paved environment in actual installations does not necessarily mirror the containerized situation that existed in this study. Skeletal soil material is commonly laid under paved surfaces and therefore does not necessarily expose itself to heavy leaching by either rain or irrigation. Previous field trials did not detect any significant growth differences between trees grown in a skeletal soil material pavement and field controls (Grabosky et al. 2001; Grabosky et al. 2002). Before working out nitrogen fertilization recommendations, further field observations are being carried out over a longer period to assess the extent of nitrogen limitations in actual site situations. As part of a separate trial, skeletal soil material containerized plants fertilized during the establishment stage had leaf tissue nitrogen levels, SPAD-502 readings and plant height comparable to those grown in large loam soil pots (Grabosky & Bassuk 2001). Nitrates are highly mobile in soils, thus it is postulated that localization of fertilizers directly adjacent to physical roots may not be necessary. Failure to detect deficiencies of immobile elements like phosphorus in skeletal soil material should ease future design of fertilizer placement strategies.

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