ROOT GROWTH OF *QUERCUS CRASSIFOLIA*, *Q. CRASSIPES*, AND *FRAXINUS UHDEI* IN 2 DIFFERENT SOIL TYPES

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Abstract. Seedlings of selected tree species were grown in small benchtop rhizotrons filled with fine- and coarse-textured soils representing 2 different urban edaphic conditions in Mexico City. Bulk density was significantly higher and porosity was significantly lower in the coarse-textured soil. The maximum depth of root penetration visible behind the glass was significantly greater in the fine-textured soil for each of the 3 species after 5 months. Roots of *Fraxinus uhdei* penetrated deeper than roots of both *Quercus crassipes* and *Q. crassifolia* in both soils. *Fraxinus uhdei* root and shoot dry weight were significantly reduced in coarse-textured soil compared to the fine-textured soil, but both *Quercus* species were unaffected by soil type. In the fine-textured soil, *F. uhdei* root and shoot dry weight was significantly greater than both *Quercus* species, but not in the coarse-textured soil. At the end of the study, *F. uhdei* growing in fine-textured soil were taller than *F. uhdei* growing in coarse-textured soil and taller than both *Quercus* species in both soils, though the difference took 6 weeks longer to develop in the coarse-textured soil.

Key Words. *Fraxinus uhdei*; *Quercus crassifolia*; *Q. crassipes*; rhizotron; urban soil; texture.

Growing conditions in urban landscapes often limit the number of species that can be grown successfully. Those that are the most successful can usually tolerate a broad range of growing conditions (Ware 1993). Poor species diversity exists in many cities around the world (Bueno 1996; Gilman et al. 1996; Gilman 1997; Nilsson et al. 1998). A tree inventory in Mexico City, showed that 72% of all the trees in the city consisted of only 9 species (7 genera). Nineteen percent of the street trees were of a single species, *Fraxinus uhdei* (Chacalo et al. 1994).

Several challenges are faced when growing urban trees in Mexico City. Air pollution is high because the city is surrounded by mountains at an altitude of 2,240 m (7,350 ft) above sea level. Rainfall occurs primarily between May and October. However, regional environmental factors are not the primary reason for such poor species diversity along the streets. The very dense and rapidly growing population often results in poor-quality planting sites and extreme people-pressure on trees. The variable quality of urban sites, lack of proper tree care, difficulty of producing some species in the nursery, and lack of knowledge about seldom-used species are also factors that limit the use of desirable trees in urban landscapes (González 1993; Romero 1993; Ware 1993; Chacalo and Fernández 1995; Gilman et al. 1996; Gilman 1997).

High diversity of native tree species exists in Mexico. More than 75 different species of trees are native to the region around Mexico City, including 27 *Quercus* species. One-hundred fifty of the 500 species of *Quercus* known worldwide are native to the country (Rzedowski and Rzedowski 1979; Nixon 1993; Romero 1993; Bonfil 1998), of which 64% are endemic (Nixon 1993).

Urban soil conditions can severely limit plant growth (Barnes et al. 1971; Craul 1992; Kozlowski 1998). A recent inventory of street trees demonstrated that site limitations related to limitations in the soil environment are present in Mexico City (Chacalo et al. 1997). The lack of information about root growth characteristics of native Mexican tree species in the local urban soils suggested the need for a study on root development. Rhizotrons were chosen over other methods because they allow repeated nondestructive root observation. This method has been used extensively in agriculture but seldom in arboriculture. Rhizotrons vary in size, construction, and operation (Böhm 1979).

The main objectives of this study were 1) to evaluate the use of small benchtop rhizotrons as a system for simulating urban soil conditions and monitoring the resulting changes in root growth, 2) to compare the penetration and total dry weight of the roots of 2 *Quercus* species seldom used as urban trees in Mexico City compared to the most common street tree, *F. uhdei*, and, 3) to determine whether the types of soils occurring in Mexico City can limit root growth of trees.

MATERIALS AND METHODS

The experiment was conducted between August 1996 and March 1997 at Colegio de Posgraduados (Montecillo, State of Mexico, east of Mexico City). The interior dimensions of the rhizotrons used in this study were 40 × 70 × 5.5 cm (front to back) (15.8 × 27.6 × 2.2 in.). The wooden box of the rhizotron was painted with an oil-based outdoor enamel to protect it from water damage. A grid 5 × 5 cm (2 × 2 in.) was painted on the removable glass side held in place by an aluminum frame. To keep light from influencing the root growth, the edges of the glass were covered with aluminum tape and the glass front was covered with thick aluminum foil. The rhizotrons were held at a 30-degree angle on benches throughout the experiment to encourage the roots to grow against the glass. The rhizotrons were arranged in a randomized design.

The rhizotrons were kept in a large shelter designed for growing plants. A translucent roof provided filtered sunlight. Wall panels could be raised an lowered for ventilation. Air temperature near the rhizotrons was monitored throughout the experiment. Daily temperature fluctuations were approximately 35°C (95°F). A maximum average daytime temperature of 42°C (107.6°F) was reached in October, and minimum overnight average temperature of −2°C (28.4°F) occurred in January. These temperatures were higher than outdoor temperatures during the day and similar to outdoor temperatures during the night.

The soils were prepared and installed in the rhizotrons during August and September 1996. Coarse- and fine-textured soils were collected from urban sites and represented 2 different types of urban soils found in Mexico City. The coarse-textured soil was a loamy sand and the fine-textured soil was a clay loam. Analysis showed that nutrients levels were within acceptable ranges for both soil types (Table 1).

The soil was sieved 3 times through a 2-mm (0.1 in.) mesh and then fumigated with methyl bromide for 5 days. Each empty rhizotron was weighed before adding the soil. To settle the soil, air-dried soil was added slowly and continuously while tipping the rhizotron from side to side and striking it against the ground when returning to center. This method was chosen over tamping the soil surface in order to avoid breaking the glass and creating layers that could interfere with root growth. The rhizotrons were weighed again after filling. The height of the soil was recorded for each rhizotron. Because the volume of soil used was too large to oven dry, samples were oven dried and used to convert air-dry weight to oven-dry weight for bulk density calculations. Average bulk density for the whole rhizotron was estimated by using the total soil weight and volume in the rhizotrons. Attempts were made to measure bulk density variations at different depths in the rhizotrons after the glass was removed at the end of the experiment, but intact cores could not be extracted successfully. Porosity was calculated using the formula: $f = (Bd/d)$ where f = porosity, Bd = bulk density, and d = particle density.

A soil thermometer installed in 1 rhizotron verified that soil temperatures remained above 4°C (39.2°F). The soil in each rhizotron was brought to field capacity before planting with a calculated volume of water delivered by a specially designed drip irrigation system. The number of days required for the wetting front to move all the way to the bottom was recorded. The rhizotrons were maintained near

Table 1. Analyses of the fine- and the coarse-textured soils used in the rhizotrons.

	Soil type	
	Coarse	Fine
pH (1:2, H_2O)	6.70	6.90
Cation exchange (dS/m)	2.98	0.49
Organic matter (%)	2.44	3.38
N total (%)	0.13	0.21
P_2O_5 (Bray P-1, ppm)	22.96	18.16
Exchangeable cations		
Ca++ (cmol/kg)	12.10	16.80
Mg++ (cmol/kg)	3.86	5.63
Na+ (cmol/kg)	0.40	0.54
K+ (cmol/kg)	0.41	0.28
Physical properties		
Sand (%)	60	26
Silt (%)	24	41
Clay (%)	16	33

field capacity during the experiment by adding measured amounts of water based on rhizotron weight loss, using the same drip irrigation system.

The criteria for native species selection included native origin, attractive ornamental features, and wide ecological distribution Growth of 2 seldom-used species, *Q. crassipes* and *Q. crassifolia*, were compared to *F. uhdei*, the most commonly planted and successful species planted on the streets of Mexico City.

To avoid problems with inconsistent germination, *Quercus* seeds were germinated before transplanting them into the rhizotrons on October 1, 1996. *Fraxinus uhdei* seeds were planted directly into the rhizotrons on October 1 and germination occurred 15 days later. There were 2 plants in each rhizotron. Plants that died during the experiment were not replaced. The plants were grown for 6 months.

Root and shoot growth were recorded weekly. Root growth was traced on the glass with markers, using a different color each week for new growth. Maximum depth of visible root penetration was also recorded weekly. Periodic shoot growth measurements included the total height of the plant when the main stem was held vertically.

The process of removing the plants from the rhizotron began on March 15, 1997. All plants of each species were harvested during the same week. The *F. uhdei* were harvested last because they were the last to germinate.

A nailboard (Böhm 1979) was used to hold the roots in place as the soil was removed. Nail locations corresponded to the line intersections of the 5 × 5 cm grid on the glass. The nails were pressed completely into the soil before turning the nailboard and rhizotron over together, and then removing the wooden back and sides of the rhizotron. The nailboard and soil were soaked together (2 to 3 hours for the clay loam soil, overnight for the loamy sand soil), and then the softened soil was washed away with a gentle stream of water. The depth of maximum penetration of the root system of each plant was recorded. The stems were then cut at the soil line, dried for 24 hours at 80°C (176°F), and then weighed.

The experimental design was a randomized balanced complete factorial (Hicks 1993). Two soils and 3 species were the treatments, with 10 replications of each combination. Treatment effects were determined by analysis of variance (ANOVA) using Sigma Stat 2.0. Differences among treatment means were separated by the Student-Newman-Keuls (SNK) at $P < 0.05$. All pairwise multiple comparison procedures using the Student Newman Keuls method were applied to raw data. A Student's t-test for independent samples was used to compare values between soils.

RESULTS AND DISCUSSION

Based on overall size and appearance of the plants and their root systems, plant vigor was generally lower in the coarse-textured soil (Figure 1). Five seedlings (17%) in the coarse-textured soil died during the experiment, while none died in the fine-textured soil.

Bulk density of the coarse- and fine-textured soils in the entire rhizotron was 1.20 and 1.01 Mg/m^{-3}, respectively. These values are lower than the "ideal soil" and well below the values of 1.70 and 1.46 Mg/m^{-3} that are generally accepted as threshold values for root growth restriction for these soils (Craul 1992). The low particle density of volcanic materials in these soils (P. Kelsey, personal communication 1997) contributes to the low bulk density.

Soil porosity of the coarse-textured soil was significantly lower than the fine-textured soil (47% and 54%, respectively). Coarse-textured soils usually have less pore space than fine-textured soils because of the smaller particle surface area in relation to volume, and closer packing of the particles (Hillel 1980; Craul 1992). Lower porosity can result in slower diffusion of soil gasses and less oxygen for roots, especially in deeper soils. Reduced aeration may have contributed to the reduced plant survival and vigor (Drew and Stolzy 1996; Kozlowski 1998).

During the initial irrigation of the dry soil in the rhizotrons, the wetting front moved significantly more slowly through the coarse-textured soil. Completely wetting the coarse-textured soils took an average of 3.5 days longer. Slower water movement through the coarse-textured soil is an indicator of greater compaction, a decrease in porosity, and loss of pore continuity (Kozlowski 1998).

Depth of Root Penetration

Roots of the 2 *Quercus* species in both soils and the *F. uhdei* in fine-textured soil were visible behind the glass in the majority of the rhizotrons by day 30

Figure 1. *Fraxinus uhdei* root system growing in the coarse-textured (left) and fine-textured (right) soil rhizotrons after 162 days, before the soil was washed away.

(Figure 2). *Fraxinus uhdei* roots growing in coarse-textured soil were not visible behind the glass until day 42 and were more shallow when they became visible.

Quercus crassifolia roots penetrated significantly deeper than *F. uhdei* on days 43 and 55 in both soils; *Quercus crassipes* roots penetrated deeper than *F. uhdei* on day 55 in both soils and on day 43 in the fine-textured soil; there was no difference between *F. uhdei and Q. crassipes* on day 43 in the coarse-textured soil.

The more rapid initial root penetration of the *Quercus* roots in both soils may be related to large energy reserves in the seed. Large seeds, such as *Quercus*, often produce strong taproots in the seedling stage (Bonfil 1998). The smaller *F. uhdei* seeds do not produce taproots, and substantial lateral root growth occurs at an early stage (Yorke and Sagar 1970, in Russell 1977).

After day 55, many weeks followed where there was no difference in depth of penetration between species in either soil type (Figure 2). *Fraxinus uhdei* root penetration became significantly deeper than both *Quercus* species in both soils on day 156. At this time, *F. uhdei* roots had penetrated 74% deeper than both oak species in the coarse soil, and 29% and 20% deeper in the fine soil, than *Q. crassifolia* and *Q. crassipes*, respectively. Final depth of visible *F. uhdei* root penetration was significantly greater than both *Quercus* species in both soils (Table 2).

Roots of the *F. uhdei* grew against the glass surface continuously, and there was no difference between visible and actual penetration of *F. uhdei* roots at the end of the experiment (Table 2). The *Quercus* roots grew away from the glass at times and reappeared a few centimeters deeper after a few days. Measurements of root pen-

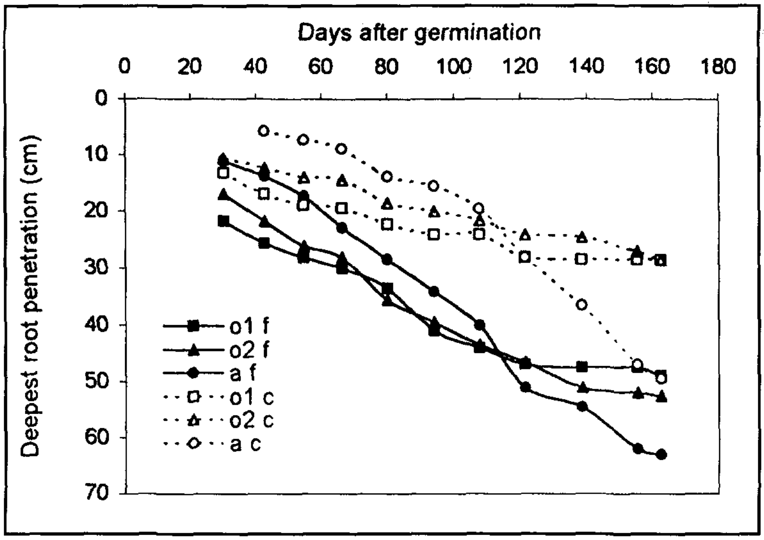

Figure 2. Visible root penetration of *Quercus crassifolia* (o1), *Q. crassipes* (o2), and *Fraxinus uhdei* (a) growing in rhizotrons filled with fine- (f) and coarse- (c) textured soils.

etration obtained when the soil was washed from the roots at the end of the experiment showed that the actual maximum root penetration (Table 2) was significantly deeper (more than 10 cm [3.9 in.]) than visible root penetration for both *Quercus* species in the fine-textured soil and for *Q. crassifolia* in the coarse-textured soil. As a result, actual *F. uhdei* root penetration was not significantly deeper than either *Quercus* species in the fine-textured soil.

Though the differences between visible and real root penetration in the small benchtop rhizotrons were measurable, they were not sufficient to change the overall perception of the vigor and character of the root systems. Such benchtop rhizotrons may be very useful in practical applications where periodic observation and characterization of overall growth of the roots is needed but may have limitations when precise quantification of root systems is needed.

Visible root penetration of all 3 species was significantly reduced by the coarse-textured soil (Table 2). The reduction was probably caused by higher mechanical impedance, lower soil aeration, or both (Alan and Bennie 1991; Craul 1992). The visible roots of both *Quercus* species penetrated to a depth of less than 30 cm (11.8 in.) in the coarse-textured soil, while in the fine-textured soil, the roots of both *Quercus* species penetrated to a depth of approximately 50 cm (19.7 in.). The *F. uhdei* roots penetrated the coarse-textured soil as effectively as the *Quercus* species were able to penetrate the fine-textured soil (approximately 50 cm). Even greater *F. uhdei* root penetration was recorded in the fine-textured soil. The ability of this species to grow on nearly all urban sites in Mexico City may be related to the ability of the root system to grow vigorously in a wide variety of soils.

Total Root Dry Weight

Fraxinus uhdei root dry weight was significantly greater in fine- than in coarse-textured soil (Table 3). The coarse-textured soil reduced *F. uhdei* total root dry weight more than it reduced maximum depth of penetration (61% versus 21%).

There were no statistically significant differences in *Quercus* root dry weights between soil types (Table 3). A significant reduction (40%) in root penetration of *Quercus* species in the coarse-textured soil (Table 2), without a significant decrease in root dry weight, indicates the roots were growing more densely in the upper soil surface where there was still ample room for root growth of these small plants. The *Quercus* species were much smaller plants than the *F. uhdei*. If the *Quercus* species had grown larger (until the shallow soils became filled to capacity with roots), such a restriction of roots to the shallow

Table 2. Final root penetration in the rhizotrons.

	Soil texture	
	Coarse	Fine
Maximum visible penetration (cm)		
Quercus crassifolia	28.5 a[†]*	49.0 a
Q. crassipes	28.5 a*	52.5 a
Fraxinus uhdei	49.5 b*	63.0 b
Actual penetration (cm)		
Quercus crassifolia	40.5 a[#]*	59.0 a[#]
Q. crassipes	34.0 a*	64.0 a[#]
Fraxinus uhdei	49.5 b*	62.5 a

[†]Within each combination of soil type and penetration type, values with the same letter are not significantly different.
[#]Indicates that root penetration of this species was significantly reduced by coarse soil.
*Indicates that actual root penetration was significantly greater than visible root penetration for this species and soil type.

soils may eventually have reduced total root growth, as it appeared to do for the larger *F. uhdei* plants.

If the distribution of roots of urban trees is restricted to the surface soil layers, similar to that of *F. uhdei* in the coarse-textured rhizotron soils, the trees may still be able to survive, though they may be more stressed, smaller, and shorter lived, primarily because water and element availability are less than optimal (Russell 1977).

Shoot Growth

Shoot dry weight of *F. uhdei* was significantly greater in fine-textured soil, but there was no difference in shoot dry weight of either *Quercus* species in the 2 soils (Table 3). There were no significant differences in shoot height prior to day 80. Starting on day 80 and continuing until the end of the study, *F. uhdei* growing in fine-textured soil were taller than *F. uhdei* growing in coarse-textured soil. Soil type had no effect on height of either *Quercus* species (Figure 3).

Between day 80 and 135 *Quercus* shoot growth virtually stopped (Figure 3). In the fine-textured soil, *F. uhdei* grew significantly taller than *Q. crassifolia* starting on day 80, and taller than *Q. crassipes* starting on day 100. In the coarse-textured soil, *F. uhdei* became taller than both *Quercus* species much later, on day 122, due to the slower growth of the *F. uhdei* in the coarse-textured soil. Because *F. uhdei* root penetration did not become greater than the *Quercus* until day 156, it appears that shoot growth is not dependent on root penetration alone.

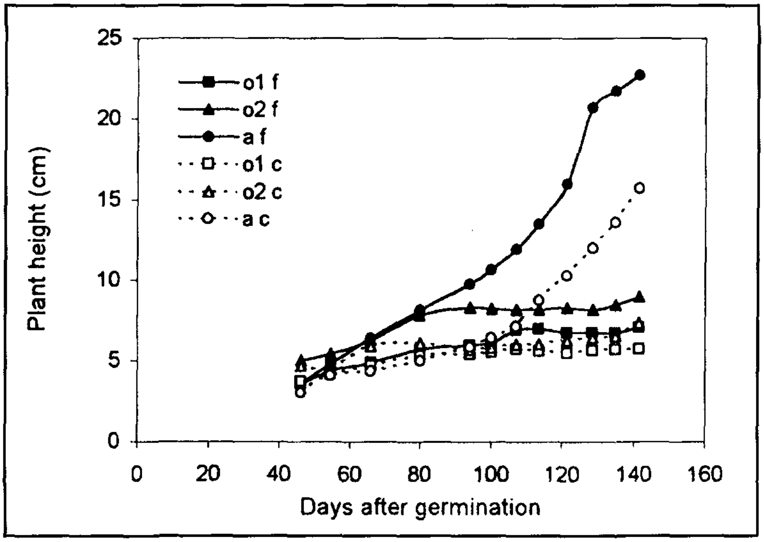

Figure 3. Shoot growth of *Quercus crassifolia* (o1), *Q. crassipes* (o2), and *Fraxinus uhdei* (a) growing in rhizotrons filled with fine- (f) and coarse- (c) textured soils.

Table 3. Total root and shoot dry weight of *Quercus crassifolia*, *Q. crassipes*, and *Fraxinus uhdei* in rhizotrons filled with coarse- and fine-textured soils.

	Root dry weight (g)		Shoot dry weight (g)	
Species	Coarse	Fine	Coarse	Fine
Quercus crassifolia	0.61 a†	1.07 a	0.56 a	1.13 a
Q. crassipes	0.60 a	1.48 a	0.60 a	1.09 a
Fraxinus uhdei	2.30 a	5.94 b*	3.53 a	9.88 b*

†Values in the same column followed by the same letter are not significantly different ($P < 0.05$) using the Student-Newman-Keuls (SNK) method.
*Indicates a significant difference ($P < 0.05$) between growth in fine- and coarse-textured soils using the SNK method.

The lack of *Quercus* shoot growth between day 80 and 135 while roots continued to penetrate deeper probably indicates that this was a natural period of slow shoot growth while the root system developed further to support future shoot growth (Bonner and Vozzo 1987; J. Kohashi, personal communication 1998).

CONCLUSIONS

Root responses to the 2 different soil types in this study show that soil conditions similar to those encountered in urban areas can be created in small benchtop rhizotrons. The vigorous growth of the *F. uhdei* roots could help to explain why this species is able to grow so readily on nearly all urban sites. Roots of *Q. crassipes* and *Q. crassifolia* penetrated the moderately favorable urban soil represented by the fine-textured soil in this experiment as well as those of *F. uhdei* but did not compare as well in the less favorable coarse-textured soil. Based on this data, *Q. crassifolia* and *Q. crassipes* may perform well on some urban sites, but probably not on the most difficult urban sites. The coarse-textured soils of Mexico City may be a substantial cause of poor root growth and low survival of trees in Mexico City. Greater knowledge of soil requirements of native Mexican species will allow better matching of plant to planting sites in Mexico City and allow a wider variety of new species to be successfully introduced.

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Résumé. Des semis d'espèces d'arbres sélectionnées ont été placés dans de petits bancs de plantation remplis avec des sols compactés à texture fine et grossière afin de simuler les conditions urbaines. La croissance des racines du *Quercus crassipes*, du *Q. crassifolia* et du *Fraxinus uhdei* a été suivie au travers d'une vitre durant une période de six mois. Les différences de profondeur de pénétration des racines, de masse sèche totale de racines et de croissance des pousses ont été évaluées pour chaque espèce dans les deux types de sol. La porosité totale est significativement inférieure dans le sol à texture grossière. Les résultats ont montré que la profondeur maximale visible d'enracinement était significativement plus élevée dans le sol à texture fine pour les trois espèces, et aussi que la masse sèche des racines du frêne était significativement inférieure dans le sol à texture grossière par rapport au sol à texture fine. La pénétration des racines des deux espèces de chêne comparée à celle du frêne était équivalente dans le sol à texture fine, mais pas dans celui à texture grossière. Ces espèces de chênes pourraient être des espèces prometteuses en milieu urbain si on prend soin de les planter dans des conditions de sols favorisant le développement de leurs racines.

Zusammenfassung. Es wurden Sämlinge von ausgewählten Baumarten in kleinen Wurzelbetten, die mit feinem und grob strukturiertem Boden gefüllt waren, gepflanzt und der Boden verdichtet, um dem Edaphon typische städtische Konditionen zu geben. Die Wurzeln von *Quercus crassipes*, *Q. crassifolia* und *Fraxinus uhdei* wurden über Monitor über einen zeitraum von sechs Monaten beobachtet. Die Differenzen bezüglich der Tiefe der Durchwurzelung, des totalen Wurzelgewichts und des oberirdischen Wachstum wurde für alle Arten und beide Bodenarten bewertet. Die totale Porösität war in grobstrukturierten Böden deutlich niedriger. Die Wurzelergebnisse zeigten, die Wurzeln aller Arten hinter der Scheibe sichtbar waren, die maximale Tiefe einer sichtbaren Wurzel war deutlich größer als in feinstrukturierten Böden und das Trockengewicht der Eschenwurzel war in dem groben Boden deutlich reduziert gegenüber dem feinen Boden. Die Durchwurzelungseigenschaften der beiden Eichen im Vergleich zur Esche war in feinem Boden besser als im groben Boden. Diese Eichenarten könnten vielversprechende Baumarten für Stadtstandorte sein, wenn dafür Sorge getragen wird, daß sie Bodenbedingen erhalten, die ihre Entwicklung fördern, da die Durchwurzelung gleich gut war wie bei dem meistvorkommenden Strassenbaum in Mexiko, der Esche.

Resumen. Brinzales de árboles de especies seleccionadas se cultivaron en pequeños rizotrones llenos con suelos de textura fina y gruesa, compactados para simular las condiciones urbanas. Fue monitoreado el crecimiento de las raíces de *Quercus crassipes*, *Q. crassifolia* y *Fraxinus uhdei* a través de los rizotrones de vidrio por un periodo de seis meses. Se evaluaron las diferencias de profundidad en penetración de las raíces, peso seco total de las raíces y crecimiento de los brotes para cada especie en los dos tipos de suelo. La porosidad total fue significativamente menor en el suelo de textura gruesa. Los resultados mostraron que la máxima profundidad de penetración visible de las raíces fue significativamente mayor en el suelo de textura fina para las tres especies y que el peso seco de las raíces de fresno fue significativamente reducido en el suelo de textura gruesa comparado el suelo de textura fina. La penetración de las raíces de las dos especies de encino, comparada con el fresno, fue igual en el suelo de textura fina, pero no en el de textura gruesa. Estas especies de encino podrían ser árboles urbanos prometedores si tenemos cuidado de plantarlos en las condiciones de suelo que favorezcan el desarrollo de su raíz.