plant breeder, Dr. Andrew Riseman, who comes to us from Penn State University and the Danish Institute of Agricultural Sciences. The next stage for the Botanical Garden is to continue to acquire new and exciting plants, to put Dr. Riseman's expertise to work, and build on the cooperation and collaboration of our nursery partners to make the Plant Introduction Program work for all of us.

Selection and Propagation of Deep-rooted Ornamental Trees for Urban Environments©

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Ornamental trees in urban environments provide myriad biological, physical, economical, and sociological benefits. Trees: (1) provide a habitat for a wide range of animal life, (2) function as a cleansing mechanism for polluted air, (3) shade houses and other structures thus reducing the need for electrically powered air conditioners during the summer, and (4) provide an environment in which human beings can connect with nature. However, some trees have root systems that cause damage to sidewalks, curbs, and gutters. This damage is the result of planting trees in planting areas that are too small or too narrow and/or the trees inherent tendency to have shallow, horizontally oriented roots (Barker, 1987; Barker and Wagar, 1987). As these shallow roots produce secondary thickening growth they tend to upheave pavements around them. Several popular tree species have been associated with sidewalk and curb displacement. They include: *Liquidambar styraciflua* (sweet gum), *Morus alba* (white mulberry), *Fraxinus* spp. (ash), *Ulmus* spp. (elm), *Magnolia grandiflora* (southern magnolia), *Prunus* spp., *Pinus radiata* (Monterey pine), *Eucalyptus globulus* (blue gum eucalyptus), and *Cinnamomum camphora* (camphor) (Hamilton, 1984a).

This problem is of major proportions in many cities in California. In a survey of cities in the Bay Area in 1984, 60% of the street trees were estimated to have caused some or severe damage (Hamilton, 1984b). A more recent survey of sidewalks in San Jose, California, found the estimated repair cost for tree related damage to be $14.3 million and annual concrete repair costs attributed to tree damage range from $0.18 to $13.65 per tree (Peper and McPherson, 1995). It's quite apparent that even a partial solution to this problem would result in substantial savings for city residents and governments.

There are engineering, design, improved materials, and biological/genetic approaches to solving this problem. Engineering solutions include the use of steel plates bolted directly to exposed roots to prevent or minimize future damage and the use of root barriers in an attempt to force roots down below sidewalks and curbs. Design solutions include providing adequate planting strip space for tree trunk diameter increases and root crown flair. Newer paving materials may provide the necessary flexibility to prevent cracking and complete disruption of the pavement.

Another possible approach to this problem is to identify, select, and vegetatively propagate trees that are deep-rooted. The basic premise behind this approach is that it is reasonable to expect as much variability in below-ground architecture for trees

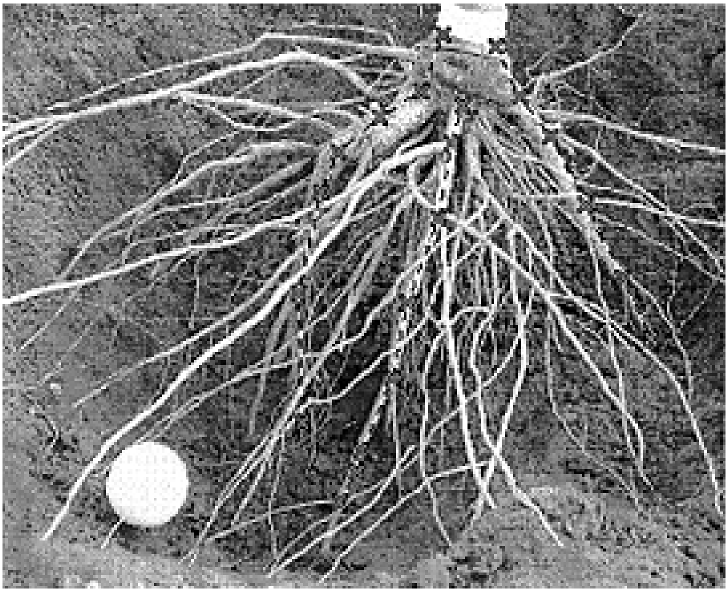


Figure 1. One of four photographs of an exposed root system that had been marked for creation of 3-D model. White sphere in lower-left corner is 2 inches (5.1 cm) in diameter.

as is found above-ground. The central question currently being asked in this research is: Are there genetic differences in root depth and orientation within a species?

MATERIALS AND METHODS

The first step in following the biological/genetic approach was to identify tree species known to cause sidewalk and curb disruption. A survey of seven northern California cities (Modesto, Redwood City, Palo Alto, Berkeley, Sacramento, Sunnyvale, and Davis) was conducted. More than 20 species were identified that cause damage in these cities and three were selected for the research project. These included *F. uhdei* (green ash), *Pistacia chinensis* (Chinese pistache), and *Zelkova serrata* (zelkova). Fifty seed-propagated individuals of each of these three tree species were planted in a field plot in Davis, California in July 1997. The field plot was chosen for its consistent soil texture (Yolo loam) and soil depth. All trees were provided with luxuriant amounts of water applied via a drip irrigation system. Deep irrigation was practiced to reduce the potential influence of shallow irrigation on root growth and development. In December, 1998, 15 trees of each species were selected to have the soil around their root systems removed. This was accomplished using a pneumatic soil excavation technique that removed the soil without significant damage to the tree root systems. Following soil excavation each root system was marked and digital photographs were taken from four vantage points roughly 90^{o} apart around the root system (Fig. 1). The digital photograph files were imported into modeling software (PhotoModeler Pro, Eos Systems, Inc., Vancouver, BC, Canada) and marked so as to label specific root locations on each photograph. Once marked, the

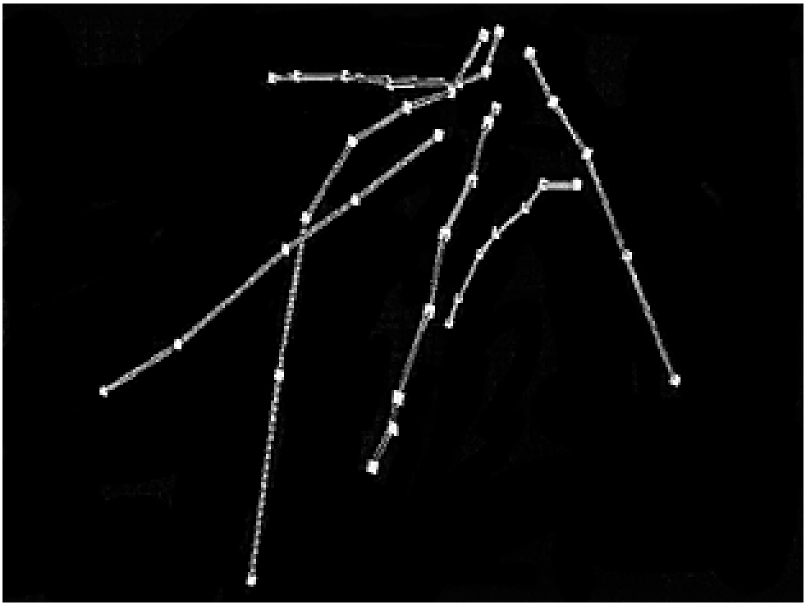


Figure 2. 3-D model showing position and angle of major structural roots for the root system photographed in Figure 1.

PhotoModeler software created three-dimensional models with accompanying coordinates for each root system (Fig. 2)

RESULTS AND DISCUSSION

Three-dimensional models of the experimental trees showed a distribution from shallow-rooted to deep-rooted (Table 1). When two-dimensional projections of the three-dimensional models were created linear regression equations could be fitted to the data. The slope of those linear regression provide a measure of the average rooting depth of each tree root system. The slopes range from -0.50 (shallow-rooted)

Table 1. Root architecture descriptors.

	Fraxinus uhdei	*Pistacia chinensis*	*Zelkova serrata*
Minimum slope (shallowest root system)	-0.50 Figure 3	-0.63 Figure 5	-0.70 Figure 7
Maximum slope (deepest root system)	-2.35 Figure 4	-2.95 Figure 6	-2.40 Figure 8
Average slope ± 1 SD	-1.1 ± 0.5	-1.5 ± 0.6	-1.2 ± 0.5
Percent of trees with slopes less than -1.0	60	79	53

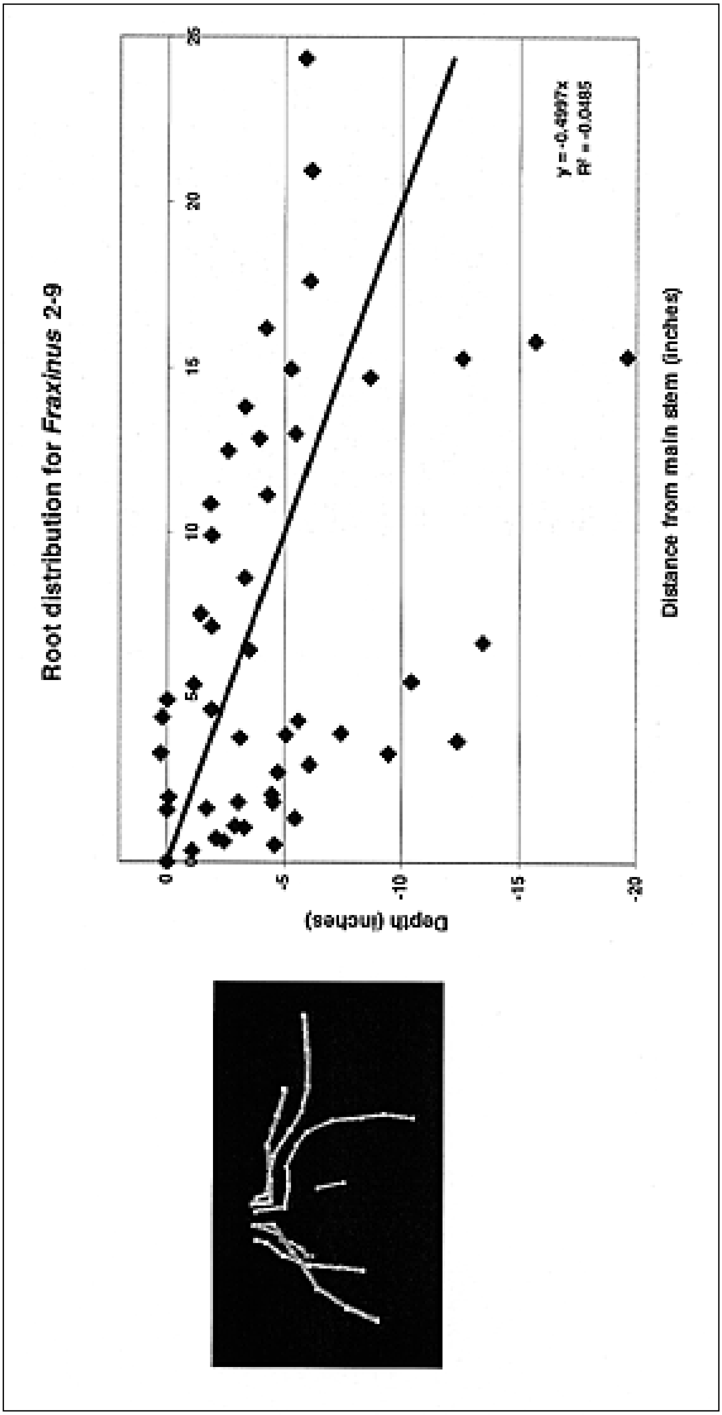


Figure 3. 3-D model (left) and 2-D root distribution projection for *Fraxinus* 2-9.

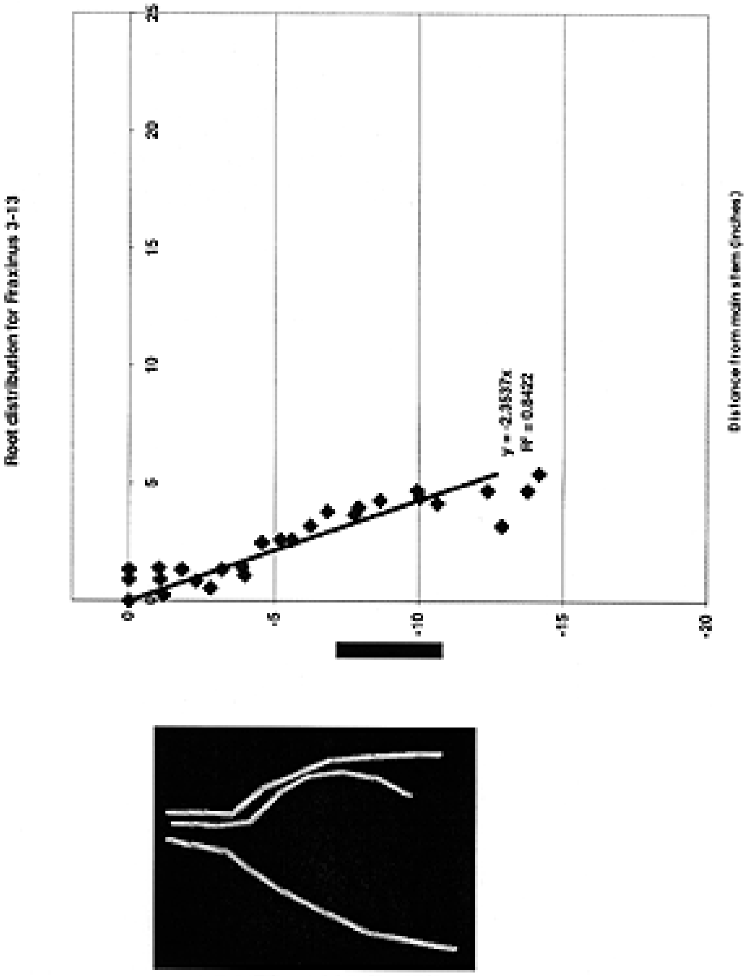


Figure 4. 3-D model (left) and 2-D root distribution projection for *Fraxinus* 3-13.

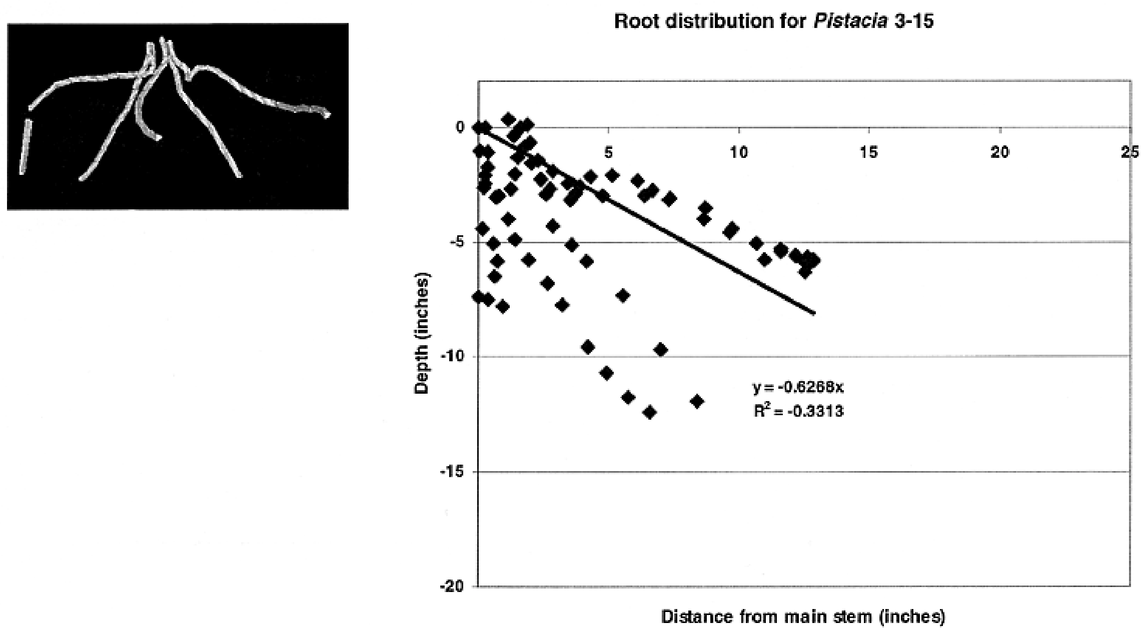
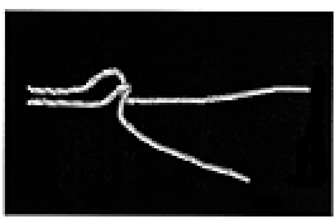


Figure 5. 3-D model (left) and 2-D root distribution projection for *Pistacia* 3-15.



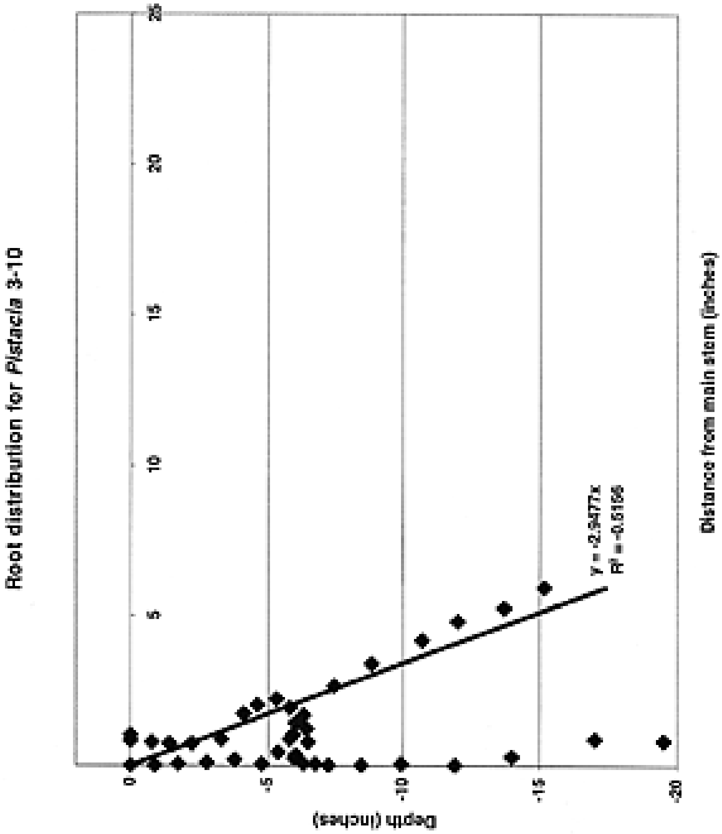


Figure 6. 3-D model (left) and 2-D root distribution projection for *Pistacia* 3-10.

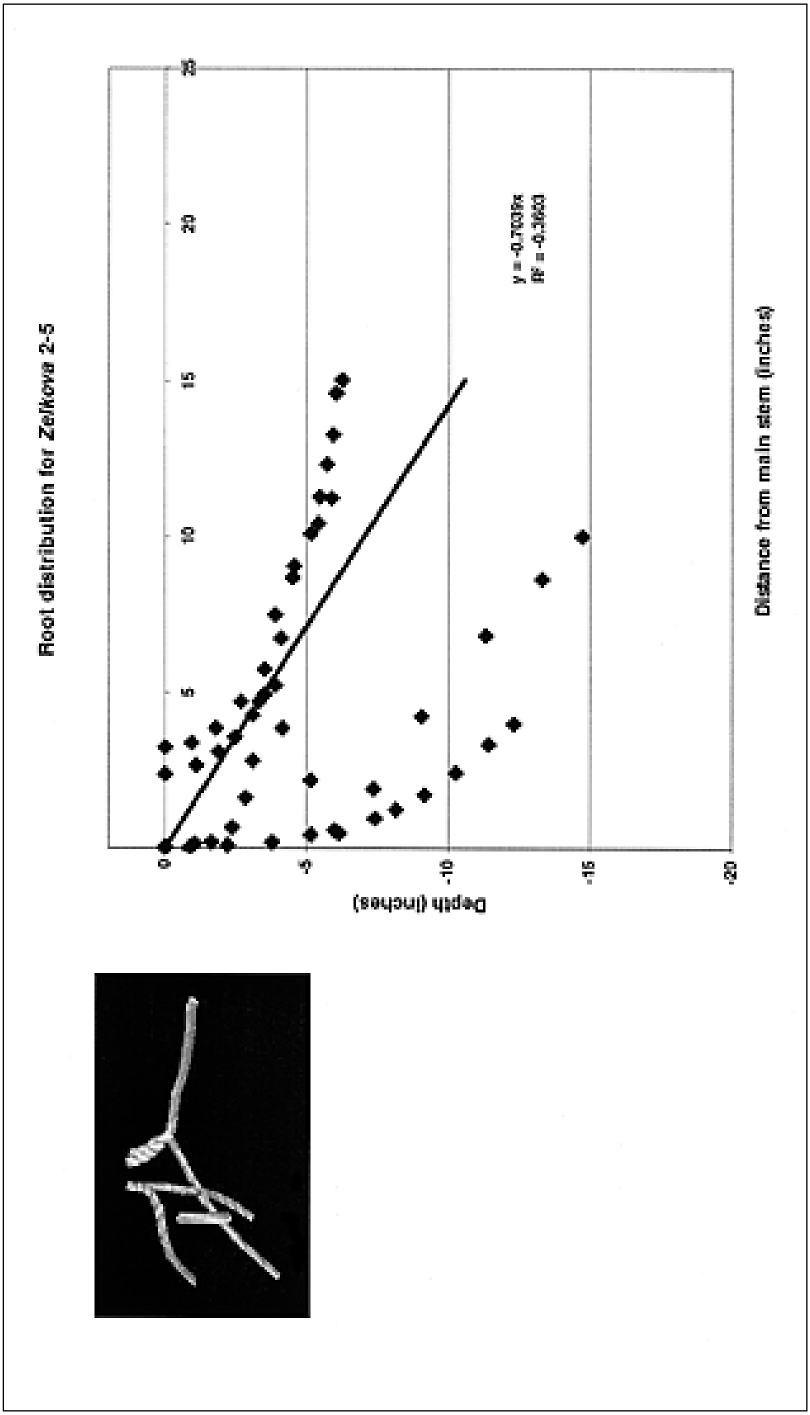


Figure 7. 3-D model (left) and 2-D root distribution projection for *Zelkova* 2-5.

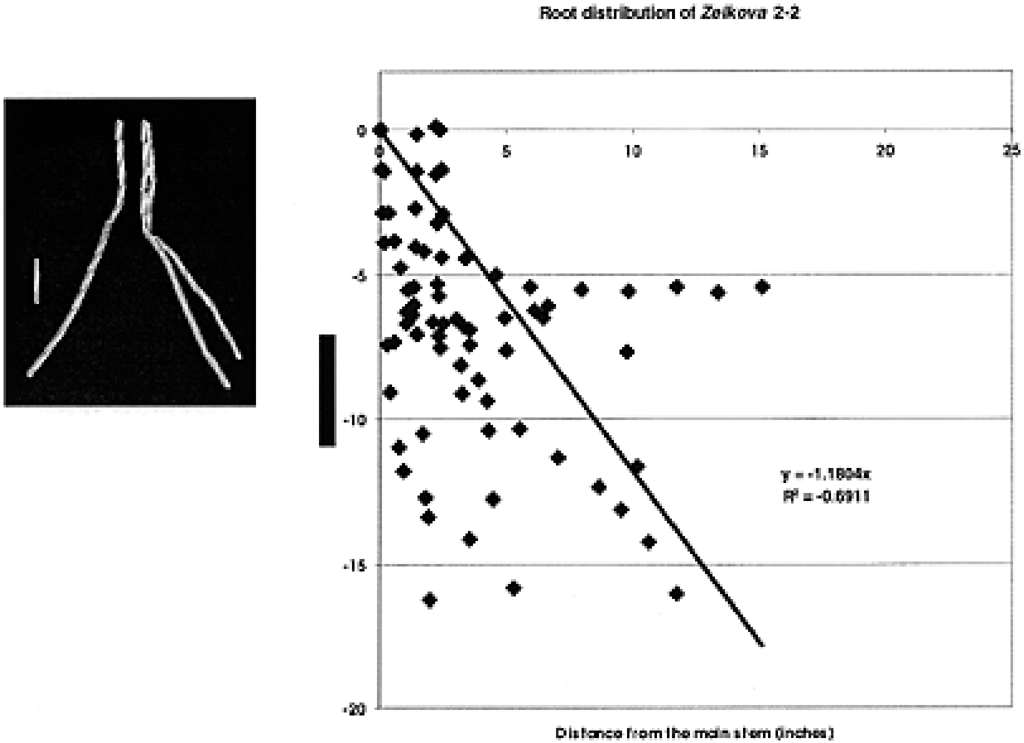


Figure 8. 3-D model (left) and 2-D root distribution projection for *Zelkova* 2-2.

to -2.95 (deep-rooted). Deeper root systems had more negative slopes of the fitted lines. Table 1 is a summary of the root distance and depth data collected from the three tree species. *Pistacia chinensis* trees had the most negative average slope (deepest root systems, on average) and also had the highest percentage of trees with slopes below -1.0. A slope of -1.0 indicates that, on average, the roots are at a 45^o angle or more from the horizontal surface.

The current research has employed a useful root visualization and measurement technique and shown that there is potential for selecting trees that are naturally deep rooted. The next step is to vegetatively propagate selected individuals that are shallow rooted or deep rooted, plant them in the field and assess their root architecture. If the vegetatively propagated clones maintain the root architecture characteristics this approach may offer one solution to the problem of tree-root damage to sidewalks and curbs in urban environments.

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