WHICH COMES FIRST, THE ROOT OR THE CRACK?

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Abstract. The Ohio State University and the City of Cincinnati Park Board conducted a study of street trees in Cincinnati, Ohio, U.S., during the summers of 1999 and 2000. Four genera of trees were examined from four different plant families. Approximately 600 trees planted within the past 20 years were observed. The condition of the nearest sidewalk joint and the incidence of a root for *Quercus* (oak), *Koelreuteria* (goldenraintree), *Zelkova* (zelkova), and *Gleditsia* (honeylocust) were observed. All genera responded similarly in that roots were more likely to be found under a crack in the sidewalk than under an intact sidewalk. During the first 20 years after planting, tree roots are more likely to be found underneath a sidewalk crack than an intact sidewalk. Of 351 joints observed with no roots, 39% were intact and 61% were cracked. Of the 260 joints where roots were observed, only 16.2% were intact while 83.9% were cracked. Oxygen measurements were made underneath selected sidewalks. Oxygen concentrations were compared for soil underneath cracked and intact sidewalk blocks. The soil underneath cracked sidewalks showed a higher concentration of oxygen. This higher oxygen concentration may contribute to root growth underneath cracked sidewalks.

Key Words. Tree root–sidewalk interaction; sidewalk–soil interaction; sidewalk construction; cracks; soil oxygen; sidewalk failure; sidewalk design.

The battle between street trees and sidewalks is one with a long history. Street trees are often blamed when sidewalks fail. McPherson and Peper (1995) estimated that municipalities in the United States spend more than $135 million annually on "tree-related" infrastructure repair costs. In the city of Cincinnati, Ohio, U.S., Public Works Department officials have shared the belief that trees are the primary culprits in sidewalk failure (Sydnor et al. 2000). Fiscally conservative members of Cincinnati's city council attempted to use this argument to justify the use of funds earmarked for street trees to repair sidewalks (Hunt 2000).

Sidewalk design is usually ignored in the discussion. Sidewalk engineers in Ohio, including those in Cincinnati, relate that sidewalks are typically designed to last between 20 and 25 years, depending on the city (Gamstetter 1997). Sidewalks are certainly not designed to last indefinitely, and construction methods have changed over time. In the 1940s, Cincinnati sidewalk engineers required sidewalks to be 13 cm (5 in.) thick with a gravel base and be inspected during and after installation. To save money, sidewalks are now framed with 2-by-4-ft (4-by-9-cm) timbers; this framing typically produces a sidewalk that is about 10 cm (4 in.) in depth as opposed to the originally specified 13 cm (5 in.). Sidewalks are now inspected only after installation and are not required to have a gravel base (Gamstetter 1997). Soil type is often not a consideration, and sidewalk construction methods are rarely adjusted to account for the properties of different soils (Sydnor et al. 2000). Do these cost-cutting measures have an impact on service life? When a sidewalk is beyond its intended service life of 25 years and is displaced by a tree root, is the root growing beneath the sidewalk a "failure," or is the failure an expected consequence of an aging sidewalk?

A citywide sidewalk study in Cincinnati in 1999 found no difference between the failure rate of sidewalk panels next to trees and the failure rate of panels that were not next to trees (Sydnor et al. 2000). The 1999 study also found that the rate of sidewalk failures that were related to trees during the first 15 to 20 years of a sidewalk's life was extremely low.

This is not to suggest that trees cannot displace sidewalks. For a tree to displace a sidewalk, a root typically must be present underneath the sidewalk. For a sidewalk to be displaced, it usually needs to crack. However, it is important to note that sidewalks are commonly displaced and cracked where no tree is present (Sydnor et al. 2000). This study examines relationships between sidewalk condition, tree age, and oxygen concentration in soil materials under sidewalks. A 1996 study conducted in the tropics found that the distance from the tree to the sidewalk, the diameter of the trunk, and species of the tree all contributed to the probability of sidewalk failure (Francis et al. 1996). This study seeks to determine whether the condition of the adjacent sidewalk contributes to the presence of tree roots growing underneath the sidewalk, and the potential for sidewalk failure attributable to roots.

METHODS

Roots and Sidewalk Condition

Trees were selected based on genera, date of planting, and tree lawn width. Data were obtained from the City of Cincinnati's planting records. Four families and genera of trees were selected for the study: *Gleditsia triacanthos* (Fabaceae); *Quercus,* specifically trees in the red oak group including *Q. rubra, Q. palustris, Q. shumardii, Q. phellos, Q. acutissima, Q. imbricaria,* and *Q. nigra* (Fagaceae); *Zelkova serrata* (Ulmaceae); and *Koelreuteria paniculata* (Sapindaceae).

The genus *Quercus* is the only genus for which observations were made on multiple species. *Quercus* is a large genus, and small numbers of many different species in this genus have been planted on Cincinnati's city streets. Species of *Quercus* were limited to the red oak group because many species in this group have similar uses in urban situations (Sydnor and Cowen 2001). The City of Cincinnati has regularly planted a single species from each of the other three genera in sufficient quantities for study.

The study focuses on trees planted in the past 4 to 20 years. The 20-year time frame was chosen because the City of Cincinnati expects sidewalks to have an effective service life of 20 to 25 years, and the city's planting records covered roughly this period. Because the 1999 study found a very low rate of tree-related sidewalk failure during the first 20 years of a sidewalk's life (Sydnor et al. 2000), tree-sidewalk interactions during this period became of primary interest.

The following data were recorded for each tree: name of the street and approximate address of the tree's location; year planted; width of tree lawn; sidewalk condition as "not cracked," "cracked but not displaced," "displaced but not failed," or "failed" (a "failed" sidewalk is defined as one that has been vertically and/or horizontally displaced 1/2 in. or more because this condition is considered condemnable by the City of Cincinnati); presence or absence of a root greater than 1 cm (3/8 in.) in diameter within 20 cm (8 in.) of the surface that was growing beneath the sidewalk; and diameter of main stem at 1.3 m (4.5 ft) (dbh).

For the purpose of this article, the term "sidewalk joint" refers to one of the designed failure points in the sidewalk or an expansion joint. To determine whether a root was growing under the sidewalk, joints located within 1.8 m (6 ft) of the trunk of the tree were examined. A nursery spade was used to dig to a depth of approximately 20 cm (8 in) immediately adjacent to the joint on the tree lawn side of the sidewalk, and the presence or absence of any root(s) at least 1 cm (3/8 in.) diameter growing underneath the walk was noted. A note was made as to whether the joint was cracked or not cracked. The term "cracked" refers to a fissure completely through the "joint." Date of planting was determined using Cincinnati planting records and the assistance of employees from the Cincinnati Park Board. Tree lawns were limited in size to a width of less than 3.5 m (11.5 ft)

Soil Oxygen

Oxygen concentrations were measured under a single 100-m (328-ft) section of sidewalk. Twelve cracked sites were selected that appeared to be unaffected by adjacent trees. Pairs of holes 15 mm (5/8 in.) in diameter were drilled through the sidewalk on each side of the crack, 5 cm (2 in.) from it. The holes were made 15 cm (6 in.) from each edge of the sidewalk and in the center. A 1-cm (3/8-in.) steel bar was driven into the base to a depth of 15 or 30 cm (6 or 12 in.) from the sidewalk surface. A 15- or 30-cm-long polyethylene tube (10 mm o.d.) was inserted into the hole made with the bar. The tube was sealed into the sidewalk with a 2.5-cm (1-in.) sleeve of rubber tubing (15 mm o.d.) coated inside and out with vinyl caulk. The tube was capped with a rubber septum seal. Similar gas-sampling tubes were set in 12 intact regions of sidewalk, and further tubes were placed in the open ground at a distance of 15 and 30 cm from each edge of the sidewalk for both cracked and intact sidewalk locations. The sample tubes were set up in two batches in July and August, and they were allowed to equilibrate for about 30 days before gas samples were first collected. Further samples were collected in July one year later. A disposable plastic syringe was use to collect a 1-mL (0.034-oz) sample from each tube, and the syringes were sealed by insertion in a rubber stopper for transport back to the laboratory. Oxygen concentration was estimated by injection into a stream of nitrogen (20 mL min^{-1}) passing through a paramagnetic oxygen analyzer (Servomex, Crowborough, England) connected to a computing integrator (Shimadzu, Kyoto, Japan).

Statistical Analysis

Statistical analysis of root occurrence for the four genera growing on city streets was performed using SAS with the assistance of the Statistics Laboratory at the Ohio Agricultural Research and Development Center. The presence or absence of cracks and the presence or absence of roots growing beneath a sidewalk were used to tabulate trees in two-way frequency tables. Chi-square tests were done for each case by genus and for all trees. The tree root observations were made over a period of two years. Only the nearest joint to the tree was used for this analysis.

RESULTS AND DISCUSSION

The sample population, including the total number of observations and planting information by genus, is given in Table 1. Some plants were eliminated because there were obstructions, recent stumps, or other interference with the observations. The average time since planting ranged from 9 years for *Zelkova* to 11 years for *Quercus* and *Koelreuteria*, with an overall average of 10 years.

Table 1. Sampling distribution summary data: average age since planting and average tree lawn widths by genus for four tree genera planted in Cincinnati, Ohio, since 1980.

Genus	Average observed	Time since planting (yrs)	Tree lawn width, m (ft)
Gleditsia	176	11	1.6 (5.3)
Koelreuteria	93	11	1.4 (4.6)
Quercus	181	10	2.3 (7.4)
Zelkova	161	9	2.1 (6.8)
Totals	**611**	—	—
Mean	**153**	**10.1**	**2.0 (6.5)**
Median	—	**9.0**	**1.9 (6.2)**
Std. dev.	—	**3.6**	**0.5 (1.8)**

The trees in this study were planted at 4 to 6 cm (1.5 to 2.5 in) dbh. Tree lawn widths were approximately 1.8 to 2.4 m (6 to 8 ft) for larger-growing trees such as *Gleditsia, Quercus*, and *Zelkova* and 1.4 m (4.6 ft) wide for the smaller *Koelreuteria*. This finding is consistent with city policy that discourages planting larger trees beneath utility lines or in tree lawns less than 6 ft wide. Cincinnati has only recently made utility lines a major consideration when planting trees. For most of the trees in this study, tree lawn size was the major factor in determining which trees to plant in which locations (Hunt 2000). Tree roots have been observed to grow at 30 to 68 cm (12 to 27 in.) per year (Watson 1982). Nursery standard root ball sizes for trees 4 to 6 cm (1.5 to 2.5 in.) in diameter range from 50 to 70 cm (20 to 28 in.) (ANSI 1996). Tree lawn widths less than 3.5 m (11.5 ft) should be sufficiently small to bring roots in contact with the sidewalk within 4 to 5 years, the lower range in this study. One large planting of honeylocust was planted 16 years prior to the study along a street with unusually small tree lawns (2.5 to 3.5 ft). The planting was done at the request of local residents despite the warning by the city's urban forester that the trees would likely disrupt the sidewalk (Sandfort 2000). This planting was included in the analysis, reducing the average tree lawn width of honeylocust to slightly more than 5 ft.

Roots vs. Cracks

There appears to be a strong relationship between the presence of a crack and whether or not a tree root is likely to grow under the sidewalk. Table 2 shows that in the case of all genera in the study, where roots were found at the nearest joint, the sidewalk was approximately five times more likely to be cracked than intact, compared to only 1.6 times as likely when roots were not found. Columns 6 and 7 of Table 2 report that of the 351 joints observed with no roots, 39% were intact and 61% were cracked. Of the 260 joints where roots were observed, only 16.2% were intact while 83.9% were cracked. An examination of 81 blocks adjacent to crabapple trees (*Malus* spp.) that were planted a few months earlier revealed no roots underneath adjacent sidewalks and that 39.5% of the blocks had already cracked (data not shown).

The data in this study were compared to the data from the 2000 study (Sydnor et al. 2000), which were also collected in Cincinnati. Sydnor et al. showed that in sidewalk blocks selected at random that were less than 20 years old, the rate of cracked joints was 17%, and there was no statistical difference in the failure rate between blocks next to trees and blocks not next to trees.

The present study examines only sidewalk joints adjacent to trees. Sidewalks of varying ages were included from new sidewalks as well as from many that were much greater than 20 years old. However, all the trees were examined 20 years after planting or sooner. Approximately 72% of the joints observed in this study had cracked, while 28% remained intact. In addition, it was noted that about 13% of the joints nearest the tree were condemnable, which is comparable

Table 2. Presence and absence of roots under sidewalks with cracked and intact sidewalk blocks by genera and across genera.

Genus	Chi-square*	Sample size for genera	Root presence under sidewalk	Number observed	Intact blocks	Cracked blocks
Gleditsia	16.4	176	No	54	46.3%	53.7%
			Yes	122	17.2%	82.8%
Koelreuteria	4.3	93	No	64	39.1%	60.9%
			Yes	29	17.2%	82.8%
Quercus	7.7	181	No	139	41.7%	58.3%
			Yes	42	19.1%	81.0%
Zelkova	7.9	161	No	94	30.9%	69.2%
			Yes	67	11.9%	88.1%
All genera	37.4	611	No	351	39.0%	61.0%
			Yes	260	16.2%	83.9%

*Chi-square values, significance levels, and sample sizes are valid for each genus. All probability levels using the Fisher Exact Test two-sided P values are significant at the 0.01 levels or better except for *Koelreuteria*, which was significant at the 0.05 levels.

to the 11% citywide rate for all blocks noted in Sydnor et al. (2000).

This finding suggests that roots have a fairly strong association with cracked joints versus intact joints and that cracked joints are often present at planting. Chi-square tests indicate that these findings are statistically significant, with P-values less than 0.01 (Table 2). The roots of *Gleditsia* appeared to have the strongest affinity for cracks followed by *Zelkova*, *Koelreuteria,* and *Quercus.* The differences among the latter three were fairly small. When roots were observed for all genera, they were nearly five times as likely to be present beneath a cracked joint than under an intact joint. Where no roots were found, the likelihood of a cracked joint was less than 1.6 times (61% ÷ 39%) that of an intact one for all genera. Chi-square tests demonstrate statistical significance with P-values less than 0.01 (Table 2).

Soil Oxygen

Soil oxygen concentrations underneath cracks in the sidewalk were higher when compared with similar areas underneath intact sidewalks (Table 3). As expected, oxygen concentrations were generally lower at 30 cm depth than at 15 cm. Under cracked blocks, oxygen concentrations increased from the tree lawn through the sidewalk to the adjacent park area. The lowest oxygen concentrations were observed at 30 cm depth in the tree lawn adjacent to an intact sidewalk.

While diffusion of oxygen into soils varies by soil texture, compaction levels, and drainage (Kramer and Kozlowski. 1960), the presence of an intact sidewalk appears to further limit the diffusion of oxygen into the soil underneath the sidewalk. Conversely, a crack appears to permit increased diffusion of oxygen underneath the sidewalk. Increased oxygen levels would be expected to increase root growth relative to areas with lower oxygen concentrations. One might also expect some accumulation of duff and nutrients that have been carried into the crack by runoff, which also might be expected to improve root growth. Wagar and Franklin (1994) found that temperature and moisture levels are higher underneath sidewalk blocks than in adjacent sod panels. Higher temperature and moisture levels and reduced oxygen diffusion rates underneath an intact block might be expected to lead to depressed root growth. Roots' response to decreased oxygen is significantly impacted by temperature, with higher temperatures leading to increased effects from lowered oxygen (Glinski and Stepniewski 1985). Yet most agree that root growth of plants adapted to aerobic conditions begins to decline at oxygen levels below 20.9% (20.5 kPa) (Glinski and Stepniewski 1985). Studies have shown that root growth of corn decreased to 50% as oxygen levels were halved. (Saglio et al. 1984). A progressive decrease in mineral uptake in apple roots was noted at partial oxygen pressures below 14.7 kPa, and root initiation was suppressed below 11.8 kPa

Table 3. Oxygen concentrations as partial pressure (kPa) for sample tubes in cracked and intact sidewalk blocks and adjacent areas at two depths (two-year average). Depth, crack, site, and depth × site interaction effects are significant at the 0.01 level or greater.

		Sample site		
Depth (cm)	Crack	Tree lawn	Sidewalk	Park
15	Yes	17.4	17.4	18.1
15	No	16.7	15.6	18.3
30	Yes	16.6	17.3	17.8
30	No	13.8	16.1	16.3

(Boynton et al. 1938). "There is no generally accepted means for determining whether growth on any given soil is being restricted by poor aeration" (Craul 1992). However, Craul notes, "the replacement [rate] of the oxygen may be more important [to root growth] than the actual concentration in the soil. The apparent length of the diffusion pathway in the liquid phase surrounding the soil roots is more important as a barrier to diffusion than the oxygen concentration." As a root grows underneath an intact sidewalk, the diffusion pathway for oxygen will lengthen considerably relative to the diffusion pathway of a root that grows beneath a crack. The diffusion pathway beneath a cracked sidewalk would remain relatively constant. Craul further notes that poor aeration always restricts root penetration before foliage growth.

APPLICATIONS

The data in this study cannot conclusively answer whether the block cracks first or the root grows under the joint before it cracks. However, the data from the 2000 study suggest that trees have a relatively small impact on sidewalks less than 20 years old (Sydnor et al. 2000), and the data from this study recorded a notably low incidence of roots underneath intact joints and a lower rate of oxygen diffusion underneath intact sidewalk blocks relative to cracked blocks. Sidewalks can also present a physical barrier to root growth. A number of cases were observed where tree roots had grown up to the edge of a sidewalk block and subsequently had grown along the edge of the block to a failed joint, where they proceeded to grow under the cracked joint to the adjacent lawn panel. In any case, it appears that one is clearly more likely to find a root underneath a cracked sidewalk than an intact one.

The City of Cincinnati is exploring different ways of maintaining tree-lined sidewalks while decreasing the likelihood of failure during their service life. The construction of sidewalks that are less likely to crack during their expected service life might reduce the incidence of root growth underneath the sidewalk during the first 20 years after a tree is planted. If we make the assumption that tree roots are capable of displacing sidewalks, then we can infer that reducing root growth underneath the sidewalk may reduce or at least delay sidewalk displacement that is caused by trees.

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Résumé. L'Université de l'État de l'Ohio et le comité des parcs de la Ville de Cincinnati ont mené une étude des arbres de rues de la ville de Cincinnati au cours des étés 1999 et 2000. Quatre genres d'arbres appartenant à quatre familles différentes ont été étudiés. Environ 600 arbres plantés durant les 20 dernières années ont été observés. La condition du joint de trottoir le plus près ainsi que l'incidence sur la racine des *Quercus* (chênes), des *Koelreuteria* (savonniers), des *Zelkova* (zelkovas) et des *Gleditsia* (féviers) ont été étudiés. Tous les genres ont réagis de la même manière en ce sens que les racines étaient généralement observées sous une fissure du trottoir et non sous un trottoir intact. Durant les 20 premières années après la plantation, les racines d'arbres se retrouvaient plutôt sous une fissure de trottoir que sous un trottoir intact. Des 351 joints observés avec absence de racines, 39% étaient intacts et 61% étaient fissurés. Des 260 joints où des racines ont été observés, seulement 16,2% étaient intacts alors que 83,9% étaient fissurés. Des mesures d'oxygène ont été prises sous des trottoirs sélectionnés. Les concentrations d'oxygène ont été comparées entre le sol sous des zones fissurées et des sections intactes de trottoir. le sol sous des sections fissurées présentait une concentration plus élevée d'oxygène. La concentration plus élevée d'oxygène pourrait contribuer au développement des racines sous des trottoirs fissurés.

Zusammenfassung. Die Universität von Ohio und die Parkverwaltung von Cincinnati haben in den Sommern 1999 und 2000 eine Untersuchung an Strassenbäumen durchgeführt. Aus 4 unterschiedlichen Pflanzenfamilien wurden 4 Arten von Bäumen ausgewählt. Es wurden schätzungsweise 600 gepflanzte Bäume aus den letzten 20 Jahren untersucht. Es wurde der Zustand des nächstgelegenen Bürgersteigs und das Vorkommen von Wurzeln der Arten *Quercus*, *Koelreuteria*, *Zelkova* und *Gleditsia* beobachtet. Alle Arten reagierten ähnlich in der Hinsicht, dass Wurzeln eher unter einem gerissenen als unter einem intakten Bürgersteig vorkamen. Während der ersten 20 Jahre nach der Pflanzung wurden Wurzeln eher unter Rissen als unter intakten Bürgersteigen gefunden. Von 351 kontrollierten Verbindungen ohne Wurzeln waren 39 % intakt und 61 % gerissen. Von 260 Verbindungen mit Wurzeln waren nur 16,2 % intakt und 83,9 % gerissen. Unter ausgewählten Bürgersteigen wurde der Sauerstoffgehalt gemessen. Die Sauerstoffkonzentration wurde verglichen zwischen Böden unter gerissenen und intakten Bürgersteigen. Der Boden unter den gerissenen Bürgersteigen zeigte höhere Sauerstoffkonzentrationen. Diese hohen Konzentrationen könnten mit dem Wurzelwachstum unter den gerissenen Bürgersteigen in Zusammenhang stehen.

Resumen. La Universidad Estatal de Ohio y la oficina de parques de la ciudad de Cincinnati condujeron un estudio de los árboles en Cincinnati durante los veranos de 1999 y 2000. Se examinaron cuatro géneros de árboles de 4 familias diferentes de plantas. Fueron observados aproximadamente 600 árboles plantados en los últimos 20 años. Se estudió la condición de la acera y la incidencia de la raíz para *Quercus* (encino), *Koelreuteria* (goldenrain tree), *Zelkova* (zelkova) y *Gleditsia* (honeylocust). Todos los géneros respondieron similarmente en que las raíces se encontraron más fácilmente bajo las grietas que bajo aceras intactas. De 351sitios observados sin raíces, 39% estaban intactos y 61% con grietas. De los 260 sitios donde se observaron las raíces, solamente el 16.2% estaban intactos mientras que el 83.9 estaban agrietados. Se hicieron mediciones de oxígeno bajo las aceras seleccionadas. Las concentraciones de oxígeno fueron comparadas para suelos bajo grietas y aceras intactas. Las aceras agrietadas mostraron una más alta concentración de oxígeno. Estas más altas concentraciones de oxígeno pueden contribuir al crecimiento de las raíces bajo las aceras agrietadas.