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Incidence of Internal Decay in American Elms (*Ulmus americana*) Under Regular Fungicide Injection to Manage Dutch Elm Disease

By Nicholas J. Brazee and Robert E. Marra

Abstract. Fungicide injection is regularly performed to prevent and manage Dutch elm disease (DED) of American elm (*Ulmus americana*). In an effort to better understand the effects of long-term fungicide injection on tree health, sonic tomography (SoT) and electrical-resistance tomography (ERT) were used to nondestructively determine the incidence and severity of internal decay in the lower trunk of American elms in suburban and urban settings. Overall, 253 sonic and electrical-resistance tomograms were generated from 210 American elms. Sampled trees were partitioned into two fungicide injection groups: (1) regular injection; and (2) irregular injection or no known history of injection. Among all American elms, the incidence of internal decay in the lower trunk was 30% (63/210) with a mean percent decay, as determined by SoT, of 39%. Based on Chi-square analysis, there were no significant differences in the frequency of elms with decay by injection history ($P = 0.799$). Mean percent decay was significantly different by dbh class ($P = 0.005$) and while linear regression demonstrated a positive correlation between percent decay and dbh, most of the variability went unexplained ($R^2 = 0.182$). For elms with decay, there was a significantly higher frequency of trees in the lowest decay class (< 25% of the cross section) compared to the highest decay class (> 75% of the cross section). The results suggest that the wounding associated with regular fungicide injection does not increase the likelihood of internal decay and that American elms exhibit a low frequency and severity of internal decay.

Keywords. Butt Rot; Decay; Risk Assessment; Systemic Fungicides; Urban Forestry.

INTRODUCTION

To manage Dutch elm disease (DED) of American elm (*Ulmus americana*), caused by the fungal pathogen *Ophiostoma novo-ulmi*, arborists often perform fungicide injections both preventatively and therapeutically (Stipes 2000). This process requires the drilling of numerous injection sites into the root flares in order to achieve thorough distribution of fungicide in the tree's canopy for effective disease management (Gibbs and Dickinson 1975; Stennes and French 1987). After multiple cycles of injection, the number of wounds on the root flares can become significant (Figure 1). Injection of fungicides into the root flare may result in staining and necrosis of xylem tissue adjacent to injection sites, separation of the bark from the sapwood, and phytotoxicity in the canopy (Andrews et al. 1982; Anderson et al. 1985; Smith 1988). In a study aimed at determining the phytotoxic effects of fungicide injection into American elm, Perry et al. (1991) found that large columns of discolored sapwood, bleeding cankers, and bark cracking were all the result of chemical injury within the trees. Additionally, the study noted that up to 20% of the tissue responsible for sugar and water transport within the trunk can be disrupted and killed as a result of a single treatment of injections on the lower bole.

Another aspect of fungicide injection that has received only limited attention is the potential for injected trees to develop internal decay from wood-rotting fungal pathogens. One study involving destructive sampling indicated that fungicide injection resulted in serious internal injuries to treated American elms (Shigo and Campana 1977). Eighty mature American elms that were regularly injected to manage DED were dissected for examination. The study found varying levels of internal decay in numerous trees and discolored wood associated with every injection wound analyzed. In a destructive study of eight trees, Andrews et al. (1982) noted that injections of thiabendazole hypophosphite (Arbotect® 20-S, Syngenta

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Figure 1. Injection-site wounds on the root flares of an American elm (*Ulmus americana*) sampled in this study.

Crop Protection, Greensboro, North Carolina) appeared to have altered the tree's natural defense response to wound closure. Specifically, tylosis formation, common in control treatments, was found only infrequently in xylem vessels above injection sites. Additionally, the fungicide inhibited the growth of hyphomycete fungi that act as initial colonizers of wounded wood but had no effect on the growth of basidiomycetes, the Division (Basidiomycota) to which most wood-decaying fungi belong. Therefore, fungicide injection sites may be more readily accessible to wood-rotting fungi compared to natural wounds.

In recent decades, tree injection techniques have vastly improved through the use of better spacing, smaller diameter injection sites, reduced wounding of surrounding tissues using higher-quality drill bits, and enhanced knowledge on timing and rate of chemical applications (Sanchez-Zamora and Fernandez-Escobar 2004; Dal Maso et al. 2014; VanWoerkom et al. 2014). However, there is little doubt that despite these advances, the risks of long-term injury still warrant concern (Smith and Lewis 2005).

The emerald ash borer (*Agrilus planipennis*) outbreak in eastern North America has renewed interest in the potential long-term consequences of trunk injection. Doccola et al. (2011) dissected 16 green ash (*Fraxinus pennsylvanica*) that were injected with seven different insecticides using multiple delivery methods. A total of 63 trunk injection sites were analyzed, and in each case the trees were able to successfully compartmentalize the wound with no evidence of internal decay. However, the studied trees were young, ranging in age from 17 to 35 years old, and were in a state of vigorous growth. Studies are lacking on the wound closure rates of older and larger trees, like surviving American elms, which may not be as responsive in their wound closure rates due to the high physiological cost of maintaining large volumes of woody tissues. In a study of six tree species, it was shown that American elm and red maple (*Acer rubrum*) exhibited faster wound closure response per unit of radial growth compared to white ash (*F. americana*), pin oak (*Quercus palustris*), tulip poplar (*Liriodendron tulipifera*), and honey locust (*Gleditsia*

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triacanthos) (Neely 1973). But later, Neely (1988) maintained that wound closure rates were directly related to tree vigor, and that slow-growing trees are able to close wounds more quickly than fast-growing trees like American elm.

Among the several methods available for detection of internal decay, tomography is one of the least invasive (Johnstone et al. 2010), an important consideration for long-term management. Sonic tomography (SoT) measures heterogeneity in sonic velocity, which is directly proportional to wood density (Arciniegas et al. 2014). Electrical-resistance tomography (ERT) measures heterogeneity in electrical fields, indicating the presence or absence of moisture and electrolytes in the wood (Bieker and Rust 2010; Benson et al. 2019). When used together, SoT and ERT provide an accurate estimate of the incidence and severity of internal decay in living trees (Brazee et al. 2011; Marra et al. 2018). Due to the accuracy with which SoT estimates the geometric configuration of internal decay, it can also be used to estimate the loss of load-bearing capacity in trees with internal decay (Burcham et al. 2019). Because of its accuracy and minimal invasiveness, tomography is well suited for decay assessments while limiting any lasting injury to culturally and historically significant trees such as American elms.

The primary goal of this study was to better understand the effects of long-term fungicide injection on the health of American elm using SoT and ERT to nondestructively determine the incidence and severity of internal decay. Fungicide injection by itself does not result in decay. However, the process associated with fungicide injection generates numerous wounds on the root flares, which could function as points of entry by wood-decaying fungi to colonize these trees. We hypothesized that trees undergoing regular fungicide injection treatments would have a higher frequency of internal decay compared to trees with irregular or no known injections. Additional objectives of the study were to: (1) provide baseline data on the incidence and severity of internal decay for American elm, data that are lacking for urban and suburban trees; and (2) support existing long-term management efforts for American elms threatened by DED in urban and suburban settings.

MATERIALS AND METHODS

Tree Selection

American elms sampled in this study were located with the assistance of tree wardens, arborists, ecologists, and homeowners. Based on the injection history information obtained from these individuals, elms were partitioned into two injection history groups: (1) regular injection; and (2) irregular injection or no known history of injection. Regular injection refers to trees receiving preventative root flare injections with thiabendazole hypophosphite or propiconazole (Alamo®, Syngenta Crop Protection, Greensboro, North Carolina) at one to three year intervals. Some of these trees also received therapeutic injections when DED was identified. Trees with irregular injection cycles were typically treated one to three times over a 30-year period, while the remaining trees had no known history of injection. The exact method of injection was not recorded. Trees were sampled in six states (Massachusetts, Connecticut, Rhode Island, New Hampshire, New York, and Minnesota), Washington D.C., and Quebec, Canada over a three-year period (2016 through 2018) from May through October. The location of sampled elms, the number of trees at each site by injection-history group, and the number of trees with decay can be found in Table S1. Prior to tomographic scanning, symptoms and signs of internal decay of the lower trunk were visually assessed and recorded.

Sonic and Electrical-Resistance Tomography

To capture sonic and electrical-resistance tomograms, the PiCUS® Sonic Tomograph 3 and TreeTronic 3 (Argus Electronic GMBH, Rostock, Germany) were used in this study. For specific details on the placement and collection of tomograms, refer to Marra et al. (2018). Briefly, tomographic cross sections were obtained on the lower trunk at a horizontal plane as close to the soil line as possible in order to account for the dramatic root flaring and subsequent cross sectional geometry exhibited by many American elms. At this location, the diameter at sample height (DSH) was recorded. For certain trees, additional sampling planes were established above the lowest plane for further scanning to corroborate the presence of decay. Galvanized roofing nails, 5.1 to 6.4 cm in length, were then inserted to a depth just beneath the outer

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bark so that the nail point contacted the sapwood, spaced 15 to 25 cm apart. These constituted measuring points (MPs) from which sonic and electrical-resistance data were collected. The MPs were sequentially numbered with MP-1 placed at magnetic north. For all cross sections, every attempt was made to use as many MPs as possible, to a maximum of 24, proportionally to the circumference of the cross section. Diameter at breast height (dbh) was also collected for each tree.

Sonic Tomography (SoT)

Sensors are magnetically attached at each SoT MP and connected via cable to a detection module that is wirelessly connected to the PiCUS software on a laptop. At each MP, sound waves are initiated with sequential taps from the “sonic hammer” connected wirelessly to the detection module. The software then uses these data along with the inter-MP distances to calculate sonic velocities. The software then produces an image with a colorimetric scale depicting wood densities at that cross section. The colorimetric scale designates intact, non-decayed wood as brown (higher relative velocities) while decaying wood is designated by green, magenta, and blue (lower relative velocities, in decreasing order).

Electrical-Resistance Tomography (ERT)

Positive and negative leads, attached to each pair of SoT-ERT MP nails, connect via cable to a detection module connected wirelessly to the PiCUS software. The detection module automates a process whereby, starting with one pair of leads and proceeding sequentially around the tree through each subsequent pair of leads, an electrical pulse is generated and detected by the other electrode pairs. Deviations from homogeneity in the wood result in a map of relative electrical resistivity, correlating principally with water content but also changes in ion concentration and/or cell structure. The ERT map uses red to portray areas of highest electrical resistivity (low conductivity), progressing through orange, yellow, green, and blue with decreasing resistivity (high conductivity).

Data from SoT and ERT must be interpreted jointly to accurately predict the internal condition at each cross section of a tree, based on the following criteria (slightly modified from Marra et al. 2018):

A) Maximum wood density and the absence of moisture represent sound (nondecayed) wood, which appears brown in the SoT and yellow, orange, and red in the ERT;

B) Maximum wood density and the presence of moisture represents incipient decay or bacterial wetwood, in that reductions in wood density are not detectable, which appears brown in the SoT and blue in the ERT;

C) Reduced wood density and the presence of moisture represent active decay, which appears green, magenta, and blue in the SoT and blue in the ERT;

D) Reduced wood density and the absence of moisture represent a cavity, which appears non-brown in the SoT and non-blue in the ERT.

This hypothesis is based on destructive samples collected from 48 hardwood trees (*Acer saccharum*, *A. rubrum*, *Betula alleghaniensis*, *B. lenta*, and *Fagus grandifolia*) during two previous studies (Brazee et al. 2011; Marra et al. 2018), as well as guidelines provided by the manufacturer.

Statistical Analyses

Chi-square goodness of fit was used to determine if there were significant differences in the frequency of decay incidence by injection history (injected vs. non-injected) using expected values (Zar 1999). Chi-square was also used to test for significant differences in the frequency of elms within each decay class. Decay classes (I = < 25%; II = 25 to 50%; III = 50 to 75%; and IV = > 75%) were established based on percent decay values generated from the SoT results.

Analysis of variance (ANOVA) was used to test for significant differences among elms by decay incidence and injection history using the following variables: (1) sampling height at MP-1 (distance from soil); (2) DSH; and (3) dbh.

For elms with internal decay, linear regression was used to determine if there were significant differences in mean percent decay by DSH and dbh. Further, ANOVA was used to test for significant differences in percent decay by injection history, DSH class (I = < 100 cm; II = 100 to 125 cm; III = 125 to 150 cm; and IV = > 150 cm) and dbh class (I = < 75 cm; II = 75 to 100 cm; III = 100 to 125 cm; and IV = > 125 cm), excluding both DSH and dbh class I due to low sample size ($n < 5$). Post hoc analyses were performed on DSH and dbh class using Tukey’s HSD test. Percent decay values were arcsine-transformed prior to analysis (Zar 1999) while untransformed values are presented in all graphs. Differences were determined to be significant at $P \leq 0.05$ for all tests.

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RESULTS

Of the 210 elms sampled in this study, 91 (43%) had a regular injection history while 119 (57%) had an irregular history or no record of injection (hereafter referred to as "non-injected"). Of the 91 injected elms, thiabendazole hypophosphite was more commonly used (80 elms; 88%) in comparison to propiconazole (11 elms; 12%) for preventative treatments. For all elms, the mean DSH was 131 cm (range of 69 to 246 cm), collected at a mean height of 37 cm from the soil line, while the mean dbh was 105 cm (range of 56 to 196 cm). Overall, 63 (30%) sampled elms were found to be harboring internal decay with similar proportions by injection history: injected elms (28/91; 31%) and non-injected elms (35/119; 29%). Chi-square analysis determined there were no significant differences in the frequency of elms with decay by injection history ($\chi^2 = 0.7$, $P = 0.799$) (Table 1).

There were no significant differences in mean sample height by decay incidence, but heights did differ significantly by injection history (Table 2). For both DSH and dbh, there were significant differences in mean values by decay incidence and injection history (Table 2).

There were no significant differences in mean percent decay at the sampled cross section by injection history ($F = 1.7$, $P = 0.205$) (Table 3). Percent decay was significantly different by DSH ($F = 20.5$, $P < 0.001$) and dbh ($F = 14.8$, $P < 0.001$) (Table 3). Linear regression showed that increasing percent decay was significantly correlated to increases in both DSH ($t = 4.531$, $P < 0.001$, $R^2 = 0.252$; Figure 2) and dbh ($t = 3.841$, $P < 0.001$, $R^2 = 0.182$; Figure 3). However, while the models showed a positive correlation, the majority of the variation was unexplained. Yet significant differences in percent decay were present by DSH class ($F = 6.1$, $P = 0.004$) and dbh class ($F = 5.9$, $P = 0.005$) (Table 3). Tukey's HSD test showed that both DSH and dbh class IV had significantly higher percent decay values compared to class II (Table 3). Lastly, Chi-square analysis showed there were significant differences in the frequency of decaying elms by decay class ($\chi^2 = 8.3$, $P = 0.04$; Figure 4), with more elms in the lowest decay class (< 25%) and fewer elms in the highest decay class (> 75%) compared to expected values. Among all American elms, only 3.3% (7/210) exhibited the most severe level of decay, defined as > 75% of the sampled cross section.

Table 1. Number of American elms with internal decay by injection history.

	Injection history		
Decay incidence	**Injected**	**Non-injected**	***P*-value[1]**
Decay	28	35	0.799
No decay	63	84	0.868
n	**91**	**119**	

[1]Probability that there are no significant differences in injection history by decay frequency based on Chi-square analysis (using expected values) at $P = 0.05$.

Table 2. Mean sample height from soil line, diameter at sample height (DSH), and breast height (dbh) in centimeters by decay incidence and injection history.

Decay incidence	*n*	Sample height[2]	DSH	dbh
No decay	147	36 (16)	120 (26)	98 (20)
Decay	63	39 (19)	157 (36)	120 (27)
P-value[1]		0.265	< 0.001	< 0.001
Injection history				
Injected	91	42 (19)	137 (37)	109 (26)
Non-injected	119	34 (15)	127 (30)	102 (23)
P-value		0.001	0.025	0.030

[1]Signficant differences determined at $P = 0.05$. [2]Standard deviations in parenthesis.

Table 3. Mean percent decay in American elms by injection history, diameter class at sample height (DSH), and breast height (dbh).

Decaying elms	*n*	Mean % decay[2]
Injection history		
Injected	28	43 (27)
Non-injected	35	35 (24)
P-value[1]		0.205
DSH class (cm)		
II (100–125)	8	23 (11)[a]
III (125–150)	14	27 (19)[ab]
IV (≥ 150)	37	48 (27)[b]
P-value		0.004
Dbh class (cm)		
II (75–100)	9	19 (10)[a]
III (100–125)	27	35 (26)[ab]
IV (≥ 125)	25	50 (25)[b]
P-value		0.005

[1]Significant differences determined at $P = 0.05$. [2]Standard deviations in parenthesis and letters denote significant differences based on Tukey's HSD.

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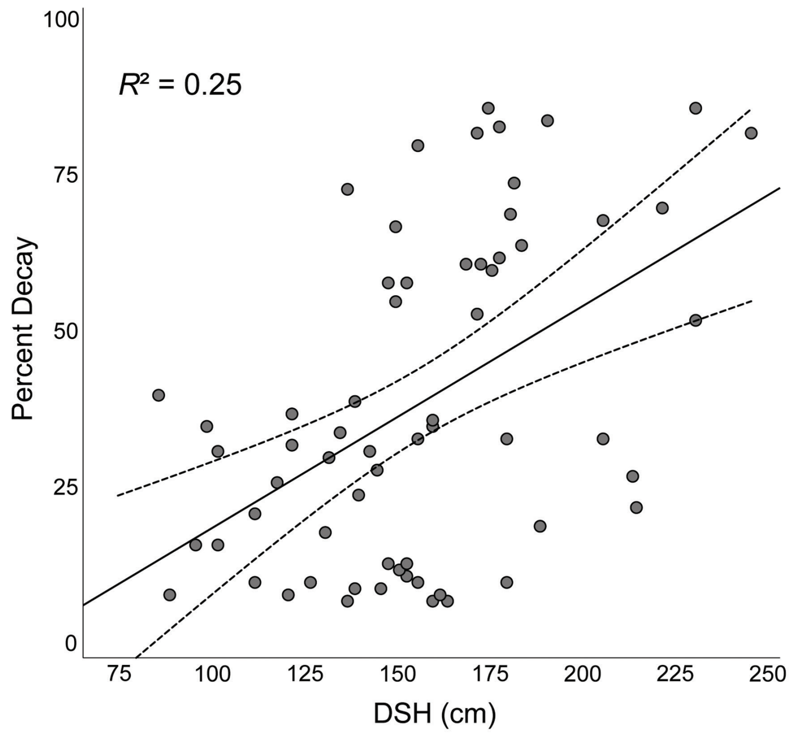

Figure 2. Linear regression of percent decay on diameter at sample height (DSH) for American elms. Dashed lines represent 95% confidence intervals.

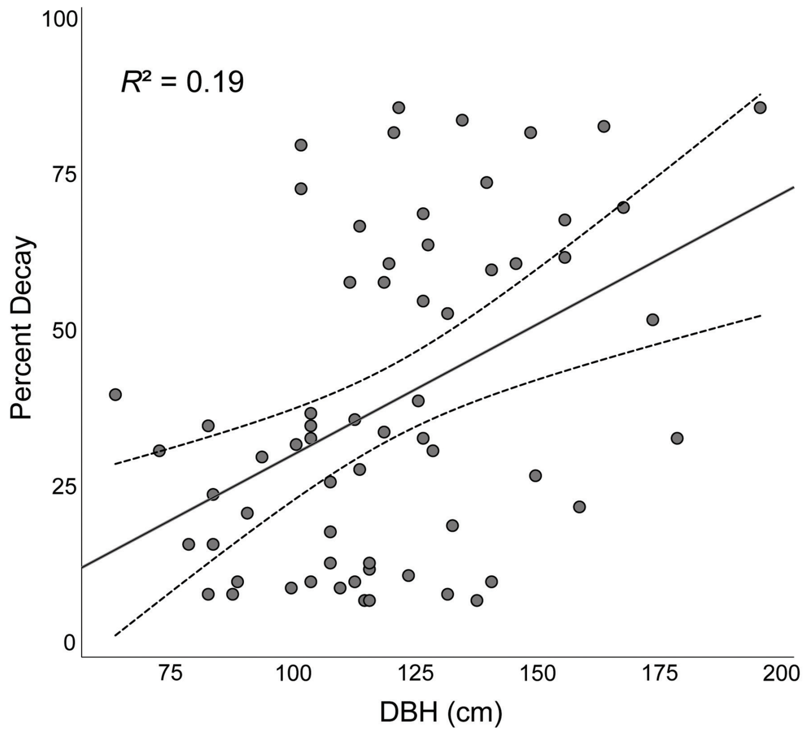

Figure 3. Linear regression of percent decay on diameter at breast height (dbh) for American elms. Dashed lines represent 95% confidence intervals.

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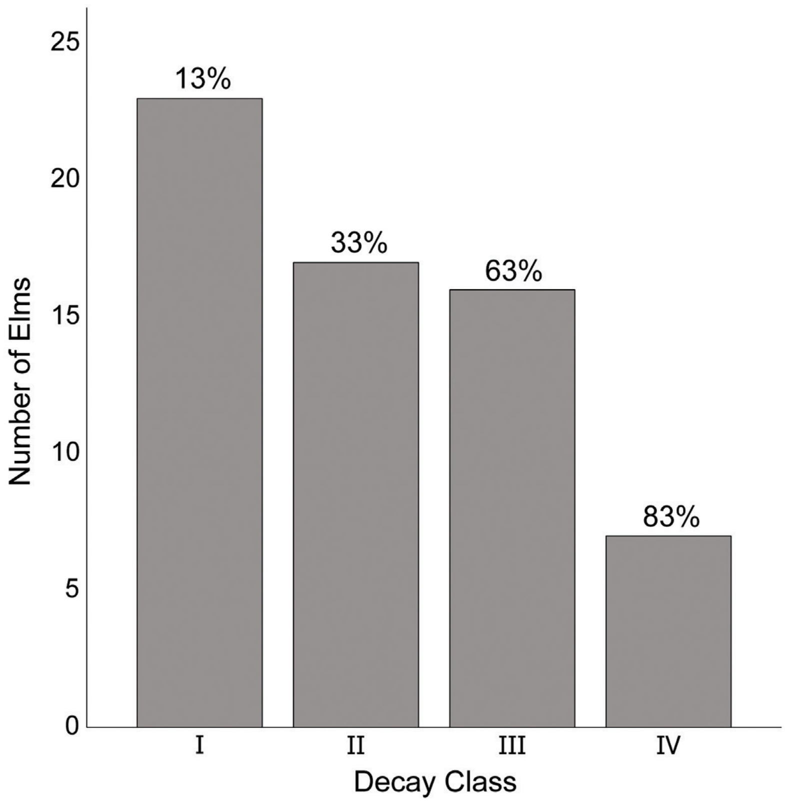

Figure 4. The number of American elms in each decay class (I = < 25%; II = 25 to 50%; III = 50 to 75%; and IV = > 75%) with mean percent decay values for each class above the bar.

DISCUSSION

We hypothesized that American elms undergoing regular fungicide injection would have a higher frequency of internal decay compared to non-injected elms. This hypothesis proved to be false, as the ratio of elms with decay that were regularly injected (28/91; 31%) was nearly identical to elms with decay that were non-injected (35/119; 29%). Not only was the incidence of decay similar among injected and non-injected elms, but mean percent decay was not significantly different by injection history. Injected elms did have larger mean DSH and dbh values compared to non-injected elms. The reasoning for the larger size of injected elms may be explained by chance or that injected elms are able to allocate more resources to growth and less to resisting DED. Another explanation may be that larger elms are more likely to be identified as valuable, thus warranting injection.

American elms with decay had significantly larger mean DSH and dbh values compared to elms without decay. Furthermore, the analysis of decay severity by DSH and dbh classes also illustrates that the largest elms had the highest mean percent decay. Additionally, the regression models illustrated a positive correlation between decay severity and diameter, but the majority of the variation in the models could not be explained by diameter alone. When the frequency of elms with decay were examined by decay class, there were more elms in decay class I and fewer elms in decay class IV compared to expected values. Therefore, when elms were found to harbor decay, they were more likely to have decay in < 25% of the cross section. The results provide further proof that decay incidence and high decay severity are more likely in larger diameter trees, but that diameter alone is not a reliable predictor of incidence and severity.

An additional objective of the study was to provide baseline data on the incidence and severity of internal decay for urban and suburban trees. Very few studies have assessed the incidence of decay for individual tree species with a robust sample size outside of forest settings. Overall, the incidence of decay in American elms was only 30%, and decay severity was also relatively low, with a mean of 39%. Only

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two other studies are comparable, however both utilized resistance drilling to detect decay. Luley et al. (2009) examined three species of maple across four cities in New York and found the frequency of decay at 53% for silver maple (*Acer saccharinum*), 62% for Norway maple (*A. platanoides*), and 63% for sugar maple (*A. saccharum*). Meanwhile, Koeser et al. (2016) determined decay incidence at 67% for laurel oak (*Quercus hemisphaerica*) and 29% for live oak (*Q. virginiana*) in Tampa, Florida. Aside from live oak, the incidence of decay for the other four tree species was 1.8 to 2.1 times higher compared to American elm. A noteworthy difference between the two previous studies and this study is the size of the sampled trees, as the mean dbh of American elms sampled here was 105 cm. While Luley et al. (2009) do not provide mean dbh values, 69% of silver, 83% of Norway, and 81% of sugar maples had a dbh < 76.2 cm. For Koeser et al. (2016), mean dbh values for laurel oak (59 cm) and live oak (61 cm) were also substantially lower than the elms sampled here.

The low incidence of decay is not altogether surprising, given that resistance to decay is a common characteristic of long-lived tree species, such as American elm (Bey 1990). Further, American elms do not experience any major root and butt rot diseases in natural and managed settings (Wargo and Houston 1981). Our findings support the commonly held view among arborists that American elm is a decay-resistant tree species, a desirable quality for urban and suburban environments. The decay resistance exhibited by American elms is most likely explained by the presence of wetwood bacteria in the lower trunk. Of the four possible internal conditions determined by SoT and ERT, as outlined in the methods, nearly 50% of American elms exhibited maximum wood density and the presence of moisture in the heartwood (Category B). While relatively higher moisture in the heartwood can indicate incipient decay or the presence of electrolytes, wetwood bacteria are known to be very common in American elm (Sinclair and Lyon 2005). Moreover, American elm sapwood colonized by wetwood bacteria has been shown to possess higher decay resistance compared to uncolonized wood (Coleman et al. 1985). This is due to the anaerobic to hypoxic conditions created by wetwood bacteria in colonized wood tissues, preventing establishment by wood-decaying fungi (Sinclair and Lyon 2005).

A final goal of this study was to support ongoing management efforts that seek to preserve American elms threatened by DED in urban and suburban settings. As surviving American elms continue to age in the landscape, their economic value and cultural significance will also continue to increase. Managing arborists should be particularly concerned about internal decay and the resulting risk of stem failure in large-diameter trees. Based on the results here, the potential for injection-site wound colonization by wood-decaying fungi does not appear to outweigh the benefits of fungicide injection to prevent and manage DED.

CONCLUSIONS

The incidence of internal decay in American elms, determined nondestructively using SoT and ERT, was 63/210 (30%) with a mean percent decay of 39%. The proportion of American elms with decay under regular injection (28/91; 31%) was nearly identical to non-injected elms (35/119; 29%). Mean percent decay was positively correlated to DSH and dbh, but diameter alone is not a reliable predictor of decay incidence and severity. Nearly half of all sampled American elms (104/210) exhibited maximum wood density and the presence of moisture in the heartwood, likely due to colonization by wetwood bacteria. The results show that American elms undergoing regular fungicide injection do not experience a higher frequency of internal decay compared to non-injected elms.

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Nicholas J. Brazee (corresponding author)
Center for Agriculture, Food and the Environment
University of Massachusetts
Amherst, MA, USA
nbrazee@umass.edu

Robert E. Marra
Department of Plant Pathology and Ecology
Connecticut Agricultural Experiment Station
New Haven, CT, USA
Robert.Marra@ct.gov

Conflicts of Interest
The authors reported no conflicts of interest.

Résumé. L'injection de fongicides est régulièrement effectuée afin de prévenir et traiter la maladie hollandaise (MHO) de l'orme d'Amérique (*Ulmus americana*). Dans le cadre d'une démarche destinée à mieux comprendre les effets à long terme de l'injection de fongicides sur la santé des arbres, la tomographie sonique (TS) et la tomographie par résistance électrique (TRE) furent utilisées pour déterminer de manière non-destructive l'incidence et la gravité de la carie interne dans la partie inférieure du tronc d'ormes d'Amérique situés en zones urbaines et en banlieues. Au total, 253 tomogrammes soniques et par résistance électrique

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furent produits provenant de 210 ormes d'Amérique. Les arbres échantillonnés furent répartis en deux groupes pour l'injection de fongicides: (1) des injections régulières, et (2) des injections irrégulières ou un historique inconnu quant aux injections reçues. Parmi tous les ormes d'Amérique, l'incidence de la carie interne à la base des troncs fut de 30% (63/210) avec un pourcentage moyen de carie de 39%, tel qu'établi par TS. Selon une analyse par chi-carré, il n'y avait aucune différence significative dans l'incidence de la carie chez les ormes traités avec des injections régulières (P = 0.799). Le pourcentage moyen de carie était considérablement différent selon la classe de diamètre (P = 0.005), et bien que la régression linéaire montra une corrélation positive entre le pourcentage de carie et la classe de diamètre, la majeure partie de la variation demeura inexpliquée (R^2 = 0.182). Chez les ormes exhibant de la carie, il y avait une incidence significativement plus élevée dans la plus basse catégorie de carie (< 25% de la surface terrière) en comparaison avec le plus haute catégorie de carie (> 75% de la surface terrière). Les résultats semblent indiquer que les blessures associées à l'injection régulière de fongicides n'augmentent pas la probabilité de carie interne et que les ormes d'Amérique montrent une faible incidence et une faible sévérité pour la carie interne.

Zusammenfassung. Die Injektion von Fungiziden wird an Amerikanischen Ulmen (*Ulmus americana*) regelmäßig durchgeführt, um die Holländische Ulmenkrankheit (DED) zu behandeln und vorzubeugen. In einem Versuch zum besseren Verständnis der Auswirkungen von Langzeit-Fungizid-Injektionen auf die Baumgesundheit, wurden Sonische Tomographie (SoT) und Elektrische Widerstandstomographie (ERT) verwendet, um verletzungsfrei den Nachweis und die Schwere des internen Fäulnis in dem unteren Stammbereich von Amerikanischen Ulmen an suburbanen und urbanen Standorten zu bestimmen. Insgesamt wurden aus 210 Amerikanischen Ulmen 253 sonische und elektrische Widerstandstomogramme erzeugt. Die untersuchten Bäume wurden in zwei Fungizid-Injektionsgruppen unterteilt: (1) reguläre Injektion, und (2) irreguläre Injektion oder mit nicht bekannter Historie der Injektion. Bei allen Amerikanischen Ulmen war der Nachweis von interner Fäulnis im unteren Stammbereich bei 30% (63/210) mit einem mittleren Prozentsatz an Fäulnis, bestimmt durch SoT, von 39%. Basierend auf einer Chi-Quadrat Analyse gab es keine signifikanten Differenzen in der Frequenz von Ulmen mit Fäulnis durch die Injektionshistorie (P = 0.799). Der mittlere Prozentsatz an Fäulnis war signifikant unterschiedlich bei den Durchmesserklassen (P = 0.005) und während die lineare Regression eine positive Korrelation zwischen Fäulnisanteil und Brusthöhendurchmesser demonstrierte, blieb die meiste Variabilität unerklärlich (R^2 = 0.182). Für Ulmen mit Fäulnis gab es eine signifikant höhere Frequenz von Bäumen in der untersten Fäulnisklasse (< 25% von dem Querschnitt) verglichen mit der höchsten Fäulnisklasse (> 75% von dem Querschnitt). Die Ergebnisse zeigen, dass die Verwundung in Beziehung mit regulärer Fungizid-Injektion nicht die Wahrscheinlichkeit einer internen Fäulnis vergrößert und dass Amerikanische Ulmen eine niedrige Frequenz und Schwere von interner Fäulnis ausstellen.

Resumen. La inyección fungicida se realiza regularmente para prevenir y tratar la enfermedad del olmo holandés (DED) en el olmo americano (*Ulmus americana*). En un esfuerzo por comprender mejor los efectos de la inyección de fungicidas a largo plazo en la salud de los árboles, se utilizaron la tomografía sónica (SoT) y la tomografía de resistencia eléctrica (ERT) para determinar de forma no destructiva la incidencia y la gravedad de la descomposición interna en el tronco inferior de los olmos americanos en entornos suburbanos y urbanos. En total, se generaron 253 tomogramas de resistencia sónica y eléctrica a partir de 210 olmos estadounidenses. Los árboles muestreados se dividieron en dos grupos de inyección de fungicidas: (1) inyección regular, y (2) inyección irregular o sin antecedentes conocidos de inyección. Entre todos los olmos estadounidenses, la incidencia de pudrición interna en el tronco inferior fue del 30% (63/210) con un porcentaje medio de descomposición, según lo determinado por SoT, del 39%. Según el análisis de Chi-cuadrado, no hubo diferencias significativas en la frecuencia de olmos con decaimiento por historial de inyección (P = 0.799). El porcentaje medio de desintegración fue significativamente diferente según la clase dbh (P = 0.005), y aunque la regresión lineal demostró una correlación positiva entre el porcentaje de descomposición y dbh, la mayor parte de la variabilidad quedó sin explicación (R^2 = 0.182). Para los olmos con descomposición, hubo una frecuencia significativamente mayor de árboles en la clase de descomposición más baja (< 25% de la sección transversal) en comparación con la clase de descomposición más alta (> 75% de la sección transversal). Los resultados sugieren que la herida asociada con la inyección regular de fungicidas no aumenta la probabilidad de pudrición interna y que los olmos estadounidenses exhiben una baja frecuencia y severidad de descomposición interna.

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CEU quiz by Eric North, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

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Table S1. Site locations and the number of American elms sampled by injection history and with decay present.

Site name	Town/city	State/ province	Total elms	Injection history		Decay present
				Regular	Irregular/ none	
University of Massachusetts	Amherst	MA	10	0	10	1
Amherst	Amherst	MA	8	3	5	1
Athol	Athol	MA	3	2	1	1
Belmont	Belmont	MA	1	0	1	0
Harvard Business School	Boston	MA	6	6	0	0
Boston Common/Public Garden	Boston	MA	4	4	0	1
Deerfield Academy	Deerfield	MA	3	3	0	2
Easthampton	Easthampton	MA	1	0	1	1
Hadley	Hadley	MA	1	0	1	0
Hatfield	Hatfield	MA	1	0	1	1
Lanesborough	Lanesborough	MA	1	1	0	1
Lee	Lee	MA	1	0	1	1
Medford	Medford	MA	4	0	4	3
Newton Cemetery	Newton	MA	6	6	0	1
Hillside Cemetery	North Adams	MA	1	0	1	0
Smith College	Northampton	MA	13	13	0	5
Northampton	Northampton	MA	13	6	7	4
Pittsfield	Pittsfield	MA	7	5	2	1
Sandwich	Sandwich	MA	4	4	0	0
Sheffield	Sheffield	MA	1	1	0	0
Southampton	Southampton	MA	1	0	1	1
Springfield	Springfield	MA	15	0	15	3
Stockbridge	Stockbridge	MA	1	0	1	1
Sunderland	Sunderland	MA	3	3	0	1
Westfield	Westfield	MA	2	0	2	0
Williams College	Williamstown	MA	7	0	7	2
Bethlehem	Bethlehem	CT	1	0	1	0
Hotchkiss School	Interlaken	CT	9	9	0	4
Litchfield	Litchfield	CT	1	0	1	1
Sharon	Sharon	CT	7	7	0	1
Southbury	Southbury	CT	1	0	1	0
Woodbury	Woodbury	CT	1	0	1	0
Little Compton	Little Compton	RI	2	2	0	1
Brown University	Providence	RI	16	0	16	1
Dartmouth College	Hanover	NH	6	6	0	4
Governors Island	Governors Island	NY	10	10	0	3
National Mall	Washington D.C.	n/a	20	0	20	8
Minneapolis	Minneapolis	MN	11	0	11	5
Quebec City	Quebec City	QC	7	0	7	3
Total			**210**	**91**	**119**	**63**

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