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Status of Black Walnut (*Juglans nigra* L.) in the Eastern United States in Light of the Discovery of Thousand Cankers Disease

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ABSTRACT *Juglans nigra* (black walnut) is widely distributed throughout the US eastern forest, with high concentrations occurring in Missouri and the Ohio and Tennessee River basins. It is an extremely desirable tree for wildlife forage and timber production on forest land, and for shade, aesthetics, and wildlife forage in urban areas. Current (2009–2010) estimates from US Forest Service Forest Inventory and Analysis (FIA) data indicated that there were 306 million live black walnut trees in the eastern United States with a live volume totaling 112.76 million cubic meters (m^3). This resource is currently threatened by the newly discovered presence of thousand cankers disease (TCD) in Pennsylvania, Tennessee, and Virginia. Thousand cankers disease may have been present in these areas for at least 10 years prior to discovery; however, no evidence of TCD in the forest at large was apparent in the crown condition and mortality data collected by FIA between 2000 and 2010. During this time period black walnut crown conditions were within the range of what is typically considered normal and healthy for hardwood trees and dead black walnut accounted for $<$ 5% of the total number of black walnut trees in 82% of the counties where black walnut occurred. Lack of evidence of TCD in our study could be due to its actual absence or to an inability of the inventory and monitoring system to detect its presence.

Key words: Black walnut, forest health, *Geosmithia morbida*, *Juglans nigra*, *Pityophthorus juglandis* Blackman, thousand cankers disease, walnut twig beetle.

INTRODUCTION Walnut twig beetle (*Pityophthorus juglandis* Blackman) (WTB) and the associated fungus *Geosmithia morbida* (Kolařík et al. 2011) that causes thousand cankers disease (TCD) was found in Knox County, Tennessee, in July 2010 (TN.gov Newsroom 2010). This was the first discovery of TCD east of Colorado and its arrival to the eastern United States poses a serious threat to the survival of black walnut (*Juglans nigra* L.). In the western United States, the WTB is found in Colorado, Idaho, Oregon, Utah, and Washington, areas where black walnuts have been widely planted (Seybold et al. 2010). The occurrence of TCD throughout the West coincides with areas along major commerce routes, which suggests that the movement of the WTB and TCD may be human-assisted (Haun et al. 2010). Since the initial discovery in Knox County, TCD has been identified in Anderson, Blount, Loudon, Sevier, and Union Counties in Tennessee; Chesterfield, Fairfax, Goochland, Hanover, Henrico, Powhatan, and Prince William Counties and the cities of Richmond and Colonial Heights in Virginia; and Bucks County, Pennsylvania (Figure 1) (Pennsylvania Department of Agriculture 2011, TN.gov Newsroom 2011, Virginia.gov 2011, Virginia.gov 2012). Transport of logs and firewood is the primary suspected avenue for the disease's spread (Hansen et al. 2011); however, its exact pathway into and about the eastern United States is unknown.

The potential impact of TCD on black walnut in its native range is enormous, both ecologically and economically. Black walnut is widely distributed throughout the US eastern forest, with high concentrations occurring in Missouri and

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Figure 1. Eastern states of the United States included in the study area. Counties and cities quarantined due to the discovery of the walnut twig beetle and thousand cankers disease are shaded gray. States inventoried by the Southern Research Station Forest Inventory and Analysis Program are dotted.

the Ohio and Tennessee River basins, and is an extremely desirable tree for wildlife forage and timber production on forest land and for shade, aesthetics, and wildlife forage in urban areas. The wood of black walnut is among the most valuable of all domestic hardwoods, finding use as veneer and lumber in furniture, cabinetry, paneling, gun stocks, and other specialty products. The nuts, both the outer shells and inner kernels, serve a wide variety of purposes as well (Williams 1990). The value of black walnut growing stock on timberland in the eastern United States is estimated at over one-half trillion dollars (Newton et al. 2009). In Tennessee alone, the commercial value of black walnut is estimated at $1.37 billion in urban areas and $1.47 billion in forest lands (Haun et al. 2010).

Symptoms of TCD include yellowing leaves and thinning foliage in the upper part of the crown. As the disease progresses, crown dieback continues with progressively larger branches dying until the tree completely succumbs to mortality, often within two to four years of the earliest visible symptoms (Seybold et al. 2010, Hansen et al. 2011, Kolařík et al. 2011). Thousand cankers disease may have been present in Tennessee for at least 10 years prior to its discovery (Haun et al. 2010). If this is the case and TCD has spread into the forest at large, then evidence of its presence might exist in the forest inventory data collected by the US Forest Service Forest Inventory and Analysis (FIA) Program. Therefore, our first objective was to explore FIA data collected between 2000 and 2010 for symptoms of TCD (i.e., poor crown conditions and high mortality, either increasing over time or clumped together in space). In addition, we also summarized the current (2009–

2010) black walnut conditions in the eastern United States so that any future changes in the black walnut resource may be adequately judged.

MATERIALS AND METHODS The FIA program has been inventorying forests in the United States for over 80 years. Prior to 1998, inventories were completed on a periodic, state-by-state basis; however, since 1998, FIA has conducted its inventories annually, assessing 10% to 20% of each state every year so that an individual state is inventoried fully once every 5 to 10 years (Bechtold and Patterson 2005). Under the current inventory, FIA has established two phases of on-the-ground data collection. Traditional timber inventory variables are collected in what is known as the phase 2 (P2) inventory and additional forest health variables are collected in the phase 3 (P3) inventory. Forest Inventory and Analysis plots are located across the United States in such a way that the sampling intensity is one P2 plot per approximately 2,428 ha. Phase 3 data are collected on one out of every 16 P2 plots. Both P2 and P3 plots consist of four 7.32 m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement on which trees at least 12.7 cm in diameter at breast height (d.b.h.) are measured. Assessments of trees at least 2.5 cm d.b.h. are assessed in a 2.07 m fixed-radius microplot established within each subplot. Phase 2 and phase 3 plots are permanently located so that, through the continuous annual inventory, individual trees are remeasured once every 5 to 10 years. Data included in this study were from the FIA P2 and P3 inventories conducted in the eastern United States (Figure 1) between 2000 and 2010. Only trees 12.7 cm d.b.h. and larger were included.

Volume and Density of Black Walnut Trees per Hectare of Forest Land

We obtained current (2009–2010) population estimates of black walnut trees from the FIA online tool EVALIDator (Miles 2011). Total number of live black walnut trees and total live volume in cubic meters (m^3) were obtained by state. Total numbers of live and dead black walnut trees per hectare of forest land were obtained by county. The total number live black walnut trees per hectare of forest land and the percentage of dead black walnut trees were mapped by county. According to FIA definitions, "forest land" is land at least 10% stocked by forest trees of any size, or formerly having had such tree cover, and not currently developed for nonforest use. The minimum area considered for classification is 0.4047 ha (1 acre). Forested strips must be at least 36.576 m (120 ft.) wide (USDA Forest Service 2008).

Crown Condition

The FIA program assesses a suite of variables describing individual tree crowns as part of its P3 data collection protocol (Schomaker et al. 2007). The three crown condition variables included in this summary are crown density (the amount of crown branches, foliage, and reproductive structures that blocks light visibility through the projected crown outline); crown dieback (recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds inward toward the trunk); and foliage transparency (the amount of skylight visible through the live, normally foliated portion of the crown, excluding dieback, dead branches, and large gaps in the crown) (Schomaker et al. 2007).

Crown density, crown dieback, and foliage transparency are visual assessments made by two-person field crews during the full leaf-on, summer season, typically June through August. They are measured in 5% increments and are recorded as a 2-digit code: 00, 05, 10 ... 99, where the code represents the upper limit of the class (e.g., 1% to 5% is code 05, and 96% to 100% is code 99). Within a species, higher crown density values, lower foliage transparency values, and lower crown dieback values typically are associated with better tree health.

Crown condition data were obtained from the FIA forest inventory database (FIADB) (Woudenberg et al. 2010). Crown density, crown dieback, and foliage transparency were summarized by plot and by year across the study area. Ratio-of-means estimators (Cochran 1977) were used to estimate the yearly means ($\hat{R}$) for density, dieback, and transparency:

$$\hat{R} = \frac{\sum_{i=1}^{n} y_i}{\sum_{I=1}^{n} x_i} \quad (1)$$

where

$y_i =$ the sum of all crown condition values of interest sampled in the population of interest on plot i

$x_i =$ the number of trees sampled in the population of interest on plot i

$n =$ total number of plots in the population of interest (including plots with no observations of interest)

with variance ($\hat{V}(\hat{R})$)

$$\hat{V}(\hat{R}) = \frac{1}{n(n-1)\left(\sum_{i=1}^{n} x_i/n\right)^2} \times \left(\sum_{i=1}^{n} y_i^2 + \hat{R}^2 \sum_{i=1}^{n} x_i^2 - 2\hat{R}\sum_{i=1}^{n} y_i x_i\right) \quad (2)$$

(Woodall et al. 2010).

In addition to these three P3 crown condition variables, the southern FIA program assesses dieback incidence (hereafter referred to as "SRS dieback") for hardwood trees on all P2 plots. SRS dieback incidence is recorded as present if 10% or more of the crown area is affected with dieback that has occurred from the branch tips inward or as absent if otherwise (USDA Forest Service 2008). The distribution of SRS dieback was summarized as percentage of trees affected by year across the southern part of study area (Figure 1).

Mortality and Cause of Death

Tree status was used to classify remeasured trees as survivors or mortality. Initially recorded for each tree as either live or dead and upon remeasurement as live, dead, or removed, trees were categorized as "recent mortality" if the status was "live" at the previous inventory (t_1, 2000–2005) but "dead" at the most recent inventory (t_2, 2005–2010). A cause of death is recorded for each tree that qualifies as recent mortality. Possible causes are insect, disease, fire, animal, weather, vegetation (includes suppression, competition, and vines), and silvicultural or land clearing activity. If the cause of death cannot be determined reliably then the cause of death is recorded as "unknown" (USDA Forest Service 2008). The percentage of black walnut trees with each of these causes of death recorded at t_2 was calculated, and plot locations of recent black walnut mortality were mapped by cause of death and visually assessed for spatial patterns.

Attempts to define crown condition thresholds beyond which trees are unlikely to recover have been limited; however, one such attempt was made by Steinman (2000), who concluded that hardwood trees with crown density <30% or crown dieback >30% were most likely to die within 1 year. Further, trees meeting both criteria were more likely to die than trees meeting only one criterion. Black walnut trees from t_1 and t_2 were categorized according to these criteria and evaluated for actual or potential risk of mortality.

RESULTS

Estimates indicated that there were 306 million live black walnut trees in the Eastern United States with a live volume of 112.76 million m^3. Missouri had the most black walnut trees (57.9 million), followed by Ohio (24.6 million), and Kentucky (24.5 million). Together, these three states accounted for 35% of the total number of live black walnut trees on forest land. Missouri, Ohio, and Iowa accounted for 33% of the total black walnut volume on forest land. In counties where black walnut occurred, the number of live black walnut trees per hectare of forest land ranged from a low of 0.14 trees/ha in Burnett County, Wisconsin, to a high of 176.5 trees/ha in DeKalb County, Illinois (Figure 2). Black walnut trees in the counties with known infestations of the WTB are probably most susceptible to devastation from TCD. In these areas the number of live black walnut trees ranged up to a high of 26.5 trees per hectare of forest land in Loudon County, Tennessee. The percentage of dead black walnut in most counties was <5% (Figure 3). Mortality of more than one-half of the black walnut stems was found in 25 of the counties with black walnut (Figure 3). One-third of the black walnut trees were dead in Knox County, Tennessee and Henrico County, Virginia, counties with known infestations of the WTB.

Crown Condition

Between 2000 and 2010, black walnut crown conditions were relatively stable and typically followed the trend exhibited by all hardwoods (Figure 4). Average crown density for black walnut trees ranged between 38.0% and 51.9% annually. Average crown dieback ranged between 2.2% and 6.3%, and average foliage transparency ranged between 20.0% and 26.4%

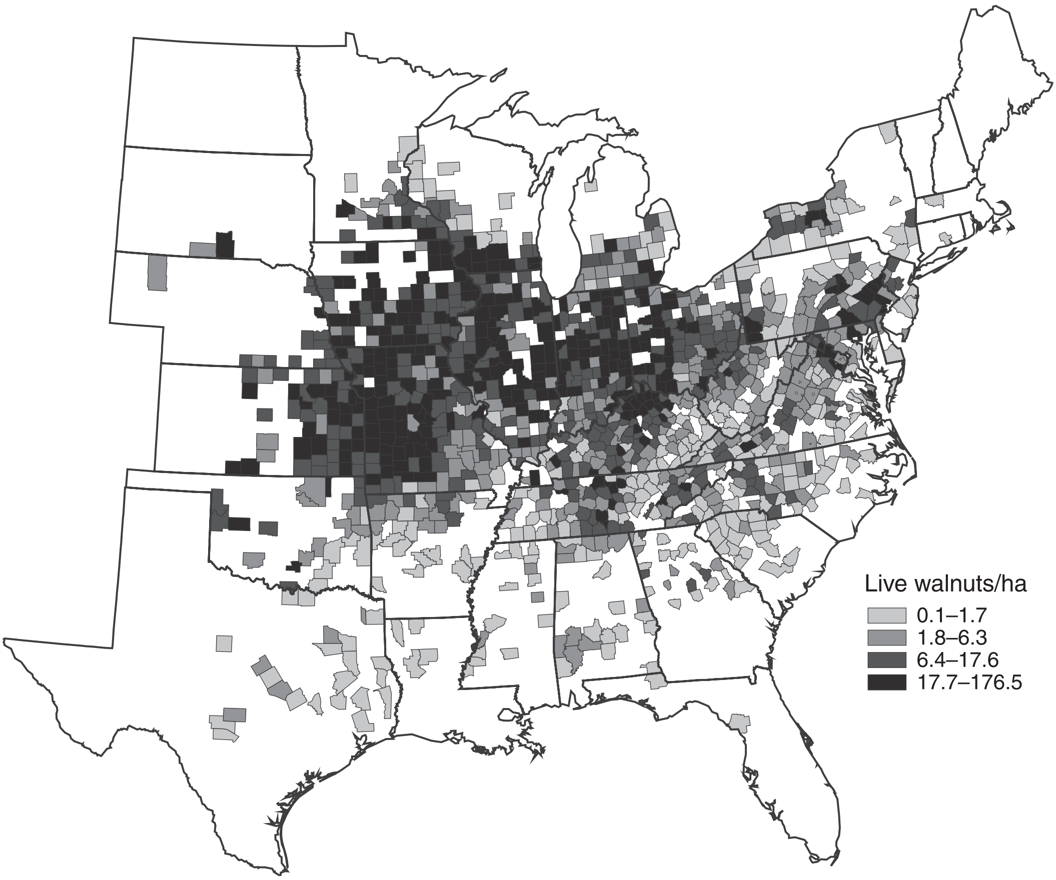

Figure 2. Current (2009–2010) population estimates of number of live black walnut trees per hectare of forest land, by county.

annually. SRS dieback incidence was observed on no more than 4.7% of the black walnut trees on which it was assessed in any given year between 2000 and 2010 (Figure 5). The highest rates of SRS dieback (i.e., >3.0%) for black walnut occurred in 2005, 2003, and 2002.

Average black walnut crown conditions per plot for plots with at least three black walnut trees at t_2 ranged between 27% and 60% crown density, 0% and 33% crown dieback, and 14% and 55% foliage transparency. Though the ranges of means are quite wide, the majority of the plot averages occurred within a smaller range: 90% of the plots had crown density averages of 36% to 55%, 95% of the plots had crown dieback averages of 0% to 10%, and 88% of the plots had foliage transparency averages of 14% to 30%. The plot averages showed no clustering of plots with poor crown conditions and thus the maps are not included.

Mortality and Cause of Death

Plots with recent black walnut mortality were scattered throughout the range of black walnut with visible concentrations in northern Kentucky, middle Tennessee, and across Missouri in particular (Figure 6). The causes of death for black walnut generally fell in line with the causes of death recorded for all other hardwood trees. The top three recorded causes of black walnut mortality between 2005 and 2010 were unknown (38.1%), vegetation (28.5%), and silviculture or land clearing activities (9.6%) (Figure 7). Black walnut suffered significantly more mortality from vegetation and significantly less mortality from disease than did the other hardwood tree species combined (Figure 7).

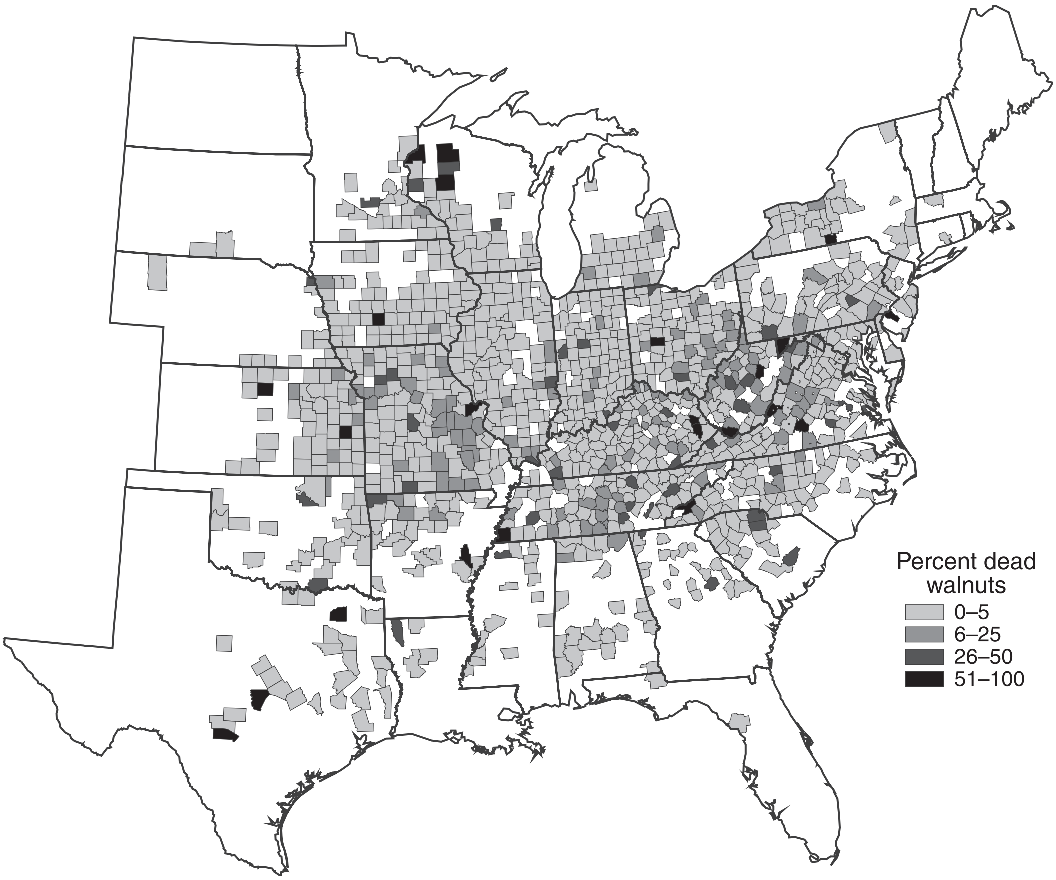

Figure 3. Current (2009–2010) percentage of black walnut trees that are dead, by county.

The recorded causes of death indicated that vegetation caused much of the mortality in northern Kentucky and disease or silvicultural/land clearing activity in middle Tennessee, whereas black walnut mortality in Missouri primarily was due to unknown causes.

The crown conditions at t_1 for the recent mortality trees were generally poorer than the crown conditions of the trees that survived. This was especially true for crown density, for which all remeasured trees with <20% crown density died during the remeasurement period (Figure 8). Among the black walnut trees that were measured at t_1, four met both of the Steinman (2000) crown condition thresholds for imminent mortality. Of these four trees, three died before they were remeasured at t_2. In addition, eight other trees met the crown density threshold when they were initially measured at t_1; two died by t_2. Among the most recent crown condition assessments made at t_2, 10 black walnut trees (2.1%) met both the crown density and crown dieback thresholds for imminent mortality and are among the trees most likely to die before their next remeasurement.

DISCUSSION We expected evidence of TCD, if present, to manifest itself in poor crown conditions and mortality, either increasing over time or clumped together in space. Neither was observed in the FIA data examined in this study. Crown conditions were reasonably stable between 2000 and 2010, and with the exception of foliage transparency, the black walnut crown condition averages generally fell within the ranges of what was observed by the US Forest Health Monitoring (FHM) Program between 1996 and 1999 (Randolph 2006, Randolph et al. 2010a, Randolph et al. 2010b). Foliage transparency averages for black walnut were slightly lower in

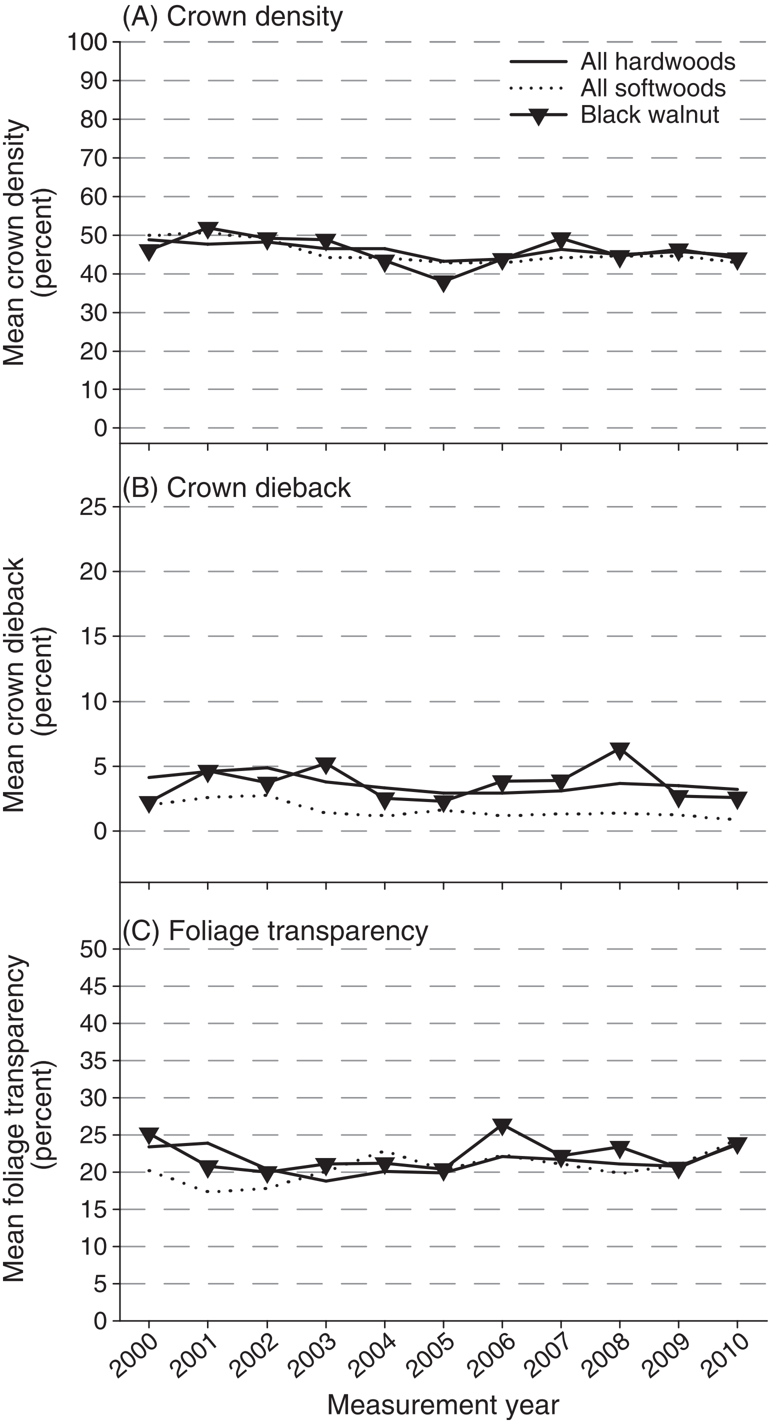

Figure 4. Mean black walnut crown conditions in the Eastern United States, by year. (A) Crown density, (B) crown dieback, and (C) foliage transparency.

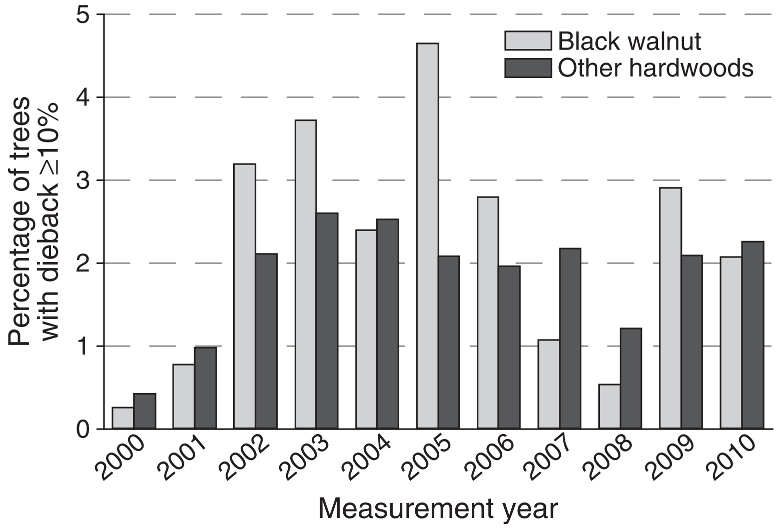

Figure 5. Percentage of hardwood trees with crown dieback >10% as recorded by the Southern Research Station Forest Inventory and Analysis Program, by year.

the late 1990s, ranging between 13.6% in the South (K.C.R., unpublished data) to 18.5% in the North Central States (Randolph et al. 2010a) compared to the 20.0% to 26.4% range of the 2000s. However, the increase in average foliage transparency was not specific to black walnut. Foliage transparency averages for all other species, combined into hardwood and softwood

Figure 6. Location of US Forest Service Forest Inventory and Analysis Program plots with live black walnut and black walnut mortality between 2005 and 2010. Plot locations are approximate.

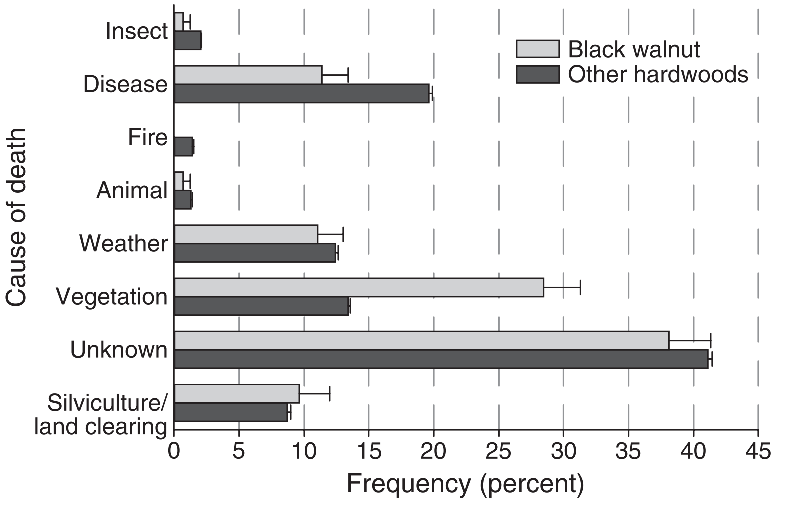

Figure 7. Frequency of the causes of death recorded for hardwood trees in the eastern United States between 2005 and 2010, with standard error bars.

groups, also were lower in the late 1990s than in the 2000s (Randolph 2006, Randolph et al. 2010a, Randolph et al. 2010b).

Given that the presence of WTB in the East was unknown when these data were collected, any mortality attributable to the WTB–TCD complex would not have been recognized as such and thus would have been recorded only incidentally in the insect or disease cause of death categories. An abundance of the "unknown" cause of death would have been expected if TCD had been present, but this was not the case. Accurately assessing the causality of tree mortality within the context of the FIA data collection procedures can be challenging. The temporally coarse nature of FIA plot visits (between 5–7 years in the eastern United States) calls for some subjectivity during the field assessment of individual tree death. Coupled with the fact that the causes of tree death are typically complex (Franklin et al. 1987), accurately capturing the true cause of individual tree mortality is often difficult. While some mortality events are simple to assess (e.g., wildfire or hurricanes), others are due to many, often complexly interrelated, contributing factors. Franklin et al. (1987) described these complex interactions as the "mortality spiral" after the disease decline spiral of Manion (1981). Therefore, describing tree mortality with a singular causal factor within the FIADB may provide a simplified picture of cause of death.

The P3 inventory, initially implemented by the FHM Program (Riitters and Tkacz 2004), employs a set of forest health indicators that, when observed over time, has the ability to detect unusual pulses or trends in forest conditions. In order to be observable on the P3 network of plots, however, the stressor must impact a wide variety of species or if the stressor is species-specific, a very large area (Bechtold et al. 2009). In the case of black walnut, WTB has been found in only 12 counties. Though black walnut grows on a wide variety of sites, it typically occurs as scattered individuals or in small clusters throughout most of its range (Williams 1990). For a strategic level inventory such as that of the FIA program, a growth pattern like that of black walnut may make it difficult to swiftly identify emerging health issues like TCD. However, data from the ongoing inventory by FIA and past inventory by FHM provide a baseline against which we can quantify any future effects of TCD.

Quarantines with varying levels of restrictions have been enacted in the eastern United States in order to protect the walnut resource. At a minimum, the export of black walnut nursery stock, green lumber, and other living, dead, cut, or fallen material is restricted from counties with known WTB infestations (Figure 1) (Pennsylvania Department of Agriculture 2011, TN.gov Newsroom 2011, Virginia.gov 2011). The fate of black walnut in the eastern United States is

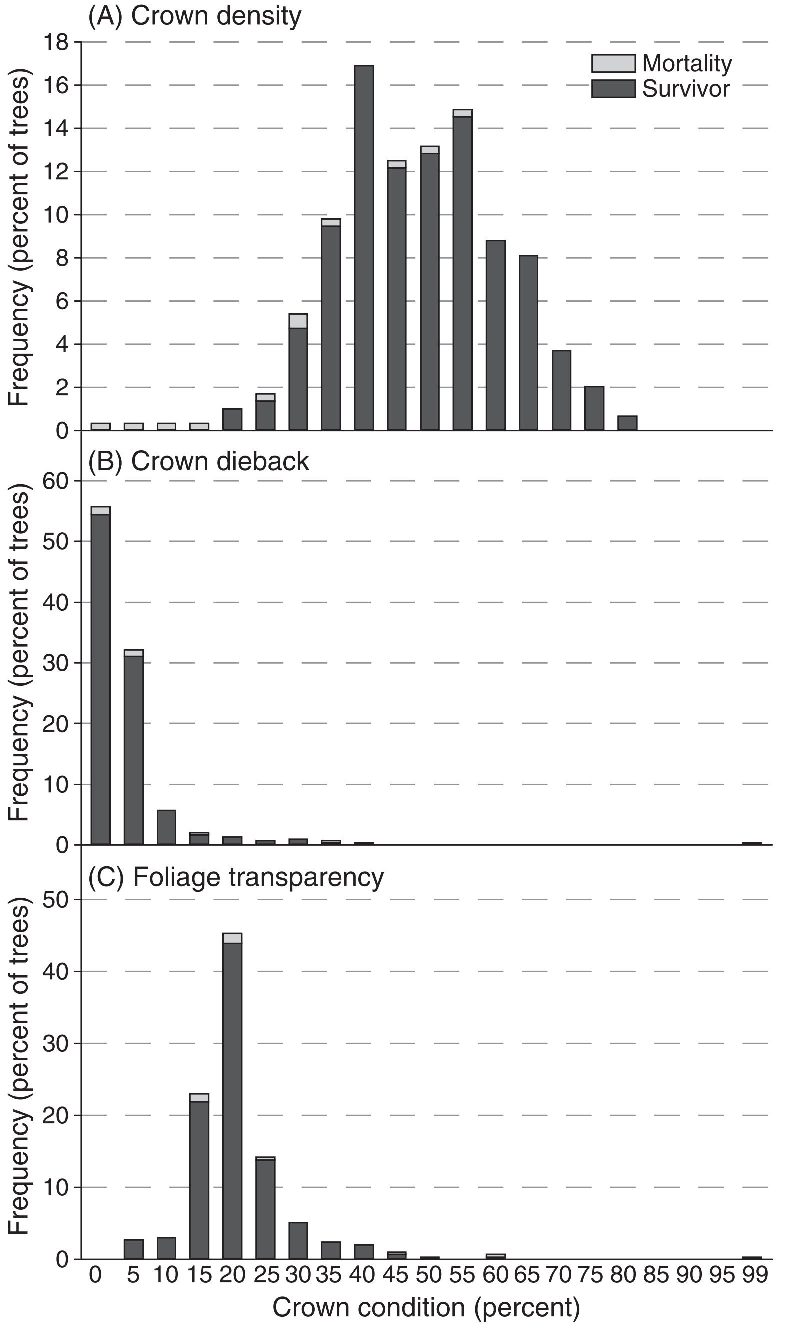

Figure 8. Crown condition distribution for black walnut trees measured between 2000 and 2005 by tree status upon remeasurement between 2005 and 2010. (A) Crown density, (B) crown dieback, and (C) foliage transparency.

largely dependent upon the effectiveness of the quarantines and eradication efforts but also on the biology of the WTB, which to this point has not been studied thoroughly.

The discovery of the WTB first in urban areas (Simmons 2010) demonstrates the need to monitor the urban tree resource. The FIA program has instituted pilot studies in Colorado and Tennessee to test the effectiveness of establishing a complementary and statistically valid inventory in urban areas (Nowak et al. 2012). Such an effort requires a great deal of effort both in pre-field planning and on-the-ground execution but could be an integral part of early pest detection if integrated with municipal forestry programs and perhaps even citizen scientist efforts (Conrad and Hilchey 2011).

SUMMARY Black walnut is a widely dispersed, very valuable hardwood tree species in the eastern United States and the advent of the WTB and TCD poses a threat to its future survival. As of the year 2011, the known distribution of WTB in the eastern United States is limited to only a few counties in Tennessee, Pennsylvania, and Virginia. Overall, there was little in the FIA crown condition and mortality data collected between 2000 and 2010 to suggest the presence of WTB and TCD in the forested landscape at large. This could be due to the actual absence of the disease complex or perhaps an inability of the inventory and monitoring system to detect its presence. Because the first visible sign of TCD is dying foliage and branch dieback, we recommend that forestry agencies and individual landowners keep track of changes in black walnut crown conditions. State plant and forestry officials can be alerted to TCD symptoms via the state-specific reporting methods listed on the TCD website, www.thousandcankers.com.

UPDATE Since this paper was accepted, Thousand Cankers Disease has been discovered in Jefferson County, Tennessee and Haywood County, North Carolina.

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