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Status and Impact of Walnut Twig Beetle in Urban Forest, Orchard, and Native Forest Ecosystems

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The walnut twig beetle, a native phloem-boring bark beetle originating on Arizona walnut, has invaded urban, orchard, and native forest habitats throughout the USA as well as in Italy. Although the beetle has been associated with dead and dying walnut trees indigenous to riparian forests of the Southwest, the primary impact appears to have been on the health of landscape black walnut trees in urban and peri-urban sites in western US states, and in Pennsylvania, Tennessee, and Virginia. This has been reflected in numbers of trees removed and tree removal costs. In addition, trees have been killed in the primary US *Juglans* germplasm repository in northern California, and low, but measureable, tree mortality has occurred in some English walnut orchards in California's Central Valley. As assessed under multiple circumstances, tree decline and mortality appear to develop gradually in response to infestations by this beetle.

Keywords: *Pityophthorus juglandis*, *Juglans californica*, *Juglans hindsii*, *Juglans major*, *Juglans nigra*, *Juglans regia*, tree mortality

The walnut twig beetle (WTB), *Pityophthorus juglandis* Blackman (Bright 1981, Wood 1982, Seybold et al. 2016b) (Figure 1), is a bark beetle native to the southwestern United States and northern Mexico that has been associated with a recently described fungus, *Geosmithia morbida* (Kolařík et al. 2011, 2017, Zerillo et al. 2014). This insect–fungal complex, also known as thousand cankers disease (TCD), is fatal to walnut trees (Figure 2) and was first noted in the late 2000s for its involvement in the gradual deterioration and mortality of several species of black walnut in the western United States (Graves et al. 2009, Flint et al. 2010, Tisserat et al. 2011, Seybold et al. 2013b). When populations of WTB are high, numerous feeding and reproductive galleries are created and colonized by the fungus, and the resulting cankers coalesce and girdle branches and stems. In greenhouse tests, the pathogen infects walnut and butternut trees (both *Juglans* spp.), but not pecan and hickory trees (both *Carya* spp.) (Utley et al. 2013). The beetle can reproduce in many species of *Juglans* (Seybold et al. 2016b, Hefty et al. 2018), as well as in several species of wingnut, *Pterocarya* (Hishinuma et al. 2016, Hefty et al. 2018). It does not

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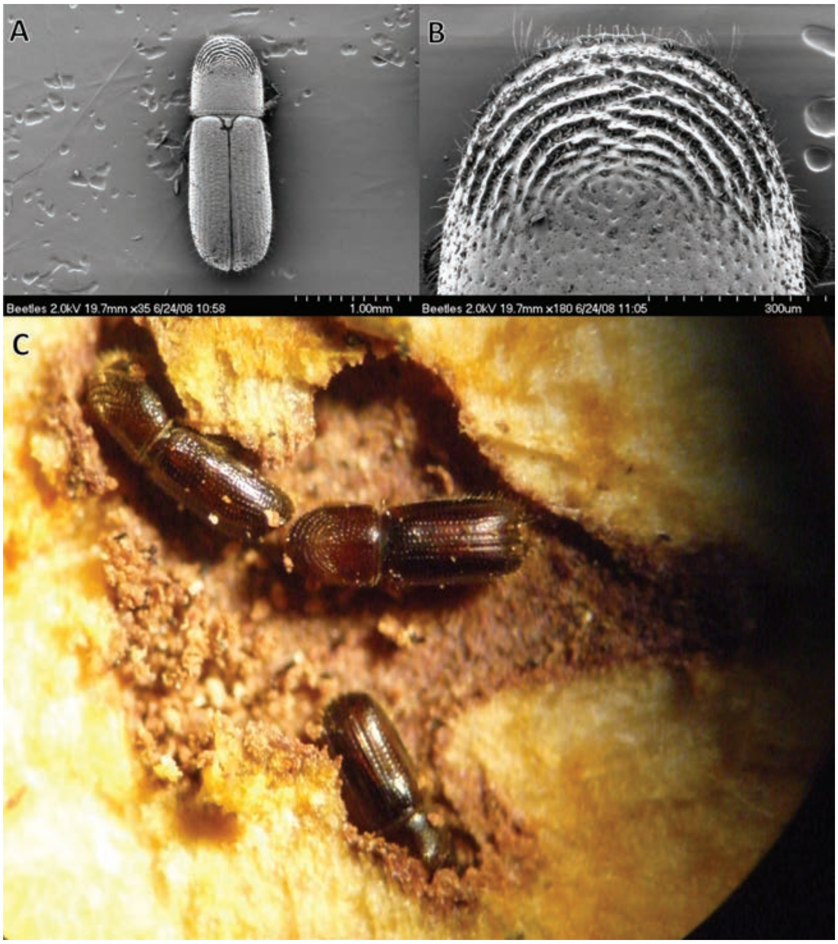

Figure 1. Scanning electron micrographs of the dorsal view of female walnut twig beetle, *Pityophthorus juglandis* Blackman, illustrating the full dorsum (A) and the pronotal asperities or ridges (B), which are relatively diagnostic for the species group. The male adult beetle (C, center) creates a nuptial chamber in the phloem of walnut (*Juglans*) or wingnut (*Pterocarya*) where it is joined by two or more females for feeding and reproduction. Scale bar at lower right of electron micrographs = 1,000 μm (A) or 300 μm (B). Beetles for images were collected in Davis, Yolo County, California, (AB) on June 13, 2008 in northern California black walnut, *Juglans hindsii*, and photographed June 24, 2008 by ADG and by Delilah F. Wood, USDA Agricultural Research Service Western Regional Research Center, Albany, California; and (C) on August 20, 2008 in the same general location in *J. hindsii* and photographed the same day by SMH.

develop in *Carya* (Hefty et al. 2018). Initial entry by the parent beetles into the branches of the upper crown of host trees takes place through lenticels, leaf scars, corky furrows, and other perturbations of the bark surface (Figure 3).

Unlike many other species of "twig" beetles (*Pityophthorus*), WTB will colonize the largest branches and main stem of large diameter trees in advanced stages of decline (Figure 4).Thus, it is never solely a twig-infesting beetle, even in its putative native host and distribution (Arizona walnut, *J. major*, in Arizona and New Mexico) (Rugman-Jones et al. 2015), where it also colonizes the larger dimensional parts of trees (Figure 4B). The WTB has a relatively long collection history in North America (collected first in 1896 from New Mexico; 1907 from Arizona; 1959 from California; 1960 from Mexico), but was never considered historically by forest entomologists to be a major pest of walnut trees (Furniss and Carolin 1977). In the early 1990s, however, walnut mortality now attributed to TCD was noted along the Wasatch Mountains of Utah and in the Willamette Valley of Oregon (Tisserat et al. 2011). In 1997, WTB was first associated with dying walnut trees in Utah Co., Utah. Subsequent WTB-associated mortality was noted in the Española Valley of New Mexico (2001) (USDA Forest Service 2002) and in Boulder, Colorado (2003) (Tisserat et al. 2011). Offsite plantings of eastern black walnut, *J. nigra*, were impacted in all of these circumstances. TCD was first detected in California in 2008 in Yolo Co. (northern California black walnut, *J. hindsii*) and Solano Co. (English walnut, *J. regia*) (Flint et al. 2010). Most significantly, TCD was detected in July 2010 in Knoxville, Tennessee; May 2011 in Richmond,

Management and Policy Implications

Impacts related to walnut twig beetle have centered on regulatory issues (e.g., intra- and interstate quarantines, monitoring costs, and risk assessments) as well as on management issues (costs of wood treatment, accelerated research, and tree removal). Concerns regarding the potential impact of the beetle on the extremely valuable black walnut timber resource in the eastern United States have driven the development of a research and management response to this pest problem.

Figure 2. Dead northern California black walnut, *Juglans hindsii*, along a rural road in Solano County, California. Inset: extensive egg galleries of walnut twig beetle, *Pityophthorus juglandis*, etched transversely on the xylem surface of the main stem, photographed April 19 and 20, 2018 by Jackson P. Audley, Department of Entomology and Nematology, University of California, Davis.

Virginia; and August 2011 in Doylestown, Pennsylvania, threatening directly for the first time the highly valuable native timber stands of *J. nigra* in the eastern United States (Moltzan 2011). A consummate invader, WTB has been recorded in at least 129 counties in the conterminous United States, i.e., south to north from Cochise and Hildago Counties (southern Arizona and New Mexico, respectively, 31°24′N) to Spokane and Kootenai Counties (northeastern Washington and northern Idaho, respectively, 47°43′N), and west to east from Humboldt and Benton Counties (California, 123°38′W and Oregon, 123°13′W, respectively) to Bucks County (Pennsylvania, 75°89′W) (Seybold et al. 2012, 2016b). The spread of WTB from its historic and isolated native range in Arizona, Mexico, and New Mexico to new locations came to the attention of land managers when apparently sudden damage to black walnut was first recorded (i.e., Colorado, Oregon, Utah, and northern New Mexico, Tisserat et al. 2011). However, the collection history of WTB in California suggests a continuous presence in that state from 1959 to the 1990s (Seybold et al. 2016b, figure 21.12A therein) and various hypothetical scenarios have been described in Rugman-Jones et al. (2015) to explain the invasion by WTB of nearly the entire western United States from a "bridgehead" invasive population in California. In 2013, it was discovered in northern Italy in *J. nigra* and *J. regia*, and has since spread more widely in Italy (Tuscany), making it a pest of international significance (Montecchio and Faccoli 2014, European Plant Protection Organization 2015, Faccoli et al. 2016, Moricca et al. 2018). WTB and TCD form a very interesting and unique convergence for the impact of a bark beetle on urban, agricultural, and forestry values.

Urban Impacts

The initial impact of WTB on urban forest values was noted in Colorado front-range cities like Boulder and Denver, where, respectively, 60 percent and 20 percent of the *J. nigra* street trees were removed between 2004 and 2010 (Tisserat et al. 2011). Removals in Boulder reached 1,300 trees during this period. Cost estimates for removal of trees in Boulder ranged from $150 to $1,200 per tree, depending on tree size and difficulty of removal (K. Alexander, pers. comm.). In and around northern California communities in the Sacramento Valley, *J. hindsii* street and rural highway trees have been in a state of gradual but

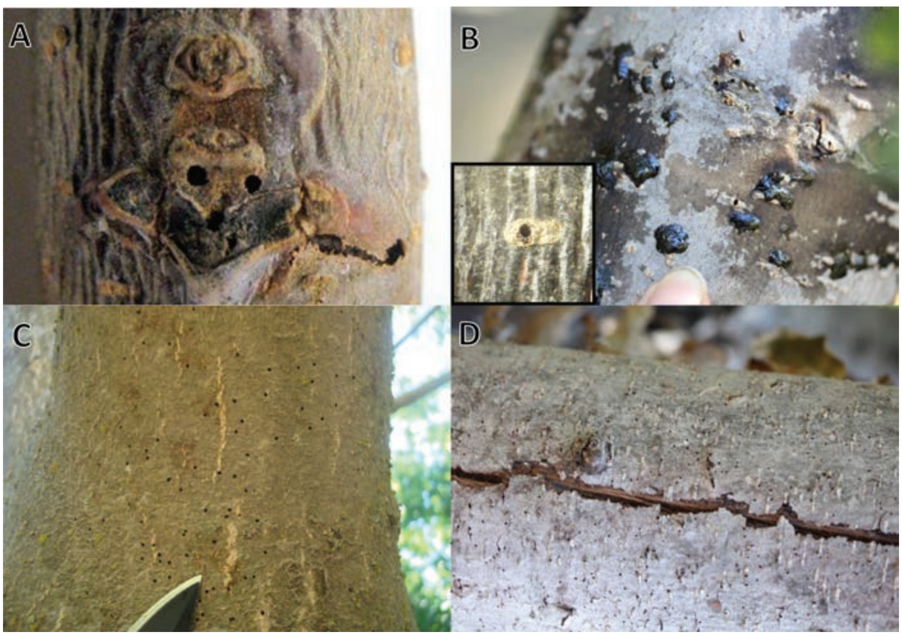

Figure 3. Entrance holes of walnut twig beetle, *Pityophthorus juglandis*, through (A) leaf scars on bark surface of 2–4-cm-diameter branch section of northern California black walnut, *Juglans hindsii*; (B) lenticels on bark surface of 10–12-cm-diameter upper stem of southern California black walnut, *Juglans californica* and (B inset) lenticel on bark surface of 2–4-cm-diameter branch section of *J. hindsii*; and (C) corky furrows on bark surface of 25–30-cm stem of 'Tulare' cultivar English walnut, *Juglans regia*. Numerous emergence holes of brood adults made through flat outer bark surfaces of *J. regia* (C) and *J. californica* (D). Photo credits: ADG, A (February 28, 2009, Davis, Yolo County, California); SMH, B and D (August 2012, Winters, Solano County, California); B inset (October 31, 2008, Davis, Yolo County, California); and Elizabeth J. Fichtner, UCCE Tulare Co., Tulare, California, C (August 17, 2010, Tulare County, California).

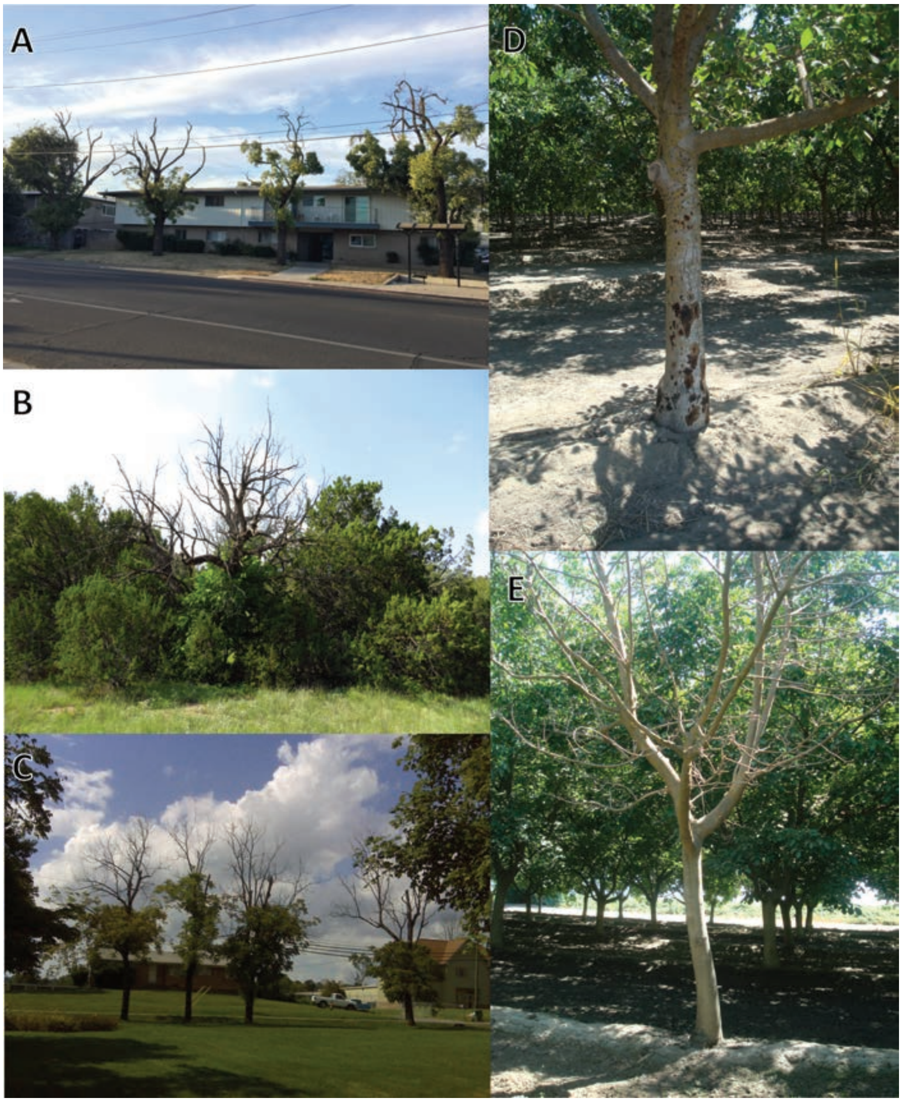

Figure 4. Crown dieback, epicormic branching, and tree mortality caused by walnut twig beetle, *Pityophthorus juglandis*, in various *Juglans* species in US urban, wildland, and agricultural environments. (A) Crown dieback and epicormic branching in northern California black walnut, *Juglans hindsii*, street trees in Davis, Yolo County, California (Photo credit: SMH, October 2016). (B) Crown dieback and epicormic branching in native, riparian Arizona walnut, *Juglans major*, in the Fort Stanton-Snowy River Cave National Conservation Area near Capitan, Lincoln County, New Mexico (Photo credit: Corwin M. Parker, UCD Department Entomology and Nematology, August 21, 2013). (C) Crown dieback and epicormic branching in black walnut, *Juglans nigra*, along East Emory Road and Andersonville Pike, Knoxville, Knox County, Tennessee (Photo credit: Bruce D. Moltzan, USDA Forest Service, July 28, 2010). (D) Stem staining and (E) mortality of 'Tulare' cultivar English walnut, *Juglans regia*, in two commercial orchards near Ivanhoe and east of Visalia, Tulare County, California. (Photo credit: Elizabeth J. Fichtner, UCCE Tulare Co., California. August 14 and 17, 2010.)

steady decline, even before the disease was first detected in Davis (Yolo County) in 2008 (Seybold and Leslie 2009) (Figure 5). For example, nearly all large-diameter *J. hindsii* in Davis show crown decline and epicormic branching such that arborists have pruned large proportions of the crown with resulting loss in shade value (Figure 4A). In mature black walnut trees (*J. nigra*, *J. hindsii*, and *J. nigra* × *hindsii*) in urban and peri-urban landscapes in Oregon's Willamette Valley, Pscheidt (2011) described a generally slow crown decline between September 2007 and July 2010. The decline was attributed to TCD. At the end of the 3-year survey, 17 of an original 51 trees had greater incidences of declining crowns, ranging from 5 to 70 percent dieback. However, 34 of the 51 trees had similar or even improved crowns when the survey ended.

In the eastern portion of the invaded range (primarily Pennsylvania, Tennessee, and Virginia), the genesis of the impact of WTB on urban forest values is perhaps more fully understood because the introductions were apparently more recent. Impacts in Pennsylvania (Turcotte et al. 2013) and Virginia (Griffin 2015) have been described elsewhere, so we will focus on the effect of WTB on *J. nigra* in eastern Tennessee (Figures 4C, 6). To this end, trees in Knox and Blount Counties, Tennessee were re-examined and rated for crown decline by one of us (WEK) in early October 2017. In some instances, the status of infestation by WTB and/or infection by *G. morbida* was validated by a new molecular technique (Oren et al. 2018). An urban and park tree inventory maintained by the

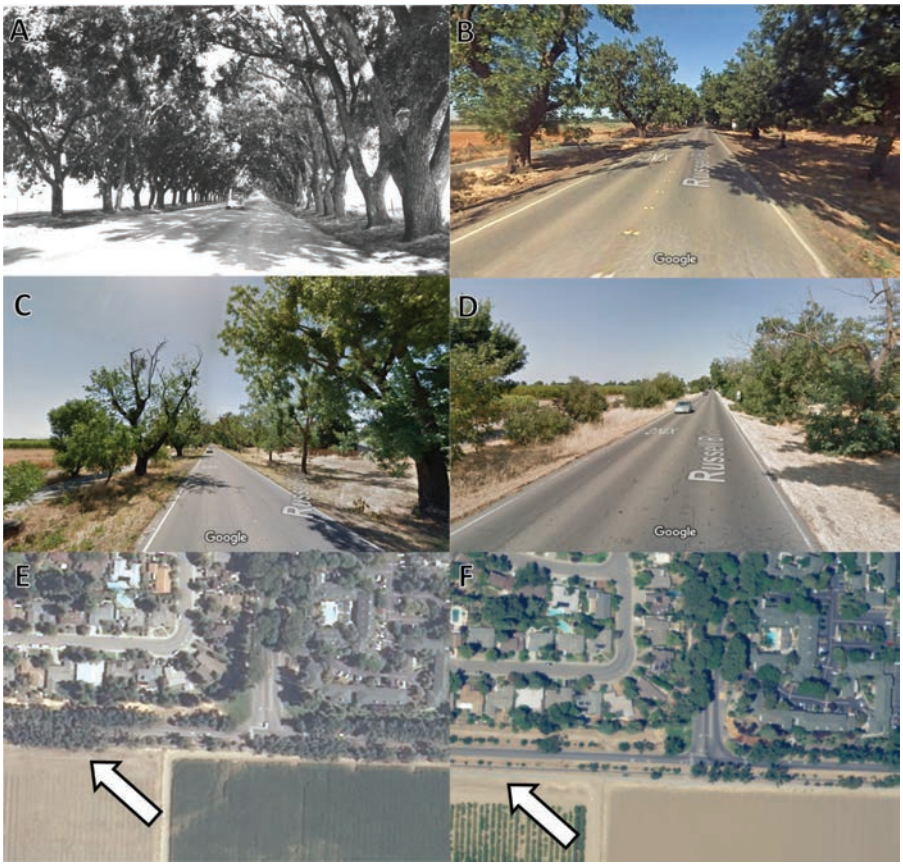

Figure 5. Photo documentation of declining health and removal of trees from a continuous canopy of northern California black walnut, *Juglans hindsii*, along the "Avenue of Trees," historic US Highway 40 (Russell Boulevard) located west of Davis, Yolo County, California. Five hundred of these trees were planted originally in 1876 to beautify the roadway and provide a barrier against the dust of the Central Valley (Seybold and Leslie 2009). Most images were captured near the intersection with Lake Boulevard. Status of trees in (A) 1961 (from a California Department of Public Works article entitled "California Roadside-1." Vol. 40 (Jan–Feb) 1961; (B) July 2007; (C) May 2014; and (D) August 2017 (B, C, D, Street View Imagery: Google). The dramatic impact of walnut twig beetle, *Pityophthorus juglandis*, on this urban windbreak is illustrated by two aerial images taken in (E) 2010 and (F) 2016 (National Agriculture Imagery Program products courtesy of the Aerial Photography Field Office of the USDA Farm Service Agency). Sprouted young trees from stumps of removed mature trees are evident in F (arrow).

City of Knoxville certified arborist includes 227 specimens of *J. nigra*, and many of these provide the basis for the 2017 survey (Table 1). However, Knoxville's urban tree inventory of *J. nigra* likely represents just a fraction of trees of this species, which also occur in this area in unmanaged, uninventoried rights of way, and privately owned lands.

The discovery of WTB and TCD in eastern Tennessee presents a valuable case study (Grant et al. 2011). During the summer of 2010, TCD was confirmed after *G. morbida* was cultured from branches removed from symptomatic trees in Anderson, Blount, Knox, and Union Counties (Figure 6A). "Symptomatic" trees also included standing trees that were already dead (Grant et al. 2011). These detection results facilitated establishment of initial state-regulated quarantine and buffer county delineations in Tennessee (Figure 6A). Quarantine areas represented locations (counties) where both disease elements were present; regulated buffer areas (counties) represented locations that bordered quarantine counties [Tennessee Department of Agriculture (TDA) 2011]. Subsequent detections of WTB by using aggregation pheromone-baited funnel traps (Seybold et al. 2013a, 2015) in regulated buffer areas stimulated attempts to culture *G. morbida* from these areas and led to an expansion of the regulated area (Figure 6B). To date, WTB has been detected in 23 counties in Tennessee (Seybold et al. 2016b), and 10 counties are under quarantine (Figure 6C).

Impact of WTB on *Juglans nigra* in the City of Knoxville

The baseline for the health of *J. nigra* growing in greater Knoxville (Knox County) at the time of the discovery of TCD can be inferred from a Street Tree Survey (unpublished) compiled by arborists and horticulturalists (Table 1). In spring 2011, these workers classified the crown condition of 85 specimens of *J. nigra* as "Fair" (46 percent) or "Poor" (46 percent). Three trees were scored as "Critical," and two trees were reported as "Dead" (but still standing). All five of these latter trees, and 15 that had been rated as "Poor," were designated for immediate removal (Table 1). Thus, approximately 24 percent of the *J. nigra* in the survey were in poor enough health, perhaps because of TCD, to be removed from the city population. In June 2013, Griffin (2015) evaluated 53 specimens of *J. nigra* in Knoxville and found that one tree had more than 50 percent crown dieback, but most (74 percent) had less than 20 percent crown dieback. Thus, Griffin (2015) documented an apparent recovery in the *J. nigra* street tree population in Knoxville.

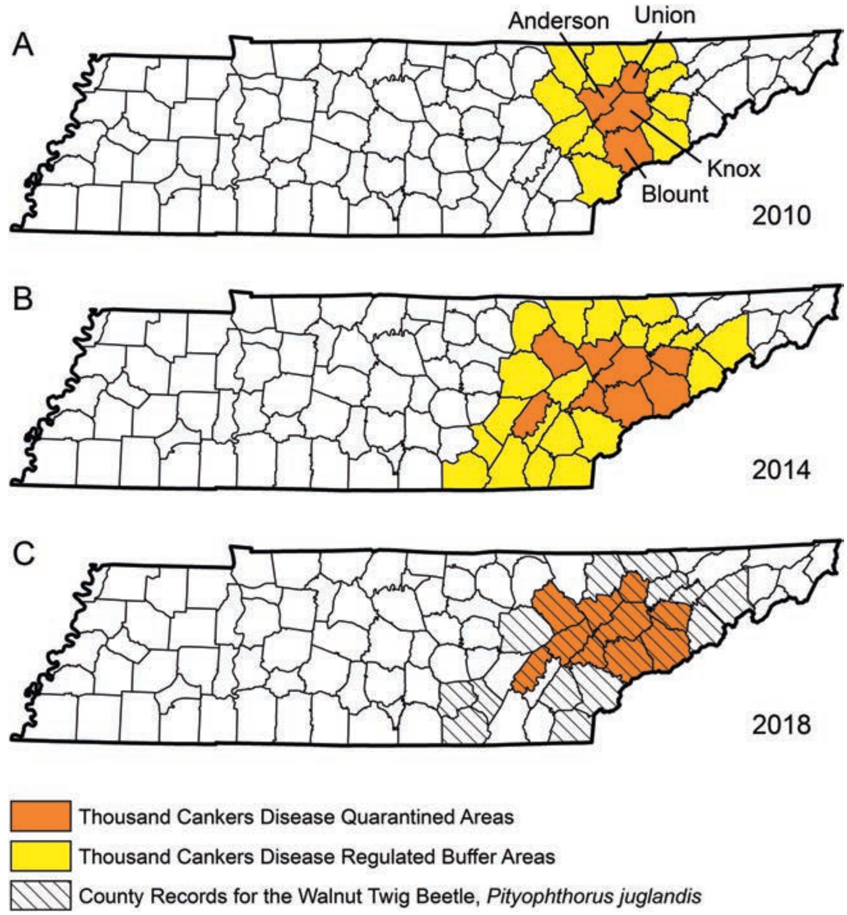

Figure 6. Development of the state quarantine system for thousand cankers disease to protect eastern black walnut, *Juglans nigra*, resources in Tennessee [Tennessee Department of Agriculture (TDA) 2011]. (A) Initial regulated area of four quarantined counties and 10 buffer counties centered on Knoxville (TDA 2010, 2011). (B) Expanded regulated area of nine quarantine counties and 19 buffer counties based on aggregation pheromone-baited trap catches of walnut twig beetle, *Pityophthorus juglandis*, and isolation and identification of *Geosmithia morbida* from *J. nigra* (TDA 2014). (C) Simplified regulated area of 10 quarantined counties, February 4, 2018 (www.tn.gov/content/dam/tn/agriculture/images/ThousandCankersMap.jpg or www.tn.gov/agriculture/businesses/plants/plant-pests--diseases-and-quarantines/ag-businesses-tcd.html). The 23 counties where *P. juglandis* has been detected in pheromone-baited traps are also indicated (Seybold et al. 2013a, 2016b, J.P. Audley, pers. comm.). Nationally, as of November 8, 2018, 18 US states have implemented interstate quarantines for TCD (www.thousandcankers.com).

In early October 2017, the crown condition of 129 specimens of *J. nigra* was assessed in Knox County (Table 1). Forty-six trees (36 percent of those assessed) were rated as having severe dieback or worse crown health (i.e., ≥50 percent crown dieback). From a molecular analysis (Oren et al. 2018) of a subsample of eight trees, one dead tree and one tree with moderate crown dieback tested positive for *G. morbida*. The trees from Knox County evaluated in 2017 included 60 trees that survived from the 2011 survey, suggesting that WTB/TCD were orchestrating a rather gradual decline on this population of *J. nigra*. The 2017 survey verified that all 20 of the *J. nigra* recommended for removal in 2011 were indeed removed at an undocumented cost to the City.

The impact of WTB on values in Knox County is illustrated by the condition of *J. nigra* trees at two urban parks. Lakeshore Park is a re-purposed 185-acre (approximately 75-ha) land parcel that has been developed from the historic Lakeshore Mental Health Institute, which was operated by the State of Tennessee (http://lakeshoreparkknoxville.org/). It provides a green rolling landscape with views of the Tennessee River and Great Smoky Mountains. The property was dotted with large deciduous trees, particularly veteran specimens of *J. nigra*. Five of these were removed in response to the 2011 survey recommendations; five additional *J. nigra* were cut and removed for research purposes, to remove an imminent threat of tree failure, or to accommodate ongoing park revitalization, walking path installation, and landscape restoration (WEK, personal observations). Of 32 *J. nigra* that were assessed at Lakeshore Park in 2017, only one was dead (died between 2016 and 2017). The role of WTB in this mortality event has not been determined. The mean crown coverage of the remaining 31 *J. nigra* was approximately 70 percent (ranging from 30 to 90 percent). West Hills/John Bynon Park (www.knoxvilletn.gov/cms/one.aspx?portalId=109562&pageId=210511) is a 45-acre (approximately 18-ha) multipurpose park

Table 1. *Juglans nigra* crown condition at locations in Knox and Blount Counties, East Tennessee.

General crown condition*	Estimated live crown coverage (Knox Co.) (%)	2011 Street Tree Survey (Knox Co.) (no. of trees)	2013 Crown rating* (Knox Co.) (no. of trees)	2017 Crown rating (Knox Co.) (no. of trees)	2017 Crown rating (Blount Co.) (no. of trees)
Slight dieback	90–100		25	7	0
Slight dieback	80	2†	14	24	4 [1]
Moderate dieback	70		5	21 [1]**	7 [3]
Moderate dieback	60	39‡	26	31	9 [1]
Severe dieback	50	39 (15)§,¶	1	12	2
Severe dieback	40		0	12	1 [1]
Severe dieback	30		0	14	1
Critical	20	3 (3)¶,‖	0	4	0
Critical	10		0	2	0
Dead (standing)	0	2 (2)¶	0	2 [1]	0
Tree count		85	53	129†† [2]**	24 [6]**

* Data as presented within, and crown condition ranges after, Griffin (2015); specific locations not reported.
† Condition recorded in 2011 Street Tree Survey (unpublished data) as "Good"; interpreted as 80 percent or more of crown intact.
‡ Condition recorded in 2011 as "Fair"; interpreted as 51–70 percent crown intact.
§ Condition recorded in 2011 as "Poor"; interpreted as 50–20 percent of crown intact.
¶ Number in parentheses is the sum of trees within condition that were recommended for removal in 2011 Street Tree Survey.
‖ Condition recorded in 2011 as "Critical"; interpreted as 20 percent or less crown remaining, or with other decline-associated faults suggesting imminent tree failure.
** Numbers in brackets indicate positive confirmation of *Geosmithia morbida* DNA from phloem tissues assayed in 2015 (after Oren et al. 2018).
†† Tree total includes 60 (remaining) trees that were also evaluated during the 2011 Street Tree Survey.

near downtown Knoxville. Of 10 trees surveyed on this property in 2011, only two remained in 2017. The condition of these two trees was reported as "Fair" in 2011 and roughly corresponds to the moderate dieback category in Griffin (2015). In 2017, both remaining trees had 80 percent live crowns. An additional 18 *J. nigra* trees were recorded at this park in 2017 (mean dbh of 6.7 inches [approximately 17 cm], ranging from 3.5 to 10.5 inches [8.9 to 26.7 cm]). The sizes suggest that the trees were young when the larger and potentially TCD-compromised trees were removed. The mean crown coverage of the younger trees in 2017 was 75 percent (ranging from 60 to 90 percent).

Impact of WTB on *Juglans nigra* in the Blount County Communities of Alcoa and Maryville

In early October 2017, 24 park and urban street trees (*J. nigra*) were assessed in Blount County in smaller communities (Table 1). Four trees (16.7 percent) showed severe crown dieback, with just one of these trees testing positive for *G. morbida* (Oren et al. 2018). However, 20 *J. nigra* showed just slight or moderate crown dieback, but this group included five specimens from which *G. morbida* had been diagnosed directly (Oren et al. 2018) (Table 1).

Factors that Modulate the Impact of WTB on *Juglans nigra* in Urban Landscapes of Eastern Tennessee

Several factors play a role to influence our interpretation of the assessment of the impact of WTB in eastern Tennessee. First, both the seasonal timing and the assessor may have a bearing on crown ratings of *J. nigra*. Ratings taken in fall 2017 may reflect a higher estimate of crown decline because of season-long leaf abscission associated with foliar-feeding arthropods and foliar plant pathogens. We have assembled data (Table 1) from at least three different assessors, so changes in estimated crown coverage with time should be interpreted conservatively. Nonetheless, the presence (in 2017) of 60 of the original 85 trees from the 2011 survey underscores the gradual nature of the impact of WTB on relatively large trees. Second, the assessment in Knox and Blount Counties does not draw from the larger population of *J. nigra* in unmanaged, uninventoried rights of way and privately owned lands. Furthermore, despite harboring considerable populations of *J. nigra*, no attempt has been made to evaluate crown condition or validate the presence of WTB or *G. morbida* on declining trees on any lands within Tennessee's other TCD quarantine counties (Figure 6C) or regulated buffer counties (Figure 6B). For example, Loudon County, adjacent to Knox and Blount Counties, has 26.5 *J. nigra* stems/hectare, which is the highest estimated stem density among Tennessee counties where TCD occurs (Randolph et al. 2013). Knox and Blount Counties average approximately 12 stems/hectare (Randolph et al. 2013). Third, several abiotic and biotic factors appear to have ameliorated the impact of WTB on the crown condition of *J. nigra* in eastern Tennessee. Higher-than-normal precipitation in 2013 may have provided some relief of suspected drought stress on *J. nigra* in both Knoxville and Richmond (VA) (Griffin 2015). As a consequence of this abiotic factor or some latent biotic factor(s), the general population density of WTB in eastern Tennessee appears to have declined. State of Tennessee surveys conducted in numerous counties since 2011 have revealed progressively lower trap catches in and around Knox County from 2014 to the present. Fifteen funnel traps deployed at 11 Knox or Blount County locations between May 14 and September 11, 2015 and between April 30 and August 11, 2016 yielded 210 and 163, WTB, respectively (WEK, unpublished data). These levels of flight activity-abundance are far lower than those observed in the western United States (Chen and Seybold 2014). It remains to be seen if persistent, but low, WTB populations in eastern Tennessee may increase to cause a greater impact as regulating factors relax.

Agricultural Impacts

In the United States, English or Persian walnut, *J. regia*, is grown primarily in California orchards in the Central and peripheral valleys (Beede and Hasey 1998). This reflects 99 percent of national production with over 80 percent of the crop exported (USDA Foreign Agricultural Service 2017). Worldwide, the USA is second (to China) in edible walnut production with a 2017–18 forecast of approximately 590,000 metric tons (USDA Foreign Agricultural Service 2017). The value of edible nut production from California walnut orchards has ranged from $1.03 to $1.24 billion in 2010 and 2016, respectively, with a peak of $1.91 billion in 2014 (USDA National Agricultural

Statistics Service, September 2017). The development of improved varieties of *J. regia* by the UC-Davis Walnut Improvement Program has been an important reason for US leadership in walnut production, with over 35 cultivars monitored in productivity assessments (USDA National Agricultural Statistics Service, September 2017). The investment and value of California walnut orchards and processing facilities are likely to be in the multibillion dollar range, but to our knowledge the value of this growing stock and infrastructure has not been quantified. Because most orchard trees are grafted onto native black or hybrid black × English (= Paradox) walnut rootstock, and both rootstocks are highly susceptible to WTB attack, TCD presents an uncertain threat to California's walnut industry. An increasing number of cases of TCD in English walnut scions in orchards have been noted recently by growers and farm advisors (Flint et al. 2010, Yaghmour et al. 2014, Hishinuma 2017).

Flint et al. (2010) reported that TCD was present in 15 counties in California, and some of these records were derived from commercial orchards of *J. regia* (Zerillo et al. 2014, Rugman-Jones et al. 2015). Expanded collecting and detection trapping have revealed that WTB is present in 32 counties in California, including 16 counties that comprise an area that circumscribes the commercial walnut growing region (Seybold et al. 2016b). In one California orchard of *J. regia* (Tulare Co.), Hishinuma (2017) noted a significant increase from 2.9 to 78 percent for actively infected trees between 2011 and 2014. However, when all commercial and research orchards in this survey were analyzed together, symptoms progressed more slowly in *J. regia* and in *J. major* (the ancestral host of WTB) than in any other *Juglans* species. A model derived from the survey data predicted 31 y as a median survival time for *J. regia* that were asymptomatic at the beginning of the survey (Hishinuma 2017). The levels of mortality among three locations with *J. regia* were similar and comprised less than 5 percent of the trees at each survey location.

In a study funded by the California Walnut Board in a commercial orchard of 'Chandler' *J. regia*, colonization by WTB was induced on relatively healthy trees by using aggregation pheromone lures (Seybold et al. 2015, 2016a), and the impact of the beetle on the health of the crown, the health of the stem, and nut production was evaluated between 2014 and 2018 in a controlled experiment. Although significantly more entrance/emergence holes of WTB were recorded on the rootstock and stem (scion) for trees in the treatment (pheromone-baited) group than in the control group and *increases* in the numbers of WTB entrance/emergence holes on the scions of the pheromone-baited trees were significantly greater than those on unbaited trees, none of the comparisons of crown condition, nut yield and quality, stem water potential, or canopy light interception between baited and unbaited control trees were statistically significant. In short, no trees declined or died in the experiment. Explanations for this outcome are that TCD is a slow-acting disease system on *J. regia* and that population density (flight activity-abundance) of WTB at the site and colonization density of WTB on the treated trees was low throughout the study. The project also evaluated the extent to which WTB are present in and emerge from *J. regia* firewood with the goal of developing written guidelines for best management practices for infested firewood and burls from English walnut orchards (Fichtner et al. 2014).

USDA germplasm repositories for *Juglans* are in California, Indiana, Missouri, and Oregon. These collections of trees represent a valuable resource for future tree breeding of *Juglans* for agriculture and forestry. Although populations of WTB have not been established in Indiana and Missouri, the beetle has been particularly destructive in the primary *Juglans* germplasm repository in Winters, Solano Co., California (Figure 7). Hishinuma (2017) reported significant increases in the percentages of actively infected trees among four species of native western North American "black" walnuts (section *Rhysocaryon*) growing at this location during the survey, but particularly noteworthy was the impact on southern California black walnut, *J. californica* (Figure 7). Of 210 accessions of this species, which had been planted at this location in the mid- to late 1980s, only 67 trees were still alive in late August 2016. Most of these live trees had severe crown dieback (no more than 24 percent live crown); only five trees had healthy crowns (100 percent live crown). Nearly 120 of the dead trees were confirmed to have been attacked by WTB (Figure 7D); and other dead trees had been removed and destroyed before any observations could be made. These impacts on offsite plantings of *J. californica* in the field are not surprising given high relative rates of WTB reproduction recorded on cut branch sections of *J. californica* in laboratory assays (Hefty et al. 2018). The WTB has also been trapped in flight in the primary collection of butternut, *J. cinerea*, located near Corvallis, Benton Co., Oregon, but there has not been any substantial damage to the accessions at this repository (SJS, unpublished).

Forestry/Wildland Impacts

Surveys of the impact of WTB in forested terrain have been carried out primarily in native walnut stands in the southwestern United States. Although the beetle was largely unrecognized historically as a pest in this region, Graves et al. (2011) examined national forest lands in Arizona, southern California, and New Mexico, and found instances of dead walnut trees with evidence of WTB galleries on six national forests. Of 194 *J. major* surveyed in Arizona and New Mexico, 6.7 percent were dead and showed evidence of WTB, whereas of 139 *J. californica* surveyed in southern California, approximately 5 percent were dead and showed evidence of WTB. Crown condition in both regions was worse when WTB had been present feeding and reproducing on the trees, which could be interpreted as symptoms of dieback occurring in association with the beetle. In Arizona/New Mexico survey plots, approximately 50 percent of the trees had evidence of WTB, whereas in California survey plots, approximately 30 percent of the trees had this evidence (Graves et al. 2011, ADG, unpublished data). Southwestern riparian habitats are critical, and *Juglans* is a significant component of the peri-riparian zone that Szaro (1989) described as an oasis that is singularly rich in bird and animal species. In Arizona and New Mexico, there are at least two community types associated with *J. major*: (1) the *J. major* type and 2) the *J. major–Platanus wrightii* type. Eastern New Mexico also hosts a *J. microcarpa* (little or Texas walnut) community type, but WTB appears to have not invaded this host and habitat (Graves et al. 2011, Seybold et al. 2016b). Field assays at the primary

Figure 7. Damage by walnut twig beetle, *Pityophthorus juglandis*, to southern California black walnut, *Juglans californica*, in the USDA ARS National Clonal Germplasm Repository, Winters, Solano Co., California. Depicted are rows of accessions of dead and dying trees (A,B) that were approximately 30 years old at the time that they were photographed. Burn pile (C) of dead *J. californica* accessions removed from collection with *P. juglandis* galleries etched on main stem xylem (D) and collection accession tag next to dead tree stem (E). (Photo credit: SMH, all photos taken on June 26, 2016.)

Juglans germplasm repository (northern California) suggest that WTB lands at a relatively low rate on branches of *J. microcarpa* (excised branch sections or on live trees) (Hishinuma 2017), and laboratory assays indicate that *J. microcarpa* was among the least suitable of reproductive hosts for WTB (Hefty et al. 2018).

Surveys of infection rates suggest that WTB/TCD is potentially damaging to California's two endemic walnut species, *J. californica* and *J. hindsii* (Hishinuma 2017), both of which have limited native distributions (Griffin and Critchfield 1972). Cumulative TCD-associated mortality between 2010/2011 and 2014 in native stands of *J. californica* (Los Angeles Co.) and *J. hindsii* (Butte Co.) was approximately 10 percent for each species type by the end of the survey (Hishinuma 2017). *Juglans hindsii* is the primary black walnut species used currently in Paradox rootstocks in the California edible walnut industry, but *J. californica* has also been an important genetic component in certain commercial rootstocks. The native populations of these two species are dwindling because of hybridization with orchard cultivars; decline of riparian woodland habitat as a consequence of urban and rural development (Katibah 1984, Jones and Stokes Associates 1987); and expansion of agriculture. They are considered "fairly endangered" to "seriously endangered," respectively (California Native Plants Society, Rare Plant Program 2018). Various species of squirrels feed on *J. californica* fruit, and 29 species of diurnal birds and many other vertebrates and invertebrates use these southern California woodlands as habitat (Horton 1949, Quinn 1990).

The impact of WTB on *J. nigra* in wild riparian forests of *J. nigra* in Tennessee and Virginia has not been quantified. This is a surprising deficiency in knowledge given that the estimated value of *J. nigra* timber growing stock in the eastern United States is over \$500 billion (Newton et al. 2009) with 12 million cubic feet (approximately 340,000 m^3) harvested annually. The export value of walnut wood products is estimated at \$325 million annually. This native walnut species is also valued somewhat for edible nut production (17 metric tons annually), which is based largely on the gathering of wild nuts. Laboratory assays have confirmed that *J. nigra* is a highly susceptible host for both WTB (Hefty et al. 2016, 2018) and *G. morbida* (Utley et al. 2013). Given the enormous values at risk to *J. nigra* plantations and wild forests, a firmer estimate of the "Sword of Damocles" represented by WTB in its invaded eastern range appears to be in order. Similarly, quantitative evidence for the impact of WTB on plantations of *J. nigra* in Italy has not been assessed or reported (Faccoli et al. 2016; Montecchio et al. 2016; Moricca et al. 2018).

In addition to costs associated with WTB and *G. morbida* detection programs (USDA Forest Service and Plant Protection and Quarantine 2018), intra- and interstate quarantines (Moltzan 2011); international quarantines (Robertson 2014), and risk assessment (Newton et al. 2009, European Plant Protection Organization 2015), the threat of introduction and presence of WTB have impacted wood-handling procedures (Audley et al. 2016a, b, Mayfield et al. 2014, 2018a) and the movement of nursery stock (Audley et al. 2017a). Kiln drying of barked wood is costly, but it is effective in killing all WTB present in wood at the time of treatment and is likely to preclude successful reproduction by subsequent generations of WTB. It appears, though, that in rare cases, WTB adults may try to colonize relatively dry, barked, raw wood products (without reproduction) and therefore could be shipped to uninfested areas (Audley et al. 2016a, Mayfield et al. 2018a). Steam heat (Chen et al. 2017) and fumigation with methyl bromide (Audley et al. 2017b) are also effective in killing WTB in infested, barked wood, but under the influence of aggregation pheromone, WTB adults may colonize logs post treatment (Audley et al. 2016a), so phytosanitized barked wood products could still serve as a pathway for introduction if WTB are given access to the treated materials prior to shipment. Both raw, barked walnut wood and burls sought for woodworking and smaller-dimensional barked wood pieces destined for firewood have been identified in the United States (Newton et al. 2009) and Europe (European Plant Protection Organization 2015) as potential pathways for spread of WTB. Firewood was estimated to have a low to moderate "approach rate" from the western into the eastern United States (Newton et al. 2009), and wood with bark (which includes firewood) was estimated to be a pathway with a "very high" likelihood of WTB entry to European Plant Protection Organization countries from Mexico and the USA (European Plant Protection Organization 2015). In California, freshly cut English walnut firewood was cleared of emerging adult WTB within 4–7 months of confinement and drying in an emergence cage (Fichtner et al. 2014).

Conclusions and the Future

WTB is one of a few invasive bark beetles in North America where expanding distribution and impact have been pronounced enough to affect other species, communities, and ecosystems to the extent that services provided by urban forests, agroecosystems, and wildland areas have been altered. Similarly invasive bark/ambrosia beetles of this stature include shot hole borer, *Scolytus rugulosus*; European elm bark beetle, *Scolytus multistriatus*; polyphagous shot hole borer, *Euwallacea* sp.; fruit-tree pinhole borer, *Xyleborinus saxeseni*; and red bay ambrosia beetle, *Xyleborus glabratus*. However, WTB is unique among these invaders because the multifaceted uses, ecological roles, and high timber and food value of its host (*Juglans*) make this a model in which to study the impact of a bark beetle on forest and agroecosystem services (Boyd et al. 2013). Host colonization by WTB can be equated with infection by *G. morbida* and development of TCD for *Juglans* and *Pterocarya* spp. As this pest complex moves eastward in North America and into Eurasia, we can anticipate declines to occur throughout the native ranges of these tree species, as well as in urban and orchard landscapes. We envision that ecological impacts of WTB will continue to unfold across a wider geographic area to affect various types of key services, i.e., provisioning (e.g., timber and nontimber products); regulating (e.g., air and water quality/quantity, climate regulation); and cultural (e.g., recreation, aesthetics, shade) services (Charles and Dukes 2008, Pejchar and Mooney 2009, Mayfield et al. 2018b). We will be challenged to standardize our assessment procedures and quantify these effects in the future.

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