Journal of Economic Entomology, 110(3), 2017, 1096–1106
doi: 10.1093/jee/tox092
Advance Access Publication Date: 30 March 2017
Research article

Optimizing Use of Girdled Ash Trees for Management of Low-Density Emerald Ash Borer (Coleoptera: Buprestidae) Populations

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Subject Editor: Timothy Schowalter

Received 30 December 2016; Editorial decision 23 February 2017

Abstract

Effective survey methods to detect and monitor recently established, low-density infestations of emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), remain a high priority because they provide land managers and property owners with time to implement tactics to slow emerald ash borer population growth and the progression of ash mortality. We evaluated options for using girdled ash (*Fraxinus* spp.) trees for emerald ash borer detection and management in a low-density infestation in a forested area with abundant green ash (*F. pennsylvanica*). Across replicated 4-ha plots, we compared detection efficiency of 4 versus 16 evenly distributed girdled ash trees and between clusters of 3 versus 12 girdled trees. We also examined within-tree larval distribution in 208 girdled and nongirdled trees and assessed adult emerald ash borer emergence from detection trees felled 11 mo after girdling and left on site. Overall, current-year larvae were present in 85–97% of girdled trees and 57–72% of nongirdled trees, and larval density was 2–5 times greater on girdled than nongirdled trees. Low-density emerald ash borer infestations were readily detected with four girdled trees per 4-ha, and 3-tree clusters were as effective as 12-tree clusters. Larval densities were greatest 0.5 ± 0.4 m below the base of the canopy in girdled trees and 1.3 ± 0.7 m above the canopy base in nongirdled trees. Relatively few adult emerald ash borer emerged from trees felled 11 mo after girdling and left on site through the following summer, suggesting removal or destruction of girdled ash trees may be unnecessary. This could potentially reduce survey costs, particularly in forested areas with poor accessibility.

Key words: *Agrilus planipennis*, detection tree, *Fraxinus*, girdled tree, invasive forest pest management

Emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), an invasive phloem-feeding pest native to Asia, threatens ash (*Fraxinus* spp.) in forests, urban, and residential areas across much of North America. First identified in 2002 in Detroit, MI, and Windsor, ON (Cappaert et al. 2005, Herms and McCullough 2014), populations of emerald ash borer have since been found in at least 29 other states and Quebec, Canada (EAB.info 2016). Ash trees in landscapes can now be effectively protected with systemic insecticides (Smitley et al. 2010, McCullough et al. 2011a, Herms et al. 2014), but hundreds of millions of ash in forests and rural areas have been killed (Knight et al. 2013, Burr and McCullough 2014, Klooster et al. 2014, EAB.info 2016). Early detection of recently established populations is a key aspect of emerald ash borer management and remains a priority for arborists, foresters, and landowners, as well as regulatory officials. Early detection provides time for managers to acquire resources and implement tactics to protect valuable landscape ash trees, reduce emerald ash borer population growth, and slow the progression of ash mortality (McCullough and Mercader 2012, McCullough et al. 2015, Mercader et al. 2016).

Identifying new emerald ash borer infestations or trees with low densities of emerald ash borer larvae, however, remains challenging. External symptoms of infestation such as D-shaped exit holes left by emerged adult beetles, larger holes left by woodpeckers preying on late instar larvae, bark cracks, and canopy decline (Cappaert et al. 2005, EAB.info 2016) are rarely apparent until larval densities have increased to at least moderate levels (Anulewicz et al. 2007, Poland et al. 2011). Currently, most operational emerald ash borer detection surveys rely on baited artificial traps that incorporate visual

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and olfactory cues to attract adult beetles (Crook et al. 2009, Crook and Mastro 2010, Poland et al. 2011, Herms and McCullough 2014, Ryall 2015). Trap designs used in the United States or Canada include purple or green coroplast prisms or green funnel traps hung in the canopy of ash trees and baited with volatile compound(s) emitted by ash trees (Francese et al. 2005, 2010; de Groot et al. 2008; Crook et al. 2014). Adult emerald ash borer do not produce long-range sex or aggregation pheromones (Rodriguez-Saona et al. 2006, Lelito et al. 2007, Crook and Mastro 2010), although a short-range mating pheromone has been used in some detection surveys (Silk et al. 2011, Ryall et al. 2015). Free-standing double-decker traps are baited with the same lures as canopy traps but incorporate two purple prisms or one green and one purple prism attached to a 2.4-m-tall polyvinyl chloride (PVC) pipe (McCullough and Poland 2009, Poland et al. 2011, Poland and McCullough 2014). In contrast to prism or funnel traps hung in ash canopies, double-decker traps are placed in full sun, 5–10 m from ash trees, to provide beetles with a highly apparent visual cue and a distinct point source of volatiles (McCullough et al. 2011b, Poland et al. 2011, Poland and McCullough 2014). Colonies of buprestid-hunting *Cerceris fumipennis* (Say) wasps (Hymenoptera: Cabronidae) have occasionally been monitored as a means to detect emerald ash borer presence (Marshall et al. 2005, Rutledge et al. 2013, Careless et al. 2014).

Girdling and subsequently debarking ash trees, however, remains the most effective option for emerald ash borer detection (McCullough et al. 2011b, Mercader et al. 2013). Adult emerald ash borer are attracted to volatiles produced by stressed ash trees (Rodriguez-Saona et al. 2006, Crook et al. 2008, de Groot et al. 2008, Grant et al. 2010, Poland et al. 2011), and female beetles preferentially oviposit on stressed ash (McCullough et al. 2009a,b). Larval densities on ash trees stressed by girdling (i.e., removing a ≥15–20-cm-wide band of outer bark and phloem from the circumference of the trunk), can be 3–10 times higher than densities on adjacent or nearby healthy ash trees (McCullough et al. 2009a,b; Tluczek et al. 2011; Mercader et al. 2011). In a large-scale field study, girdled ash trees and three different artificial trap designs baited with host volatiles were established systematically across a 16-ha area with a low-density of emerald ash borer (McCullough et al. 2011b). At least one emerald ash borer beetle was captured on 25% of the purple canopy traps, 56% of double-decker traps with two green prisms, and 81% of double-decker traps with two purple prisms. When ash trees were debarked in fall, however, current-year emerald ash borer larvae were present in 100% of the girdled trees compared to 72% of nongirdled trees, and at densities that were five times greater in girdled than in nongirdled trees (McCullough et al. 2011b). Similarly, in a multiyear project spanning an extensive area in northern Michigan, girdled trees were substantially more likely to detect emerald ash borer than baited purple prism traps suspended in ash trees, particularly at low emerald ash borer densities (Mercader et al. 2013). For example, in a very low-density emerald ash borer population, the probability of emerald ash borer detection with a girdled tree was 80% compared to only 15% for a baited purple canopy trap. Girdling adjacent trees or a cluster of trees would presumably increase the amount and concentration of the volatile compounds that attract emerald ash borer adults, perhaps enhancing attraction of emerald ash borer (McCullough et al. 2015).

In four field studies presented here, we examined key aspects of using girdled ash trees operationally to detect or manage low-density emerald ash borer infestations in forested areas. In the first study, we evaluated the detection efficiency of a low density of girdled trees (4 trees per 4 ha) versus a higher density of girdled trees (16 trees per 4 ha). In the second study, we examined emerald ash borer attraction to clusters of 3 girdled trees versus 12 girdled trees. Girdled tree clusters could potentially be used for detection or as trap trees (e.g., population sinks) to slow emerald ash borer population growth and, correspondingly, ash mortality (McCullough et al. 2015, Mercader et al. 2015). In the third study, we evaluated within-tree distribution of emerald ash borer larvae in girdled and nongirdled ash trees to identify optimal sections to debark to locate larvae in locations with light to moderate infestations. In the fourth study, we assessed the risk of emerald ash borer adult emergence from trees girdled in spring then felled approximately a year later and left on site through a following summer. This may be particularly important to land managers in situations where removing and destroying girdled ash trees used operationally as detection or management tools (e.g., population sinks) is not feasible due to associated costs and accessibility issues.

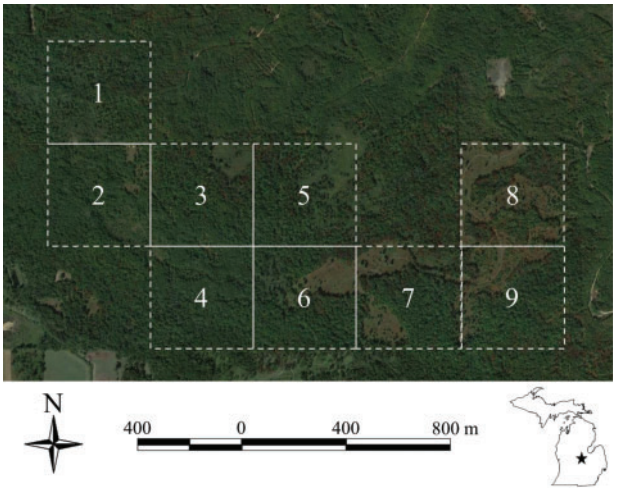

Fig. 1. The study site on the Au Sable State Forest in Jasper Twp., Midland Co., MI, indicated by the star in the Michigan outline, encompassed nine 16-ha (400 by 400 m) blocks with abundant overstory green ash (*F. pennsylvanica*). Baseline surveys to inventory ash and estimate emerald ash borer density were conducted in March–April 2007 and January–March 2008. Trees in Blocks 4, 6, 7, and 9 were used for Study 1 (Girdled Tree Density) in 2008–2009; trees in Blocks 1, 2, 4, 6, 7, and 9 were used for Study 2 (Girdled Tree Clusters) in 2009–2010 and for Study 3 (Within-Tree Emerald Ash Borer Distribution) in 2008–2010; and trees in Blocks 1, 2, 6, 7, and 9 were used for Study 4 (Emerald Ash Borer Emergence) in 2009–2010. Trees in remaining blocks (3, 5, and 8) were not used in this research.

Materials and Methods

Study Area and Ash Inventory

Studies were conducted from 2007 to 2010 in the Au Sable State Forest in Jasper Township, Midland County, MI [43.534° N, 84.552° W] (Fig. 1) in a 144-ha site with abundant overstory green ash (*Fraxinus pennsylvanica* Marsh.). We delineated nine 16-ha (400 by 400 m) contiguous blocks (Fig. 1), then partitioned each block into an 8 by 8 grid consisting of 64 geo-referenced cells, each 50 by 50 m (0.25 ha). In each block, we tallied all live ash trees >2.5 cm in diameter at breast height (dbh; 1.3 m aboveground) by size class (Table 1). Blocks 1 and 2 were inventoried from March to April 2007, while the remaining seven blocks were inventoried from January to March 2008. We estimated total area of ash phloem (m^2) for all ash trees in each block using dbh and following methods described in McCullough and Siegert (2007).

Table 1. Number of ash stems and estimated ash phloem surface area (m^2) by ash diameter class per 16-ha (400 by 400 m) block in Jasper Township, Midland County, MI

Block		Ash diameter class (dbh)					All size classes combined
		2.5–13 cm (1–5 in)	14–25 cm (6–10 in)	26–42 cm (11–17 in)	43–60 cm (18–23 in)	>60 cm (>23 in)	
1	No. trees (*n*)[a]	3,267	974	231	19	3	4,494
	Sum of phloem area (m^2)[b]	2,133	5,349	5,096	983	261	13,822
2	No. trees (*n*)[a]	3,847	551	34	1	0	4,433
	Sum of phloem area (m^2)[b]	2,512	3,026	750	52	0	6,340
3	No. trees (*n*)	3,950	707	269	24	0	4,950
	Sum of phloem area (m^2)[b]	2,580	3,882	5,935	1,241	0	13,638
4	No. trees (*n*)	6,537	595	93	9	4	7,238
	Sum of phloem area (m^2)[b]	4,269	3,267	2,052	465	348	10,401
5	No. trees (*n*)	5,837	1,154	330	40	4	7,365
	Sum of phloem area (m^2)[b]	3,812	6,337	7,280	2,069	348	19,846
6	No. trees (*n*)	4,226	619	245	27	2	5,119
	Sum of phloem area (m^2)[b]	2,760	3,399	5,405	1,396	174	13,134
7	No. trees (*n*)	1,256	641	254	27	0	2,178
	Sum of phloem area (m^2)[b]	820	3,520	5,604	1,396	0	11,340
8	No. trees (*n*)	1,192	265	169	27	3	1,648
	Sum of phloem area (m^2)[b]	778	1,455	3,728	1,396	261	7,322
9	No. trees (*n*)	2,611	612	254	38	6	3,521
	Sum of phloem area (m^2)[b]	1,705	3,361	5,604	1,965	522	13,157
Overall	No. trees (*n*)	32,723	6,118	1,879	212	22	40,946
	Sum of phloem area (m^2)[b]	21,369	33,596	41,453	10,964	1,915	109,000

[a]Ash was inventoried in Blocks 1–2 in March–April 2007; Blocks 3–9 were inventoried in January–March 2008.
[b]Phloem area of trees was estimated using methods developed by McCullough and Siegert (2007).

Baseline Emerald Ash Borer Density

Although low-density emerald ash borer populations were thought to be present in the vicinity of our study site, we observed no declining ash trees nor any signs or symptoms of emerald ash borer infestation in 2007 or 2008. To assess presence and estimate baseline densities of emerald ash borer larvae, we systematically selected, felled, and sampled a total of 250 ash trees across the nine blocks (Table 2), concurrently with the ash inventories. Thus, trees in Blocks 1 and 2 were sampled from March to April 2007, while trees in the remaining blocks were sampled from January to March 2008.

Sampling consisted of felling one or two ash trees per 1.0 ha (e.g., 2 by 2 grid of 50 by 50 m cells) throughout the nine 16-ha blocks, excluding cells where no ash occurred (Table 2). Size of felled trees ranged from 6.4 to 48.0 cm dbh and average (±SE) dbh within blocks ranged from 17.4 ± 1.5 cm to 23.1 ± 1.6 cm (Table 2). We delineated and closely examined three to four (depending on tree size) evenly spaced areas, each ~30 by 100 cm, between the mid-trunk and the upper canopy (>4 cm in diameter) on each felled tree. On the 250 trees we sampled to assess baseline emerald ash borer density, we debarked a total of 295.5 m^2 of phloem area and exposed an average (± SE) of 1.1 ± 0.1 m^2 per tree (Table 2). Number of distinctive D-shaped holes left by emerging emerald ash borer adults and holes from woodpeckers preying on emerald ash borer larvae (Cappaert et al. 2005, Lindell et al. 2008) were counted. Each area was then carefully debarked, measured, and the number and stage of emerald ash borer larvae were recorded. Larval density was standardized per m^2 of exposed phloem area for each tree.

Study 1—Girdled Tree Density

In late April 2008, we subdivided four of the 16-ha blocks (Blocks 4, 6, 7, and 9; Fig.1) into four contiguous 4-ha plots (each 200 by 200 m). In two randomly selected plots in each of the four blocks, we girdled either four ash trees (low-density) or 16 ash trees (high-density; Fig. 2a). Trees were girdled using drawknives to remove the outer bark and phloem from a 50–70-cm-wide band around the circumference of the trunk, roughly 1 m aboveground. An equivalent number of nongirdled ash trees were selected in the other two 4-ha plots in each block. Girdled and nongirdled trees were similar in size (Table 3) and approximately equidistantly spaced within plots. Selected trees were spaced at about 100 by 100 m in low-density plots and 50 by 50 m in high-density plots (Fig. 2a). Occasionally fewer than 16 trees were selected in high-density plots (treatment or control) if suitable ash trees were not present in the vicinity.

From late January to early April 2009, the 76 girdled and 76 nongirdled trees were felled, limbed, and the trunk and large branches (down to ≈ 6 cm diam.) were sectioned into 1-m-long bolts ($n = 152$ total trees). We debarked, measured, and recorded the number and stage of larvae on alternate bolts from each tree, beginning 2 m above the ground (to avoid the girdled area) and continuing along the main stem until the diameter was ≈ 6 cm (1,174 total sections). Overall, we debarked an average of 3.6 ± 0.1 m^2 of phloem area per tree, exposing a total of 552.9 m^2 of phloem on the felled trees (Table 3). Larval density was standardized per m^2 of exposed area for each tree. Data from plots were analyzed using two sample *t*-tests (pooled variance, Bonferroni adjusted probability) conducted with SYSTAT analytical software (Systat Software, Inc. 2009) at $P < 0.05$ level of significance to assess differences in larval densities between treatments (low-density versus high-density) and between girdled and nongirdled trees.

Study 2—Girdled Tree Clusters

In late April 2009, we established 3-tree and 12-tree clusters of girdled ash trees in six of the 16-ha blocks (Blocks 1, 2, 4, 6, 7, and 9; Fig. 1). As in Study 1, each 16-ha block was subdivided into four

Table 2. Summary of baseline surveys to assess emerald ash borer larval density, including number of trees sampled, mean (±SE) diameter at breast height (dbh) of sampled trees, mean and total area of phloem exposed on sampled trees, percentage of sampled trees that were infested, and density of emerald ash borer larvae (m^{-2}) in each of the 16-ha (400 by 400 m) blocks in Jasper Township, Midland County, MI

Block	No. trees	Mean (±SE) dbh (cm)	Mean (±SE) phloem area (m^2)	Total phloem area (m^2)	Infested trees (%)	Larval density (m^{-2})
1[a]	16	20.8 ± 1.6	0.5 ± 0.04	7.5	0	0
2[a]	13	17.4 ± 1.5	0.5 ± 0.05	6.5	15.4	1.9 ± 1.5
3	36	21.4 ± 1.8	1.2 ± 0.07	44.9	61.1	3.9 ± 1.3
4	29	17.4 ± 1.5	1.3 ± 0.06	37.6	17.2	0.5 ± 0.2
5	60	21.3 ± 1.1	1.1 ± 0.02	68.6	31.7	1.3 ± 0.4
6	28	22.4 ± 1.4	1.3 ± 0.03	37.5	21.4	0.7 ± 0.3
7	27	23.1 ± 1.6	1.4 ± 0.04	37.3	7.4	0.05 ± 0.04
8	18	23.0 ± 1.8	1.2 ± 0.04	21.6	5.6	0.08 ± 0.08
9	23	21.2 ± 1.7	1.5 ± 0.06	34.0	34.8	1.0 ± 0.4
Overall	250	20.9 ± 0.7	1.1 ± 0.1	295.5	21.6 ± 6.3	1.0 ± 0.4

[a]Baseline emerald ash borer density was sampled in Blocks 1–2 in March–April 2007 and in Blocks 3–9 in January–March 2008.

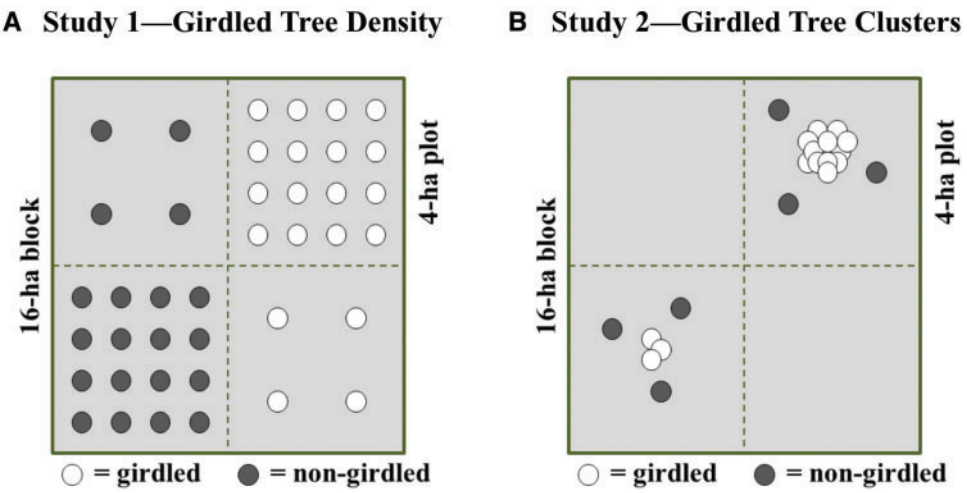

Fig. 2. Diagrams of the basic plot layout at each 16-ha block used for (**a**) Study 1 (Girdled Tree Density) and (**b**) Study 2 (Girdled Tree Clusters). Study 1 compared detection efficiency of 4 versus 16 girdled trees per block in low-density emerald ash borer populations. Approximately equidistantly spaced girdled trees and nongirdled trees were established in randomly selected plots. Study 2 evaluated 3-tree and 12-tree clusters of girdled trees for emerald ash borer detection. Clusters were established in two randomly selected plots in each block. Three nongirdled control trees were located ~25 m around the perimeter of each cluster.

Table 3. Summary of the number of girdled and nongirdled ash trees sampled, mean (±SE) diameter at breast height (dbh) of sampled trees, mean (±SE) phloem area sampled per tree, and total area of phloem exposed on sampled trees in each study

Study	Treatment	Girdled trees				Nongirdled trees			
		No. trees	Mean (±SE) dbh (cm)	Mean (±SE) phloem area (m^2)	Total phloem area (m^2)	No. trees	Mean (±SE) dbh (cm)	Mean (±SE) phloem area (m^2)	Total phloem area (m^2)
Study 1	4 trees per 4 ha	16	23.2 ± 1.6	4.1 ± 0.4	65.2	16	23.0 ± 1.8	4.3 ± 0.5	69.0
	16 trees per 4 ha	60	21.2 ± 0.8	3.3 ± 0.2	195.4	60	21.6 ± 1.1	3.7 ± 0.3	223.4
Study 2	3-tree clusters	18	22.6 ± 1.7	3.8 ± 0.5	68.6	18	22.8 ± 1.6	4.0 ± 0.4	71.6
	12-tree clusters	18	22.5 ± 1.6	3.5 ± 0.3	63.9	18	22.9 ± 1.6	3.9 ± 0.4	69.9
Study 3	Emerald ash borer-infested trees only	119	22.0 ± 0.6	3.5 ± 0.1	412.0	89	24.9 ± 0.8	4.4 ± 0.2	392.1
Study 4	Bucked trees	15	24.6 ± 1.4	3.4 ± 0.4	50.9	na	na	na	na
	Intact trees	15	22.0 ± 1.4	2.7 ± 0.3	40.3	na	na	na	na

contiguous 4-ha plots. In one randomly selected plot, we girdled three ash trees in an area encompassing ≈ 60 m^2. In a second randomly selected plot, we girdled 12 ash trees in an area encompassing ≈ 360 m^2 (Fig. 2b). We selected three nongirdled ash trees to serve as controls in each plot; these trees were distributed around the perimeter of each cluster of girdled trees, ~25 m from any girdled tree (Fig. 2b). Girdled and nongirdled trees were similar in size (Table 3).

From late January to early March 2010, we felled, debarked, measured, and estimated emerald ash borer larval density in three

girdled trees from each cluster and in the three nongirdled trees around the perimeter of each cluster, using the previously described methods of Study 1. All girdled trees in the 3-tree clusters were sampled, while we randomly selected three girdled trees from each 12-tree cluster ($n = 72$ total trees; 559 sections sampled, each 1 m in length). Overall, we debarked an average of 3.8 ± 0.2 m^2 of phloem per tree, exposing a total of 274.0 m^2 of phloem from 36 girdled and 36 nongirdled ash trees (Table 3). Data from plots were analyzed to assess differences in larval densities between 3-tree and 12-tree clusters and between girdled and nongirdled trees overall using two sample *t*-tests (pooled variance, Bonferroni adjusted probability) conducted with SYSTAT analytical software (Systat Software, Inc. 2009) at the $P < 0.05$ level of significance.

Study 3—Within-Tree Distribution of Emerald Ash Borer Larvae

We used emerald ash borer data collected from the debarked bolts from the girdled and nongirdled trees sampled for Study 1 and Study 2 (Blocks 1, 2, 4, 6, 7, and 9; Fig. 1) to evaluate within-tree distribution of emerald ash borer larvae ($n = 208$ infested trees; 1683 sections). Girdled trees ($n = 119$ trees) and nongirdled trees ($n = 89$ trees) used for this analysis averaged (±SE) 22.0 ± 0.6 cm and 24.9 ± 0.8 cm dbh, respectively (range: 6.0–33.8 cm dbh for girdled trees; 6.4–39.7 cm dbh for nongirdled trees; Table 3). We calculated larval density on each section and determined the height of the 1-m section with the greatest larval density on each tree. Overall, we debarked an average of 3.9 ± 0.1 m^2 of phloem per tree, exposing a total of 804.1 m^2 of phloem area on the 208 trees with light to moderate infestations (Table 3).

We also assessed the position of the section with the greatest larval density relative to tree size and architecture. In other words, the relative position of a section could be more informative than simply the height of the section, especially given variation in tree size. For instance, a section 7 m above ground would be located in the upper portion of a 9-m-tall tree (relative position = 0.78), but would be in the lower portion of a 25-m-tall tree (relative position = 0.28). We additionally recorded bark texture of each section and distance of the section to the base of the canopy (i.e., lowest prominent branch) of each tree for the trees selected from Blocks 4, 6, 7, and 9 (72 infested girdled trees; 42 infested nongirdled trees). We grouped the infested trees into four classes: <17, 17–23.5, 23.5–26.1, >26.1 cm dbh for girdled trees and <19, 19–26, 26–29, >29 cm dbh for nongirdled trees. Similarly, we identified four categories of emerald ash borer infestation levels: <5.5, 5.5–12.5, 12.5–20.5, and >20.5 emerald ash borer larvae per m^2 for girdled trees and <0.9, 0.9–2.5, 2.5–8.5, and >8.5 emerald ash borer larvae per m^2 for nongirdled trees. Height above ground and distance from the base of the canopy of the section with the greatest emerald ash borer larval density were compared among tree diameter classes and emerald ash borer infestation levels by ANOVA. When results of the ANOVA were significant, Fisher's protected least significant difference (LSD) test was used to identify differences among the categories. All analyses were conducted at the $P < 0.05$ level of significance with SYSTAT analytical software (Systat Software, Inc. 2009).

Study 4—Adult Emerald Ash Borer Emergence From Girdled Trees

For this study, we revisited five blocks (Blocks 1, 2, 6, 7, and 9; Fig. 1) where we had established clusters of 12 girdled trees in April 2009 for Study 2. Between late January and early March 2010, three of the 12 girdled trees in each block were felled, limbed, and sectioned into 1-m-long bolts, then alternate bolts from those trees were debarked, as described previously for Studies 2 and 3. We debarked an average of 3.8 ± 0.4 m^2 of phloem per tree, exposing a total of 57.5 m^2 of phloem on the alternate 1-m sections from the bucked (e.g., cut into 1-m sections) trees to determine emerald ash borer densities. The remaining bolts with bark from these trees were used for this study ($n = 15$ trees with cut bolts; Table 3). In addition to the cut bolts from the bucked trees, we randomly selected three of the nine remaining girdled trees in each cluster. These trees were felled in mid-March 2010, but left whole (i.e., not limbed or cut into bolts; Table 3). We delineated 1-m-long sections on the whole trees ($n = 15$ trees left intact), beginning at 3 m above ground (to match sections on our trees with cut bolts) and continuing along the main stem until the diameter was ≈ 6 cm.

We intensively examined the outer bark on the cut bolts (left from Study 2) and on the delineated sections of the intact trees to identify adult emerald ash borer exit holes or larger holes left by woodpeckers preying on emerald ash borer larvae ($n = 30$ trees total). Cut bolts were carefully rolled over to examine all sides. On the intact trees, the trunk and lower canopy were usually left suspended 1–2 m off the ground by supporting limbs and, if not, we positioned the base of the trunk on the stump so all sides could likewise be examined. Overall, we inspected an average of 3.0 ± 0.2 m^2 of surface area per tree, examining a total of 91.2 m^2 of surface area on the logs from the bucked trees and the marked sections of the intact trees (Table 3). All emerald ash borer exit holes and woodpecker holes were marked with staples ($n = 195$ sections examined and marked; 105 on bolts, 90 on intact trees). After the visual inspections were completed, the 1-m-long bolts were carefully repositioned on the ground, in sequential order as they were originally cut.

In September 2010, roughly six weeks after adult emerald ash borer activity ceased, the bolts and the delineated sections on the intact trees were re-examined and new emerald ash borer exit holes and woodpecker holes were identified. We assessed differences in densities of the new emerald ash borer exit holes and woodpecker holes between trees with cut bolts and trees left intact with two sample *t*-tests (pooled variance, Bonferroni adjusted probability). Simple linear regression was applied to examine whether density of emerald ash borer prepupal larvae or total emerald ash borer density affected the density of new exit holes or woodpecker holes. Analyses were conducted using SYSTAT analytical software (Systat Software, Inc. 2009) at the $P < 0.05$ level of significance.

Results

Ash Inventory and Baseline Emerald Ash Borer Density

Overall, the number of ash stems (>2.5 cm dbh) tallied in our Jasper study site averaged (±SE) 4,550 ± 654 per 16-ha block and the total area of ash phloem available for emerald ash borer colonization averaged 12,111 ± 1,328 m^2 per block (Table 1). Across all blocks, on average, only $21.6 \pm 6.3\%$ of the sampled trees had been colonized by emerald ash borer and baseline emerald ash borer densities were extremely low, averaging only 1.0 ± 0.4 larvae per m^2 (Table 2).

Baseline emerald ash borer densities collected in 2007 and 2008 were consistent among the blocks used in the four studies presented here (Table 2). In the four blocks used for Study 1, we found 20.2% of the sampled trees were colonized by emerald ash borer and baseline densities averaged (±SE) 0.6 ± 0.2 larvae per m^2. In the six blocks used for Study 2 and Study 3, 16.0% of the trees were colonized and baseline densities averaged 0.7 ± 0.3 emerald ash borer larvae per m^2. In the five blocks used for Study 4, we found 15.8%

of the trees were colonized, with average baseline densities of 0.7 ± 0.3 larvae per m^2.

Study 1—Girdled Tree Density

Establishing four girdled trees per 4 ha was as effective at detecting emerald ash borer as girdling 16 trees per 4 ha (Fig. 3a), even in these forested areas where ash was abundant and widely distributed. Larval densities in girdled trees did not differ between treatments ($t = -0.832$; df = 6; $P = 0.438$). Similarly, larval emerald ash borer densities in nongirdled trees did not significantly differ between plots with four girdled trees and 16 girdled trees ($t = -0.941$; df = 6; $P = 0.383$). As expected, however, girdled ash trees were attacked more frequently and colonized at higher densities by emerald ash borer than the surrounding nongirdled trees in all plots (Fig. 3a), regardless of the number of girdled trees. In plots with a low density of girdled trees, emerald ash borer colonized $87.5 \pm 7.2\%$ of girdled trees compared to $56.3 \pm 6.3\%$ of nongirdled trees. Girdled trees in these plots averaged ($\pm$ SE) 10.7 ± 2.9 larvae per m^2 while nongirdled trees in the control plots averaged 1.3 ± 0.9 larvae per m^2 (Fig. 3a). Similarly, in plots with a high density of girdled trees, emerald ash borer colonized $96.7 \pm 1.9\%$ of girdled trees but only $57.8 \pm 15.0\%$ of the nongirdled trees. Density of emerald ash borer averaged 13.8 ± 2.3 larvae per m^2 and 3.4 ± 2.0 larvae per m^2 on girdled and nongirdled trees, respectively, in the high-density plots (Fig. 3a).

Overall, a greater percentage of girdled trees were colonized by emerald ash borer ($t = 4.154$; df = 14; $P = 0.001$) and girdled trees had significantly greater densities of emerald ash borer larvae compared to nongirdled trees ($t = 4.679$; df = 14; $P < 0.0001$). When data were pooled across all plots, emerald ash borer colonized $92.1 \pm 3.9\%$ of girdled trees and $57.0 \pm 7.5\%$ of nongirdled trees. Larval densities averaged ($\pm$SE) 12.2 ± 1.8 and 2.4 ± 1.1 per m^2 on girdled and nongirdled trees, respectively.

Study 2—Girdled Tree Clusters

Clusters of three girdled ash trees were as effective at detecting low densities of emerald ash borer as clusters of 12 girdled ash trees (Fig. 3b). Densities of emerald ash borer larvae did not differ significantly between 3-tree and 12-tree clusters for either girdled trees ($t = -0.417$; df = 10; $P = 0.686$) or nongirdled trees ($t = 0.143$; df = 10; $P = 0.889$). Girdled trees, however, in either 3-tree or 12-tree clusters, were colonized more frequently and at marginally higher densities than nongirdled trees. In plots with 3-tree clusters, 100% of girdled trees and $77.8 \pm 11.1\%$ of nongirdled trees had larval galleries. Mean ($\pm$ SE) larval density on girdled trees in 3-tree clusters was 16.0 ± 4.6 larvae per m^2 compared to 6.1 ± 3.2 larvae per m^2 on surrounding nongirdled trees (Fig. 3b). In 12-tree clusters, larvae were present on $94.5 \pm 5.5\%$ of girdled trees but only $66.7 \pm 17.2\%$ of the nongirdled trees. In 12-tree clusters, larval densities averaged 13.0 ± 5.5 and 6.9 ± 3.9 larvae per m^2 on girdled trees and nongirdled trees, respectively (Fig. 3b).

Similarly, when data from 3-tree and 12-tree clusters were pooled, more girdled trees were colonized ($t = 2.427$; df = 22; $P = 0.024$) at marginally higher larval densities ($t = 1.907$; df = 22; $P = 0.07$) than nongirdled trees. Overall, $97.3 \pm 2.8\%$ of girdled trees were colonized by emerald ash borer compared to $72.3 \pm 9.9\%$ of nearby nongirdled trees. Mean ($\pm$ SE) larval densities averaged 14.5 ± 3.5 emerald ash borer per m^2 and 6.5 ± 2.4 emerald ash borer per m^2 on girdled and nongirdled trees, respectively.

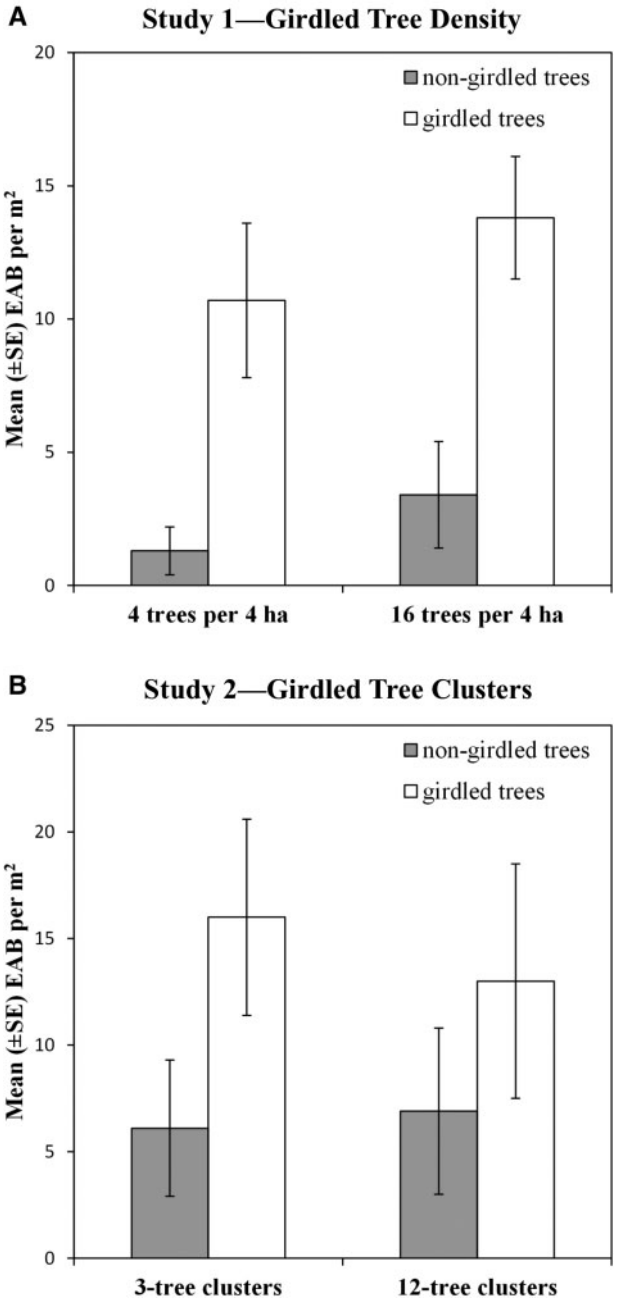

Fig. 3. Mean ($\pm$SE) number of emerald ash borer larvae per m^2 of ash phloem on girdled and nongirdled trees in 4-ha plots in (**a**) Study 1 (Girdled Tree Density) with either a low density (4 trees per plot) or high density (16 trees per plot) of girdled trees, and (**b**) Study 2 (Girdled Tree Clusters) with either 3-tree clusters or 12-tree clusters of girdled trees. There were no significant differences between 4-tree versus 16-tree density treatments in Study 1 or 3-tree clusters versus 12-tree clusters in Study 2.

Study 3—Within-Tree Distribution of Emerald Ash Borer

Heights of the 1-m section with the greatest emerald ash borer density per tree did not differ significantly among categories of emerald ash borer infestation levels for either girdled trees ($F = 1.28$; df = 3, 115; $P = 0.284$) or nongirdled trees ($F = 0.70$; df = 3, 85; $P = 0.552$). Overall, height of the 1-m-long sections with the greatest emerald ash borer density averaged 10.3 ± 0.5 m for girdled trees and 12.9 ± 0.5 m for nongirdled trees. However, heights of the sections with the greatest emerald ash borer density per tree differed

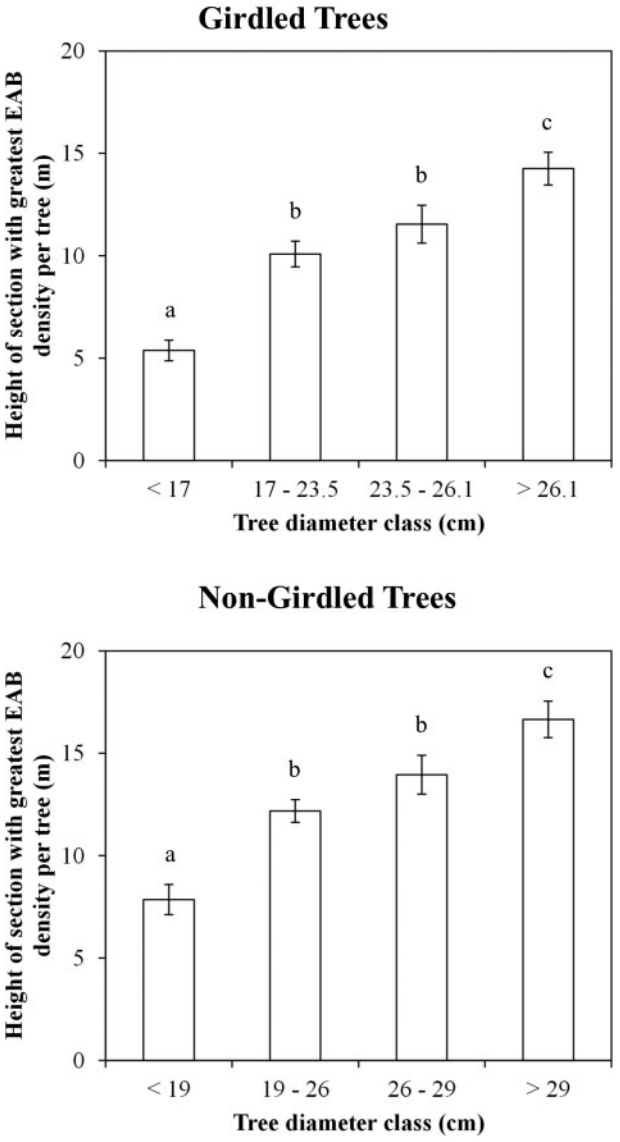

Fig. 4. Mean (± SE) height (m) of 1-m section with greatest emerald ash borer density per tree by tree diameter class (cm) for girdled and nongirdled trees. Sample sizes were similar among tree diameter classes; 29–33 trees per diameter class for girdled trees and 21–23 trees per diameter class for nongirdled trees. Different letters above the bars denote significant differences ($P < 0.05$) among tree diameter classes.

significantly among tree diameter class categories for both girdled trees ($F = 26.656$; df = 3, 115; $P < 0.001$) and nongirdled trees ($F = 20.55$; df = 3, 85; $P < 0.001$). Not surprisingly, the sections with high emerald ash borer densities were closer to the ground on small ash trees than on larger trees for both girdled and nongirdled trees (Fig. 4). Diameters of the sections with the greatest emerald ash borer density per tree averaged 10.1 cm to 14.8 cm for the girdled trees in the smallest (< 17 cm) and largest (> 26.1 cm) tree diameter classes, respectively. Similarly, diameters of the sections with the greatest emerald ash borer density per tree averaged 9.9 cm in the smallest tree diameter class (< 19 cm) and 15.0 cm in the largest tree diameter class (> 29 cm) for the nongirdled trees. After accounting for tree size, the highest larval densities occurred more frequently in the upper half rather than in the lower portions of the trees for both girdled and nongirdled trees. For girdled trees, 76% of the sections with the greatest emerald ash borer density were in the top half of the trees compared to 92% for nongirdled trees.

Assessing the distance of the section with the greatest emerald ash borer density to the base of the canopy further elucidated the within-tree distribution of emerald ash borer relative to tree architecture in these lightly to moderately infested trees. Overall, the section with the greatest emerald ash borer density was located 0.5 ± 0.4 m below the base of the canopy on girdled trees, whereas it was 1.3 ± 0.7 m above the base of the canopy on nongirdled trees. The height of the section with the greatest emerald ash borer densities, however, did not differ significantly among categories of emerald ash borer infestation for either girdled trees ($F = 0.99$; df = 3, 68; $P = 0.404$) or nongirdled trees ($F = 0.14$; df = 3, 38; $P = 0.937$; Fig. 5). Sections with the greatest emerald ash borer density were more frequently classified as having rough bark as opposed to smooth bark for girdled trees (94%) and nongirdled trees (83%).

Study 4—Emerald Ash Borer Emergence From Girdled Trees

Density of emerald ash borer on the trees used in this study averaged (± SE) 15.0 ± 3.7 larvae per m^2. Woodpeckers had preyed on roughly half of the prepupal emerald ash borer larvae (3.5 ± 1.5 per m^2) before trees were felled in mid-March 2010, which left an average of 3.7 ± 1.4 prepupal larvae per m^2 to potentially develop and emerge as adults from these girdled trees during the 2010 summer. The remaining emerald ash borer larvae (7.6 ± 1.9 per m^2) had overwintered as early instars and few, if any, would have completed development before the phloem in the girdled trees had desiccated.

Densities of new emerald ash borer exit holes or woodpecker holes in September were very low on the intact trees. Less than half of the intact trees had new emerald ash borer exit holes (47%) or woodpecker holes (40%). Density of new emerald ash borer exit holes and woodpecker holes on the intact trees averaged 0.6 ± 0.2 and 0.9 ± 0.4 per m^2, respectively. Similarly, densities of new emerald ash borer exit holes or woodpecker holes on the cut bolts left on the ground were also very low. Bolts from nine of the 15 bucked trees (60%) had at least one new emerald ash borer exit hole, while none of the bolts had additional woodpecker holes. Density of new emerald ash borer exit holes on these logs was 0.7 ± 0.2 per m^2 and was positively related to prepupal density ($r^2 = 0.83$; $F = 14.358$; $P = 0.032$) and, to a lesser degree, overall emerald ash borer density ($r^2 = 0.63$; $F = 5.14$; $P = 0.108$) per plot.

Discussion

Our results support the findings of previous studies demonstrating the remarkable ability of girdled ash trees to attract emerald ash borer in low-density infestations (McCullough et al. 2011b, Mercader et al. 2013) and suggest potential options for incorporating girdled trees into operational efforts to slow emerald ash borer population growth and ash mortality. At the onset of our research, emerald ash borer densities across the study area were extremely low. We suspected in 2007 that emerald ash borer had probably invaded this area but we observed no signs or symptoms of emerald ash borer until we felled and debarked trees in the early spring of 2007 and 2008. At that point, less than 25% of the sampled trees were infested and larval densities across the entire 144-ha area averaged only 1.0 larva per m^2 of exposed phloem. Previous studies have shown canopy decline is rarely apparent until emerald ash borer densities approach 20–25 larvae per m^2, while ash trees typically do not succumb until densities exceed 80–100 larvae per m^2

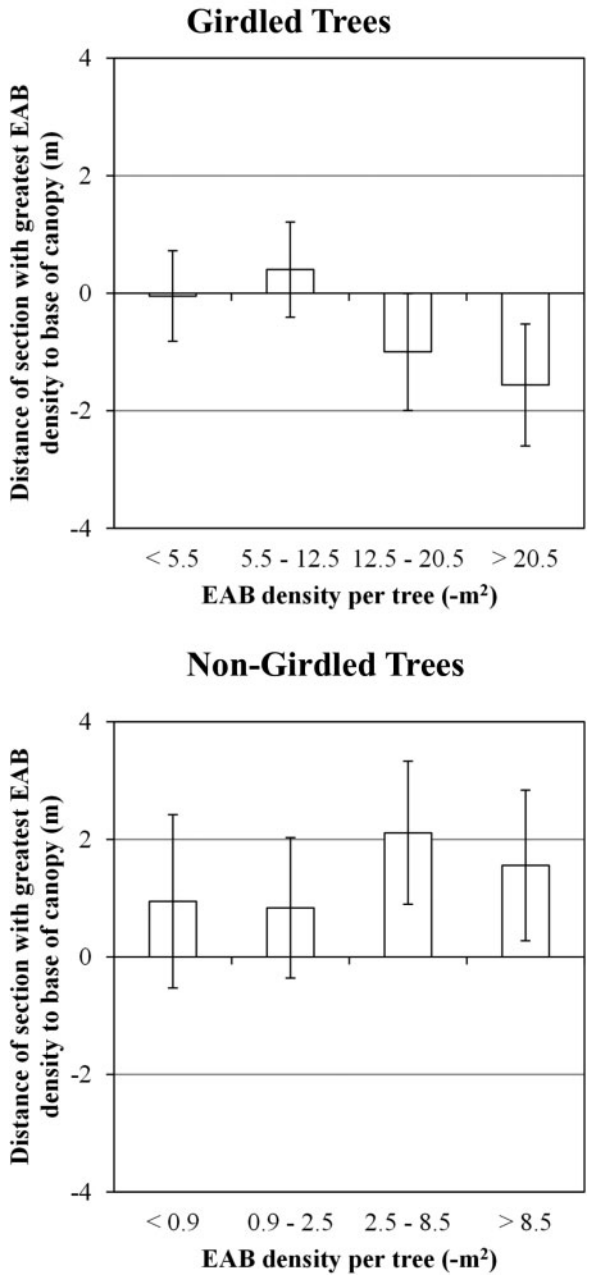

Fig. 5. Mean (± SE) distance from base of canopy (m) of 1-m section with greatest emerald ash borer density (per m^2) per tree by emerald ash borer infestation level per tree for girdled and nongirdled trees. Sample sizes ranged from 16 to 20 trees per diameter class for girdled trees and from 6 to 18 trees per diameter class for nongirdled trees. Negative values on the y-axis reflect distance (m) below the base of the canopy, while positive values reflect distance above the base of the canopy.

(Anulewicz et al. 2007, McCullough and Siegert 2007). By spring 2010, average larval densities on nongirdled trees were still less than 10 larvae per m^2. Our data, therefore, were collected under conditions comparable to areas where emerald ash borer detection or delineation surveys or operational projects to slow emerald ash borer population growth might occur.

Our results clearly demonstrate the effectiveness of girdled ash trees as a means to detect or survey emerald ash borer populations well before external signs of infestations become apparent. Approximately 1,125 ash trees were growing in each of the 4-ha replicates where we girdled 4 or 16 trees or clusters of 3 or 12 trees for Studies 1 and 2. Despite the low density of girdled trees relative to nongirdled trees, emerald ash borer females identified and preferentially oviposited on the girdled trees. Although results of simulation models suggest girdling more trees in a given location should increase the likelihood of detecting low-density emerald ash borer infestations (Mercader et al. 2012), we found a cluster of 3 girdled trees was nearly as effective as girdling a cluster of 12 trees. From a detection efficacy perspective, clustering girdled trees together was not necessary to detect emerald ash borer at the infestation levels present at our study site in 2009. Rather, the value of clustering girdled trees together is maximized when using them as population sinks to reduce emerald ash borer populations (McCullough et al. 2015).

Girdling not only increased the likelihood that trees would become infested, it resulted in larval densities that were three to five times greater than on adjacent or surrounding nongirdled trees. Concentrating emerald ash borer larvae onto girdled trees increases the likelihood that survey crews will be able to find galleries when girdled trees are debarked, thus reducing false negatives in very low-density infestations (Mercader et al. 2013). In a recent 4-yr project encompassing 390 km^2 in northern Michigan, systematic grids of 444 to 855 small (10 to 20 cm dbh) girdled ash detection trees were deployed annually. Data acquired by debarking the girdled trees provided forest and city managers, regulatory officials and outreach specialists with extensive information on emerald ash borer distribution, density and spread across the landscape (McCullough et al. 2015; Mercader et al. 2015, 2016). The debarked trees also functioned as population sinks, resulting in detectable effects on local emerald ash borer population growth (Mercader et al. 2011, 2015).

In addition to detection, girdled ash trees can be used for other purposes in the course of managing a local emerald ash borer infestation. In a previous field study, ash trees were injected with a highly effective systemic insecticide in spring, then girdled a few weeks later, creating highly attractive but lethal trap trees (McCullough et al. 2016). Surrounding a girdled tree or a cluster of girdled trees with insecticide-treated trees could similarly enhance effects of the insecticide by increasing the likelihood that emerald ash borer adults will encounter a toxic tree (McCullough et al. 2007, 2015; Mercader et al. 2015).

The low emerald ash borer densities that characterized our study site contributed to the strong attraction of emerald ash borer beetles to the girdled trees. Like its North American congeners such as two-lined chestnut borer (*Agrilus bilineatus* Weber) (Coté and Allen 1980, Haack and Benjamin 1982), bronze birch borer (*Agrilus anxius* Gory) (Anderson 1944, Barter 1957) and bronze poplar borer (*Agrilus liragus* Barter & Brown) (Barter 1965), emerald ash borer is a secondary pest in its native range in China, where it colonizes stressed, declining, or dying ash trees (Liu et al. 2003, Herms and McCullough 2014). Girdling alters the volatiles produced by ash foliage, wood, or bark used by adult emerald ash borer to identify suitable hosts for foliage-feeding, locating mates, and oviposition (Rodriguez-Saona et al. 2006, Crook et al. 2008, de Groot et al. 2008, Grant et al. 2010). Preferential colonization of ash trees that have been girdled or are otherwise severely stressed has been reported from several emerald ash borer studies in the United States (McCullough et al. 2009a,b; Tluczek et al. 2011; Siegert et al. 2010a,b; Mercader et al. 2013) and when girdled ash trees were used operationally in Michigan and Ohio from 2004–2006, numerous emerald ash borer infestations were detected (Rauscher 2006, Poland and McCullough 2006, Hunt 2007). As emerald ash borer densities build and many trees are stressed by larval feeding, the

preference of emerald ash borer adults for girdled trees is diminished. Using data from 16 localized emerald ash borer infestations, Mercader et al. (2011a) determined that the differential proportion of larvae in girdled trees relative to nongirdled trees declined rapidly once larval densities approached 20 larvae per m^2.

Concerns about logistical issues and labor costs have limited interest in using girdled trees for emerald ash borer detection or monitoring, in favor of baited artificial traps. Sampling girdled or nongirdled ash trees to assess emerald ash borer larval presence or to estimate larval density can be labor intensive, especially with large, thick-barked trees with complex canopies. In the extensive multiyear survey in northern Michigan encompassing 390 km^2 (Mercader et al. 2013, McCullough et al. 2015), surveyors selected pole-sized trees (10–20 cm dbh) for girdling. Pole-sized trees have thinner bark, less surface area to sample and are considerably easier to girdle and debark than larger trees. Smaller trees that could break under high winds were excluded and larger trees were avoided to minimize time needed for girdling and sampling (Mercader et al. 2013, McCullough et al. 2015). Tluczek et al. (2011) reported larval densities on pole-sized, girdled ash trees were consistently highest between 2 and 5 m above ground, a pattern that is not surprising given that most phloem available for larval feeding in small trees occurs on the trunk (McCullough and Siegert 2007).

Results from our study, which included 208 infested trees encompassing a wide range of tree diameters (6.0–39.7 cm), identify optimal areas to sample and suggests careful selection and sampling of trees can increase survey efficiency. While other researchers have suggested targeting specific stem diameters to sample (e.g., Timms et al. 2006; Marshall et al. 2009, 2011; Foelker et al. 2013), our study shows that tree size and architecture affect where emerald ash borer larval densities are greatest on girdled and nongirdled trees in light to moderate infestations. For example, as tree size increased, the height and diameter of the 1-m section with the highest larval densities also increased. Proximity to the base of the canopy, however, was a more consistent metric for locating low-density emerald ash borer infestations on girdled and nongirdled trees. Specifically, we found that the 1-m section with the highest larval densities was 0.5 m below the base of the canopy on girdled trees, whereas it averaged 1.3 m above the base of the canopy for nongirdled trees. Similarly, Ryall et al. (2011) found that sampling low to mid-crown branches in large, nongirdled ash trees (24–34 cm dbh) maximized emerald ash borer detection rates. Sampling efforts would be most productive, regardless of tree size, if focused on sections within 1–2 m of the base of the canopy, which would also eliminate the need to laboriously remove thick bark from the lower portion of the tree trunk.

Artificial traps must be deployed in spring, retrieved in late summer or fall, and may require periodic or mid-season visits to collect captured beetles or replace lures. Girdled trees need to be visited twice; once in spring or early summer for girdling and again in fall or winter to sample for emerald ash borer larvae. In our experience, girdling and debarking small girdled trees (e.g., 10 to 20 cm dbh) generally requires less time overall than installing and retrieving artificial traps. Additionally, while lures used with artificial emerald ash borer traps are composed of relatively few compounds or even a single compound (de Groot et al. 2008, Grant et al. 2010, Crook and Mastro 2010, U.S. Departmentof Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine [USDA APHIS PPQ] 2016), complex blends of volatile compounds emitted by girdled ash trees are undoubtedly more likely to attract emerald ash borer adults (Rodriguez-Saona et al. 2006).

In addition, our results suggest that it may not be necessary to collect or destroy girdled trees after sampling in some management situations. The timing of tree felling, as well as the degree of infestation and development of emerald ash borer larvae, will affect the likelihood of successful adult emergence (Petrice and Haack 2006). In our study, trees were felled in March, roughly 11 mo after they were girdled and three months before emerald ash borer that overwintered as prepupae would have begun to emerge as adult beetles. Many larvae on these trees had overwintered as second or third instars and would have required another year to develop, a pattern common in recently infested trees that remain fairly healthy (Siegert et al. 2010a, Tluczek et al. 2011). Sectioning felled trees into logs increases desiccation rates and further reduces the suitability of phloem for larval feeding. In our study, only a few adult emerald ash borer beetles emerged from the meter-long cut logs or from the intact trees that were supported above the ground by branches, suggesting removal or destruction of girdled ash trees may be unnecessary at sites with low infestation levels where many overwintering larvae are early instars and would require 2 yr to complete development. In trees with relatively high emerald ash borer larval densities, however, most larvae will overwinter as prepupae (Cappaert et al. 2005, Siegert et al. 2010a) and would be more likely to successfully emerge as adults from felled girdled trees. Removal, destruction, or other treatment of felled trees with high emerald ash borer larval densities is recommended to minimize adult emergence.

Woodpecker predation on late instar emerald ash borer larvae can be an important source of mortality (Lindell et al. 2008, Jennings et al. 2013, Koenig et al. 2013, Flower et al. 2014), contributing to reduced emergence of emerald ash borer adult beetles. In our study, woodpeckers preyed on late instar larvae prior to felling the girdled trees in March, reducing the density of emerald ash borer that could have emerged as adults by about half. Additional woodpecker predation on late instar emerald ash borer larvae occurred on the felled, intact trees (but not on the cut logs) between March and September, further reducing the number of adult beetles that could have emerged. Predation by woodpeckers commonly occurs in winter (Jennings et al. 2016) and its potential impact on late instar larvae in girdled ash trees at sites with low emerald ash borer infestation levels may be maximized by felling girdled trees in late winter or early spring (N.W.S., unpublished data). In situations such as remote or difficult-to-access forested sites, negligible emerald ash borer emergence from felled or felled-and-sectioned trees would outweigh costs of removing those trees.

Multiple emerald ash borer survey options, including girdled ash trees, different types of baited artificial traps, and monitoring of buprestid-hunting ground wasps, are currently available. Employing a suite of these tools can increase the effectiveness and efficient use of resources available for emerald ash borer surveys. While girdled ash trees are not appropriate in all situations, they represent a highly effective and cost-efficient means to detect or delineate new emerald ash borer infestations or monitor the expansion of known emerald ash borer infestations. Monitoring emerald ash borer expansion could be particularly valuable in states or counties that are regulated by federal emerald ash borer quarantines but are not yet generally infested. In these circumstances, there is still value in monitoring local emerald ash borer infestations to ensure landowners, communities, and resource managers have the opportunity to protect individual trees, the local ash resource, and implement emerald ash borer response plans.

Acknowledgments

We gratefully thank Andrea Anulewicz, Jacob Baker, Jacob Bournay, Stephen Burr, David Cappaert, Tara Dell, Nicholas Gooch, Emily Pastula, Ben

Schmitt, Andrew Tluczek, and James Wieferich (all of Michigan State University) for their assistance in the field where copious amounts of ash were debarked. Funding for this work was provided by the USDA Animal and Plant Health Inspection Service, Plant Protection and Quarantine, Center for Plant Health Science Technology and the USDA Forest Service, Northeastern Area State and Private Forestry, Forest Health Protection.

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(USDA APHIS PPQ) U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine 2016. Emerald Ash Borer Survey Guidelines 2016. (https://www.aphis.usda.gov/plant_health/plant_pest_info/emerald_ash_b/downloads/survey_guidelines.pdf) (accessed November 2016).