Effects of Cutting Time, Stump Height, and Herbicide Application on Ash (*Fraxinus* Spp.) Stump Sprouting and Colonization by Emerald Ash Borer (*Agrilus planipennis*)

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ABSTRACT

Efforts to eradicate or slow the spread of emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire [Coleoptera: Buprestidae]) include cutting infested and nearby uninfested ash (*Fraxinus* spp.) trees. However, ash trees readily sprout after they have been cut, providing potential host material for EAB. In 2004–2005, we conducted studies to determine how different cutting times (midspring, late spring, and late summer), different cutting heights (0–5, 10–15, and 20–25 cm above the ground), and triclopyr (44% active ingredient) stump treatment of green ash (*Fraxinus pennsylvanica* Marsh.) trees affected subsequent stump sprouting and colonization by EAB. We also cut white ash (*Fraxinus americana* L.) and black ash (*Fraxinus nigra* Marsh.) trees 20–25 cm above the ground in late spring. Some stumps of each ash species tested sprouted and were colonized by EAB. All green ash stumps treated with triclopyr died and were not colonized by EAB. Stump sprouting was significantly lower for stumps cut in late spring compared with stumps cut in midspring or late summer. Stump sprouting did not vary significantly among cutting heights. None of the green ash stumps cut in midspring or cut 0–5 cm above the ground were colonized by EAB; however, the frequency of stump colonization by EAB did not vary significantly among cutting times or cutting heights.

Keywords: Buprestidae, control, coppice, eradication, triclopyr

Emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire [Coleoptera: Buprestidae]), is a serious nonnative invasive pest of ash (*Fraxinus* spp.) trees. EAB was established in 15 US states and 2 Canadian provinces as of November 2010. Since the discovery of EAB near Detroit, Michigan, in 2002, several state and federal agencies have implemented aggressive eradication efforts in several individual disjunct EAB infestations by removing large numbers of infested and uninfested ash trees (Haack et al. 2002, Cappaert et al. 2005, Poland and McCullough 2006, McCullough and Siegert 2007). However, because of difficulty in containing EAB, it continues to spread both naturally and with human assistance, such as through movement of infested firewood, logs, and nursery stock (Haack 2006, Haack et al. 2010). Some managers are currently implementing practices to reduce ash density with the objective of slowing EAB spread rates and reducing the number of beetles produced in specific areas.

EAB adult emergence begins after accumulation of 230–260 degree-days (base 10°C) (Brown-Rytlewski and Wilson 2005, Cappaert et al. 2005). In southern Michigan, this is usually reached in late May, and adult flight continues into early August. Adults feed on ash foliage before mating and laying eggs on live ash trees. EAB eggs hatch in about 2 weeks, and larvae tunnel into the cambial region of host trees to feed. Mature EAB larvae tunnel into the bark or outer sapwood and construct pupation chambers. EAB overwinter as mature larvae in pupation chambers or as immature larvae in the cambial region of ash trees. Most pupation occurs in spring and early summer. Although most EAB have a 1-year life cycle, some EAB may need 2 years to complete development (Cappaert et al. 2005).

Ash tree stumps frequently sprout after cutting, and sprouts can quickly grow into trees (Sterrett 1915). Sprouting ash stumps pose a problem for eradication and management strategies aimed at reducing the amount of host material available to EAB, because stump sprouts produce foliage that supports EAB adults, and live stumps and larger sprouts (≥2.5 cm) may serve as oviposition sites for egg-laying females (T.R.P., personal observation). Numerous studies have found that timing of cutting and stump height can affect stump sprouting of several species of hardwood trees (Harrington 1984, Kays and Canham 1991, Ducrey and Turrel 1992, Johansson 1992a, 1992b, Tappeiner et al. 1996, Bell et al. 1999, Belz 2003). Also, herbicide treatments can effectively kill stumps and prevent sprouting (Ballard and Nowak 2006, Kochenderfer et al. 2006). In 2004–2005, we conducted a study to determine the effects of cutting ash stumps at three different heights and at three different times of the year, as well as applying triclopyr to cut stumps on subsequent sprouting and EAB colonization of ash stumps.

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; square centimeters (cm^2): 1 cm^2 = 0.155 $in.^2$; hectares (ha): 1 ha = 2.47 ac.

Methods

Stump Height, Cutting Time, and Herbicide Treatment

In spring 2004, we conducted studies at three locations in southeastern Michigan where EAB was common. At each location there was noticeable EAB damage on local ash trees, including tree mortality. We selected 201 green ash (*Fraxinus pennsylvanica* Marsh.) trees at Kensington Metro Park (near Milford, MI, latitude 42.5500°N, longitude 83.6376°W), Island Lake State Recreation Area (near Brighton, MI, latitude 42.5178°N, longitude 83.6914°W), and Hudson Mills Metro Park (near Dexter, MI, latitude 42.3866°N, longitude 83.9080°W). We selected ash trees (mean diameter ± SE = 13.3 ± 0.2 cm) that were alive and apparently uninfested or lightly infested with EAB. Selection criteria for trees included apparently healthy crowns, no or few woodpecker excavations along the trunk (which is evidence of woodpeckers foraging for EAB larvae), and no EAB exit holes on the bark surface of the lower trunk when viewed from the ground. We randomly assigned 147 of the trees to one of three cutting heights measured from groundline (0–5, 10–15, or 20–25 cm) and one of three cutting times (midspring [Apr. 22 to May 6, 2004], late spring [June 1–3, 2004], or late summer [Sept. 9–10, 2004]). Nineteen trees were cut 20–25 cm above groundline in midspring (May 6, 2004) or late spring (June 1–3, 2004), and the cut surface of each stump was treated with triclopyr (Garlon 3A, 44.4% active ingredient, undiluted, Dow Agrosciences LLC, Indianapolis, IN). A thin layer of triclopyr was applied with a paintbrush over the entire cut surface of stumps within 30 minutes after cutting. The remaining 35 ash trees were left standing to serve as uncut controls.

After each tree was cut, we removed the bark from a 50-cm-long section of the lower trunk, just above where the stump was cut, to examine the cambial region for EAB larvae. If EAB larvae or their galleries were found, then the tree was excluded from the study, given that such evidence would suggest that EAB larvae could also be present in the remaining stump. If no EAB larvae were found in the debarked area, we assumed that the associated stump was uninfested, given that initial EAB infestation usually begins in the tree canopy and moves downward in subsequent years (Cappaert et al. 2005). Felled trees were left onsite, but the lower trunk was cut into shorter lengths and moved at least 3 m away from any stumps.

On May 26–27, 2004, we placed nylon mesh screening (18 × 16 openings per 2.5 cm^2) around the lower meter of trunk on those ash trees scheduled to be cut in late summer 2004 to prevent EAB adults from laying eggs on the lower trunks of these trees during the 2004 flight season. The bottom of the screening was buried in the soil and the top was secured tightly around the lower tree trunk with duct tape. Screening was placed loosely around the tree trunk to allow a minimum of 2.5 cm of open space from the bark surface to inhibit EAB egg-laying on the bark through the screening. The screening was removed from these trees when they were cut on Sept. 9–10, 2004.

Ash Species

At the Hudson Mills Metro Park, we selected 15 trees: 5 each of green, white (*Fraxinus americana* L.), and black (*Fraxinus nigra* Marsh.) ash. Trees (mean diameter = 15.0 ± 0.6 cm) were cut 20–25 cm above groundline on June 3, 2004. All trees selected for this portion of our study were located within a 0.1-ha area to minimize differences in soil condition and microclimate.

Data Collection

On Apr. 12–13, 2005, we recorded the number of live sprouts that had developed on each stump cut in 2004. We counted all live sprouts that originated directly from the vertical portion of each stump and those from exposed roots within 2.5 cm of the stump base. In addition, we removed the bark from several of the stumps that were created in midspring and late spring 2004 for the cutting-height and cutting-time portions of this study to examine for EAB galleries and life stages and determine whether stumps were alive or dead on the basis of the appearance of the phloem; white and moist phloem was considered alive, whereas brown, discolored, or dry phloem was considered dead. None of the stumps created in late summer 2004 were dissected in April 2005 because they had not yet been exposed to egg-laying EAB adults. We counted sprouts and dissected all remaining stumps during the period Aug. 24 to Sept. 7, 2005.

Statistical Analysis

PROC GLIMMIX (SAS Institute 2006) was used to analyze data in a completely randomized block experimental design, with cutting time and cutting height as fixed effects and study site as a random effect. Because the response variables (stump sprouting, stump mortality, and colonization by EAB) were binary (yes/no), we used a binary distribution with a logit link function to more effectively model each response variable. Nonconvergence of the GLIMMIX model due to perfect data, e.g., all "yes" or all "no" data, for certain treatments prevented us from testing the interaction of cutting time with cutting height (Allison 1999). Effects of stump height and cutting time were tested separately on stump sprouting, stump mortality, and colonization by EAB. Only data collected after two growing seasons were analyzed, given that data for all treatments were not collected after the first growing season, i.e., none of the stumps cut in late summer 2004 were dissected in April 2005. Stumps colonized by EAB were excluded from analyses on stump sprouting and mortality, given the possible effects that EAB larval feeding could have had on stump sprouting and mortality. For analysis on stumps colonized by EAB, entire treatments in which no EAB colonization occurred (e.g., no EAB colonized 0–5-cm stumps or stumps cut in midspring) were excluded to avoid model nonconvergence (Allison 1999). PROC GLIMMIX was also used to compare frequency of EAB colonization between uncut trees and cut stumps with study site as the random effect. An α level of $P = 0.05$ was used for all analyses. Least squares means that were significantly different at the $P < 0.05$ level were separated using the Tukey-Kramer method for pairwise comparisons.

Results and Discussion

Stump Height, Cutting Time, and Herbicide Treatment

The stumps cut and treated with triclopyr herbicide in 2004 failed to sprout and were not colonized by EAB by the end of the 2004 or 2005 growing seasons. All triclopyr-treated stumps were dead when dissected in September 2005. Overall, EAB colonization of cut stumps not treated with triclopyr was relatively low, 6.7 ± 2.9%. By contrast, EAB colonization of the lower trunks of the uncut control trees was significantly higher (61.9 ± 10.9%; $F = 21.64$; degrees of freedom [df] = 1, 92; $P = 0.0001$).

No EAB larvae or galleries were found on any stumps created in midspring 2004 or any stumps cut at heights of 0–5 cm that were dissected after one (dissected April 2005) or two growing seasons

Table 1. Mean percentage (±SEM) of green ash (*F. pennsylvanica*) stumps created in 2004 at three field sites in southeastern Michigan and assessed in spring (April) and fall (September) 2005 for live stump sprouts, condition (live or dead), and evidence of emerald ash borer (EAB) infestation (live larvae and exit holes) by treatment.

		Assessment in spring 2005				Assessment in fall 2005				
Cutting time or treatment	Stump height (cm)	Colonized by EAB	Live sprouts present[a,b]	Stumps dead[a]	n^c	Colonized by EAB	Live sprouts present[a]	Stumps dead[a]	Exit holes present	n^c
		. . . . (%)				. . . . (%)				
Time of cutting for all heights combined										
Midspring	All	0	97.6 ± 2.4	0	18	0	95.8 ± 4.2*[d]	4.2 ± 4.2†[d]	0	24
Late spring	All	21.1 ± 9.6	84.2 ± 5.9	20.0 ± 10.7	19	11.5 ± 6.4*[d]	47.8 ± 10.6†	52.2 ± 10.6*	7.7 ± 5.3	26
Late summer	All		4.0 ± 4.0		0	8.0 ± 5.5*	91.3 ± 6.0*	4.3 ± 4.3†	0	25
Time of cutting by stump height										
Midspring	0–5	0	90.0 ± 10.0	0	7	0	100 ± 0	0	0	4
	10–15	0	100 ± 0	0	5	0	100 ± 0	0	0	5
	20–25	0	100 ± 0	0	6	0	93.3 ± 6.7	6.7 ± 6.7	0	15
Late spring	0–5	0	83.3 ± 11.2	40.0 ± 24.5	5	0	57.1 ± 20.2	42.9 ± 20.2	0	7
	10–15	14.3 ± 14.3	80.0 ± 13.3	16.7 ± 16.7	7	20.0 ± 20.0	50.0 ± 28.9	50.0 ± 28.9	0	5
	20–25	42.9 ± 20.2	87.5 ± 8.5	0 ± 0	7	14.3 ± 9.7	41.7 ± 14.9	58.3 ± 14.9	14.3 ± 9.7	14
Late summer	0–5		0		0	0	100 ± 0	0	0	8
	10–15		11.1 ± 11.1		0	11.1 ± 11.1	75.0 ± 16.3	12.5 ± 12.5	0	9
	20–25		0		0	12.5 ± 12.5	100 ± 0	0	0	8
Other treatments										
Triclopyr[e]			0		0	0	0	100 ± 0	0	19
Uncut control[f]		57.1 ± 13.7	28.6 ± 7.7	14.3 ± 9.7	14	61.9 ± 10.9	52.4 ± 11.2	9.5 ± 6.6	0	21

[a] Stumps colonized by EAB were excluded.
[b] Includes all stumps created (i.e., stumps dissected in spring 2005 and fall 2005).
[c] Number of stumps dissected (i.e., replicates).
[d] Means for all cutting heights combined from the fall 2005 assessment within columns followed by the same symbol were not significantly different at the $P < 0.05$ level (PROC GLIMMIX; Tukey-Kramer method for pairwise comparisons). Means that equaled 0 were excluded from the analyses to prevent nonconvergence of the GLIMMIX model.
[e] Triclopyr was brushed on cut surface of stumps within 30 minutes after trees were cut in midspring (May 6, 2004) or late spring (June 1–3, 2004).
[f] Apparently healthy uncut trees. Data are based on dissection of lower 25 cm of trunk.

(dissected September 2005; Table 1), whereas some stumps cut at heights of 10–15 and 20–25 cm during late spring were colonized by EAB within one growing season. When stumps were dissected after two growing seasons, evidence of EAB colonization was found in stumps cut at heights of 10–15 and 20–25 cm during late spring and late summer 2004; however, the percentage of stumps with evidence of EAB colonization did not vary significantly between cutting heights ($F = 0.01$; df = 1, 33; $P = 0.9108$) or cutting times ($F = 0.13$; df = 1, 33; $P = 0.7171$; Table 1). It is important to note that stumps created in midspring and late spring 2004 were exposed to 2 years of EAB attack, whereas those cut in late summer 2004 were subjected to only 1 year of attack before dissection in fall 2005 because stumps cut in late summer 2004 were created after EAB adult flight in 2004. We do not know in which year EAB attacked the stumps created in midspring or late spring 2004 and later dissected in September 2005, but EAB exit holes were found only when stumps were inspected after two growing seasons and only on the tallest stumps (20–25 cm) cut in late spring.

It is possible that stumps cut at 0–5 cm were so short that they were not visually attractive to egg-laying EAB females. It is also possible that EAB females did not find the 0–5-cm-tall stumps suitable for egg-laying after landing because they somehow assessed them to have too little phloem for their progeny to complete development. Also, it is unclear why none of the stumps created in midspring were colonized by EAB. Previous studies have found that EAB are more attracted to girdled trees than to wounded trees or undamaged, healthy trees (McCullough et al. 2009a, 2009b). Perhaps the cut surface of stumps created in midspring had sufficient time to dry or callus over before EAB flight began in late May or early June 2004, whereas the freshly cut stumps created in late spring were likely still releasing stress volatiles during the EAB flight period and thus were more attractive to EAB. We also realize that EAB colonization of 0–5-cm stumps and midspring-cut stumps may have been documented if our sample sizes had been larger. EAB populations at our study sites would be considered moderate to high given our field experience with EAB over the past 9 years. We would expect colonization of stumps to have, in general, a positive correlation with increasing EAB densities, i.e., the frequency that stumps were colonized by EAB would increase with higher EAB populations. Also, stumps in this study were surrounded by many other live, standing ash trees in addition to the control trees. If this source of host material was not present, EAB colonization of cut stumps may have been higher.

Most untreated stumps (91.3 ± 3.2%; $n = 80$; stumps colonized by EAB excluded) created in midspring and late spring 2004 sprouted before the end of the 2004 growing season (Table 1). Few stumps created in late summer 2004 sprouted by winter 2004, probably because ash trees have a determinate growth pattern, and fall senescence had already begun at the time of cutting (Kays and Canham 1991). By the end of the 2005 growing season, significantly fewer of the untreated stumps created in late spring 2004 had live sprouts compared with stumps created in midspring or late summer 2004 ($F = 7.51$; df = 2, 63; $P = 0.0012$). Similarly, significantly more of the untreated stumps created in late spring 2004 were completely dead by the end of the 2005 growing season compared with stumps created in the midspring or late summer 2004 ($F = 7.79$; df = 2, 63; $P = 0.001$). The percentage of untreated stumps with live sprouts at the end of the 2005 growing season did not vary significantly among the three stump height categories ($F = 0.49$; df = 2, 63; $P = 0.6127$). Also, the percentage of dead stumps did not vary significantly among the three stump height categories when compared at the end of the 2005 growing season ($F = 0.20$; df = 2, 63; $P = 0.82$).

Stumps created in late spring likely would have had smaller root starch reserves than stumps created in midspring or late summer, given that most starch reserves would have been assimilated for

Table 2. Percentage of green (*F. pennsylvanica*), white (*F. americana*), and black (*F. nigra*) ash stumps created on June 3, 2004, in southeastern Michigan and assessed in spring and fall 2005 for live stump sprouts, condition (live or dead), and signs of emerald ash borer (EAB) infestation (live larvae and exit holes) by ash species.

		Assessment in fall 2005				
Species	Live sprouts present in spring 2005	Colonized by EAB	Live sprouts present	Stumps dead	EAB exit holes present	n^a
	(%)					
Green ash	100 ± 0	80.0 ± 20.0	60.0 ± 24.5	60.0 ± 24.5	80.0 ± 20.0	5
White ash	100 ± 0	80.0 ± 20.0	80.0 ± 20.0	40.0 ± 24.5	80.0 ± 20.0	5
Black ash	80.0 ± 20.0	40.0 ± 24.5	20.0 ± 20.0	80.0 ± 20.0	40.0 ± 24.5	5

[a] Number of stumps dissected.

vegetative growth by late spring and there would not have been sufficient time to allow significant amounts of current year photosynthates to be translocated back to the roots before our late spring cut dates (Kays and Canham 1991, Kozlowski et al. 1991). Sprout development after cutting in 2004 would have further depleted root starch reserves; this depletion is reflected by reduced sprouting and increased mortality during the 2005 growing season for stumps created in late spring 2004 compared with those created in midspring or late summer 2004. Previous studies have also found that cutting trees in late spring or early summer reduced sprouting in many hardwood species (Ducrey and Turrel 1992, Johansson 1992a, 1992b, Bell et al. 1999, Belz 2003). Furthermore, Kays and Canham (1991) determined that white ash stumps cut during a 9-week period beginning in late spring had significantly lower root starch reserves when sampled later that same fall. Also, the weakened state of stumps created in late spring, presumably because of depleted root starch reserves, may have made them more attractive to EAB than stumps created in midspring or late summer. Studies with the native twolined chestnut borer, *Agrilus bilineatus* (Weber), found adult beetles more attracted to oak (*Quercus* spp.) trees with low starch reserves compared with trees with moderate or high starch reserves (Haack and Benjamin 1982, Dunn et al. 1987).

Stumps of the trees used for this study ranged from 26 to 47 years old and averaged 38 ± 1 years old. Stump sprouting has been found to be negatively correlated with tree age (Roth and Hepting 1943, Kays and Canham 1991, Tredici 2001). Although the trees used in the current study were relatively mature, most stumps still had live sprouts two seasons after cutting, with the exception of late spring stumps. It is likely that stumps of younger ash trees would sprout more frequently and more vigorously compared with stumps in the present study. However, it is unclear how EAB would respond to younger more vigorous sprouting stumps.

Ash Species

EAB was able to complete development on stumps of all three ash species tested (Table 2). This is not surprising given that EAB readily colonizes black, green, and white ash, as well as other ash species (Poland and McCullough 2006, Anulewicz et al. 2008). All (100%) of the green and white ash stumps sprouted, and most (80%) of the black ash stumps sprouted the same growing season they were cut (Table 2). After two growing seasons, most stumps and their sprouts had died: mortality was 80% for black ash, 60% for green ash, and 40% for white ash.

Management Implications

Treating stumps with triclopyr was the most (100%) effective practice for killing green ash stumps and preventing successful colonization by EAB in our study. Other herbicides formulated for stump treatment may show similar effectiveness. White ash and black ash stumps also sprouted and were colonized by EAB, and thus stumps of these two ash species should be treated with triclopyr or a similar herbicide if the management objectives are to reduce stump sprouting and EAB colonization. If stumps cannot be treated with triclopyr or a similar herbicide, then cutting ash stumps low to the ground (≤2.5 cm) during late spring should be considered to reduce sprouting and colonization by EAB. It should be noted, however, that the effectiveness of reducing EAB host material, by itself or in combination with other treatments, for slowing the spread of EAB has not yet been documented.

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