

Movement of *Xylosandrus germanus* (Coleoptera: Curculionidae) in Ornamental Nurseries and Surrounding Habitats

MICHAEL E. REDING,^{1,2} CHRISTOPHER M. RANGER,¹ BLAIR J. SAMPSON,³
CHRISTOPHER T. WERLE,³ JASON B. OLIVER,⁴ AND PETER B. SCHULTZ⁵

J. Econ. Entomol. 1–7 (2015); DOI: 10.1093/jee/tov174

ABSTRACT Some exotic ambrosia beetles are damaging pests in ornamental nurseries. *Xylosandrus germanus* (Blandford) is the most problematic ambrosia beetle in Ohio nurseries. Movement of *X. germanus* in nurseries has not been characterized, and knowledge is lacking on whether infestations originate from within nurseries or surrounding habitats. Flight activity of *X. germanus* was monitored in nurseries and adjacent wooded areas to determine the source of beetles infesting nurseries, and characterize their movement within nurseries. Ethanol-baited bottle traps were positioned within wooded areas adjacent to commercial nurseries and within nurseries at various distances from the nursery woodlot interface. Flight activity of overwintered *X. germanus* occurred in wooded areas adjacent to nurseries before occurrence within nurseries. There was a direct relationship between degree-days and the distance from woodlots when *X. germanus* were first found in traps in spring, with earlier captures closest to wooded areas and latest ones furthest away into the nursery. *X. germanus* appeared to move into nurseries from adjacent wooded areas, with numbers trapped within nurseries decreasing with distance away from wooded areas. Trees in the interior of nurseries would appear to be subjected to less attack pressure than trees near the nursery border. Intercepting beetles as they move into nurseries might be an effective strategy to reduce attack pressure on valuable trees.

KEY WORDS ambrosia beetle, dispersal, monitoring, degree-days

Exotic ambrosia beetles (Coleoptera: Curculionidae: Scolytinae) are serious pests in ornamental tree nurseries in North America (Hudson and Mizell 1999, Oliver and Mannion 2001, Hale 2007). *Xylosandrus crassiusculus* (Motschulsky) and *Xylosandrus germanus* (Blandford) are two of the most problematic exotic species in North American nurseries (Hudson and Mizell 1999; Oliver and Mannion 2001; Hale 2007; Reding et al. 2010, 2011). *X. crassiusculus* and *X. germanus* overwinter as adults in galleries of host trees. In spring, attacks on nursery trees occur when emerging females fly from overwintering sites to colonize new hosts. Ambrosia beetles typically colonize trees by boring into the xylem creating tunnels and galleries, which are inoculated with symbiotic fungi (Wood 1982, Kühnholz et al. 2001). Symbiotic fungi are the food source for larvae and adults, and eggs are laid in galleries after the fungi

start growing (French and Roeper 1972, Weber and McPherson 1983, Peer and Taborsky 2005). In nurseries, seasonal flight activity of *Xylosandrus* species is highest in spring (Oliver and Mannion 2001, Reding et al. 2011), suggesting that is the time of greatest colonization activity. Though efficacy is inconsistent, nursery growers use trunk sprays of insecticides to protect trees from colonizing ambrosia beetles. Sprays generally begin when emergence of overwintered beetles is expected in spring.

Many wood-boring ambrosia beetles, including certain *Xylosandrus* species, preferentially colonize unhealthy, physiologically stressed, or dying trees (Hoffman 1941; Wood 1982; Weber and McPherson 1984; Kühnholz et al. 2001; Ranger et al. 2010, 2013a). Ambrosia beetles have efficient host-seeking capabilities, able to differentiate among slight differences in host vigor (Weber and McPherson 1984), to select stressed trees for preferential attack from other nonstressed trees (Ranger et al. 2013a, 2015). Ethanol is emitted from trees under physiological stress (Moeck 1970, Kimmerer and Kozłowski 1982, Kelsey and Joseph 2001, Ranger et al. 2013a), and acts as a primary attractant for ambrosia beetles including *X. crassiusculus* and *X. germanus* (Graham 1968, Cade et al. 1970, Moeck 1970, Montgomery and Wargo 1983, Klimetzek et al. 1986, Oliver and Mannion 2001, Ranger et al. 2010).

The sources of ambrosia beetles colonizing (attacking) nursery trees are uncertain. In preliminary

¹Horticultural Insects Research Group, USDA-Agricultural Research Service, Ohio Agricultural Research and Development Center, 1680 Madison Ave., Wooster, OH 44691.

²Corresponding author, e-mail: mike.reding@ars.usda.gov.

³USDA-ARS Thad Cochran Southern Horticultural Lab, Poplarville, MS 39470.

⁴Otis L. Floyd Nursery Research Center, Tennessee State Univ., College of Agriculture, Human, and Natural Sciences, McMinnville, TN 37110.

⁵Hampton Roads Agricultural Research and Extension Center, Virginia Tech Univ., Virginia Beach, VA 23455.

research, ethanol-baited traps placed in the interior of nurseries had low capture rates, but captures increased when traps were positioned near the perimeters of nurseries. Ranger et al. (2013b) reported that attack rates on ethanol-injected trap trees decreased with distance from adjacent wooded areas. Furthermore, nursery growers usually remove trees when ambrosia beetle attacks are detected. Consequently, ambrosia beetles originating from within the nursery seem unlikely. Habitats, especially wooded areas, surrounding nurseries are potential sources of beetles infesting nurseries. However, this hypothesis has not been tested experimentally, nor has the movement of beetles within nurseries been characterized.

X. germanus is the most problematic ambrosia beetle in Ohio nurseries (Reding et al. 2010, 2011), and was therefore a primary focus of this research. The objectives of the current research were to 1) determine the likely sources of *X. germanus* and other ambrosia beetles infesting ornamental nurseries; 2) characterize movement of *X. germanus* in nurseries during spring and the timing of their movement in relation to emergence of overwintered beetles.

Materials and Methods

To determine the most probable source of *X. germanus* and other ambrosia beetles infesting ornamental nurseries, and characterize their movement within nurseries, flight activity was monitored in nurseries and the adjacent wooded areas (hereafter referred to as woodlots) using ethanol-baited bottle traps from emergence in early spring through mid-summer. Traps were deployed in commercial nurseries located in Lake (2013 and 2014), Lorain (2013), and Wayne (2014) counties, Ohio before emergence of *X. germanus* was expected in spring. Traps were positioned in woodlots adjacent to each nursery and within nurseries at various distances from the woodlot or nursery interface (border). The experiments were set up in four to five commercial nurseries as generalized randomized block designs (GRBD), allowing multiple replications per block and a treatment \times block interaction effect in the model (Addelman 1969, Zhang et al. 1996, Quinn and Keough 2002). Each nursery agro-ecosystem was unique, with different combinations of trees and pest management programs, and variable characteristics in adjacent woodlands. Therefore, including a nursery (block) \times distance (treatment) interaction effect in the model was desirable to examine whether the nursery agro-ecosystem (nursery + surrounding habitats) influenced occurrence of *X. germanus* within nurseries (Underwood 1997). Two or three fully replicated plots (each plot with a replication at each trap distance) were set up within each nursery, totaling 11 plots in 2013 and 10 in 2014. Distances (treatments) were positions of traps in relation to the nursery-woodlot interface (Fig. 1). Distance treatments included traps positioned in adjacent woodlots 13 meters from the nursery (-13m), and into the nursery 13, 25, 50, and 100 m from the nursery-woodlot interface (Fig. 1). Within plots, traps were spaced laterally 25 m apart (Fig. 1),

and plots within nurseries were spaced ≥ 25 m apart. Orientation of the plots depended on the nursery and location of the adjacent woodlot, thus no specific cardinal orientations were used. Traps were deployed on 9 April 2013 and 10 April 2014, and checked at 6–15-d intervals through mid- to late-June, then once in late July. On each sample date, beetles were retrieved from traps, transported to the laboratory, and stored in 70% ethanol. All Scolytinae were counted and identified to the species level using available keys (Wood 1982, Rabaglia et al. 2006).

Traps and Lures. Traps were constructed of two clear plastic bottles (0.5 and 1 liter) with the mouth ends connected by a plastic threaded tube ("Tornado Tube," item # WTUB-500, Steve Spangler Science, Englewood, CO), which was modified to increase the size of the opening. Hereafter, the traps will be referred to as bottle traps (Reding et al. 2011). The 1-liter bottle was positioned on top with two vertical openings (approximately 12.5 by 7.5 cm) cut into the sides to allow entrance of ambrosia beetles. The small bottle (0.5 liter) functioned as the collection receptacle and was filled with ~100 ml of a 50% solution of propylene glycol (CAS Registry # 57-5506, Sierra Antifreeze/Coolant, Old World Industries, Northbrook, IL) as the killing agent. The lures were commercially available pouch-style dispensers loaded with 10 ml of 95% ethanol with a release rate of 65 mg/d at a constant 30°C (Standard Release ethanol lures, AgBio, Westminster, CO).

Data Analysis. Captures of *X. germanus* at the various distances were analyzed within years and sampling dates by analysis of variance for a GRBD with a block \times treatment interaction effect in the analysis of variance model (Addelman 1969, Zhang et al. 1996, Quinn and Keough 2002, Analytical Software 2003). The block \times treatment interaction was possible because there were multiple replications per block in the design (Addelman 1969, Zhang et al. 1996). Data were analyzed by count date and $\log(X+1)$ transformed for analysis to meet assumptions of homogeneity of variances and normality (Zar 1999). Logistic regression was used to examine the relationship between the occurrence of *X. germanus* at each distance through late May and degree-day (10°C base) accumulation from 1 January. Logistic regression was also used to examine the relationship between *X. germanus* flight activity in adjacent woodlots (derived from total captures within a plot's woodlot [-13 m] trap) and occurrence of *X. germanus* at each distance within nurseries. Weather data for degree-days in Lake and Lorain counties were obtained from U.S. Department of Agriculture-Agricultural Research Services (USDA-ARS) weather stations within 5 km of the nursery plots; Wayne County weather data came from a station located at The Ohio State University's Ohio Agricultural Research and Development Center, in Wooster, OH, ~16 km from the nursery. Data for 2013 and 2014 were combined for logistic regression analyses. Logistic regression is used to analyze binary data (one or zero) such as presence or absence responses (Quinn and Keough 2002, Analytical Software 2003). The occurrence of *X.*

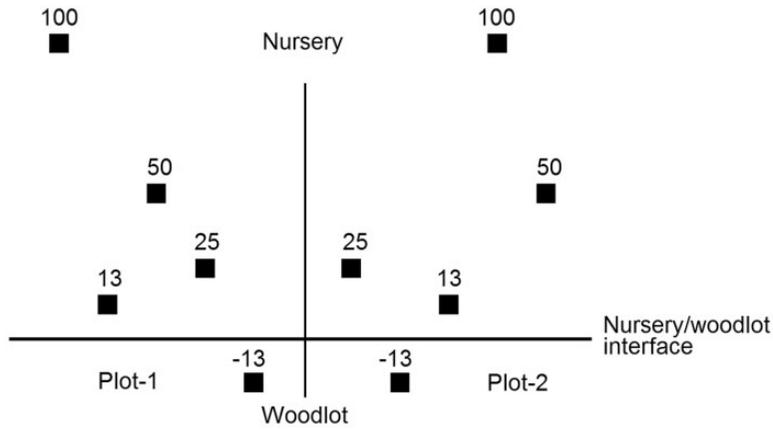


Fig. 1. Diagrammatic representation of typical movement plots in a nursery. The symbols represent position of traps in relation to the nursery–woodlot interface (border), with a lateral separation of 25 m between traps and plots.

germanus (present or absent) in traps at each distance during a trapping period was used as the dependent variable. The logistic function was of the form $p = [e^{(B0+B1*X)} / (1 + e^{(B0+B1*X)})]$, where p is the probability of capturing *X. germanus*, X is degree-days or *X. germanus* captures within adjacent woodlots (–13-m traps), $B0$ is the constant, and $B1$ is the regression coefficient that measures the rate of change in probability for a given X (Quinn and Keough 2002).

Results

Seventeen and 16 species of Scolytinae were captured in 2013 and 2014, respectively, with the largest proportions of most species captured within woodlots adjacent to the nurseries (–13-m traps; Table 1). In 2013, 59% of the total Scolytinae species captured were not native to North America, while in 2014, 50% were nonnative species (Table 1). Most of the nonnative species, including *X. germanus*, were endemic to Asia or Eurasia. *X. germanus* was the most numerous species representing 67.7 and 82.5% of the total Scolytinae specimens captured in 2013 and 2014, respectively. First captures of *X. germanus* occurred 25 April (Lake Co.) and 2 May (Lorain Co.) in 2013, and 17 April (Wayne Co.) and 23 April (Lake Co.) in 2014. Most *X. germanus* were captured within woodlots (–13-m traps) adjacent to nurseries each year (57.3 and 69.6% of the total captured in 2013 and 2014, respectively) (Table 1). In 2013, higher numbers of *X. germanus* were captured in adjacent woodlots (–13-m traps) than all other distances on every date, however, captures in woodlots were not significantly different than 25 m into the nurseries on 30 May, or at 13 and 25 m on 20 June (Tables 2 and 3). Captures 13 and 25 m from the nursery–woodlot interface were usually greater than at 50 m and 100 m, but differences were not significant on most dates (Table 2). In 2014, captures of *X. germanus* were higher in woodlots adjacent to nurseries than all locations within nurseries on every date (Tables 2 and 3). However, differences were not significant on 17 and 25 April, and 8 May, even though

X. germanus were captured only in woodlots on 17 April and 8 May. There was no statistical difference in captures between woodlots and 13-m traps on 14 May (Table 2). As in 2013, captures of *X. germanus* were usually higher at 13 and 25 m from the nursery–woodlot interface than at 50 and 100 m in 2014, but differences were not statistically significant on most dates (Table 2). In 2013, there were significant nursery \times distance interactions on 25 April, 5 June, and 25 July, but no significant interactions were detected in 2014 (Table 3).

The presence of *X. germanus* at each distance was significantly related to degree-days (Table 4). Based on logistic regression analysis, first captures of *X. germanus* associated with lowest degree-days were in traps in woodlots adjacent to nurseries (–13-m traps; Table 5). *X. germanus* were found in 13- and 25-m traps at similar degree-days, significantly less (earlier) than first captures at 50 and 100 m, which were similar to each other (Table 5; Fig. 2). The occurrence of *X. germanus* at each location within nurseries was significantly related to flight activity in woodlots adjacent to nurseries (Table 4). Logistic regression analysis revealed relatively low counts in adjacent woodlots just prior to detection in 13- and 25-m traps, compared with when beetles were first found in traps placed at 50 and 100 m from the nursery–woodlot interface (Table 5; Fig. 3).

Discussion

In the current research, most *X. germanus* and other Scolytinae were captured within woodlots adjacent to commercial nurseries, while captures declined within nurseries as the distance to adjacent woodlots increased. Traps in woodlands generally caught higher numbers of *X. germanus* overall on most dates compared with all other locations. Ranger et al. (2013b) found that attacks on ethanol-injected trees also decreased as the distance to woodlots increased. Ornamental nursery growers that experience damage from ambrosia beetles usually implement management

Table 1. Species of Scolytinae captured in 2013 and 2014 with the proportion captured at each distance

Year	Species	Origin	Total captured	Proportion of total captured within species				
				-13 m	13 m	25 m	50 m	100 m
2013	<i>Ambrosiodmus obliquus</i> LeConte	S. America	1	0.0	0.0	1.00	0.0	0.0
	<i>Ambrosiodmus rubricollis</i> Eichhoff	Asia	4	0.75	0.0	0.0	0.25	0.0
	<i>Anisandrus maiche</i> Stark	Asia	19	0.95	0.0	0.05	0.0	0.0
	<i>Anisandrus sayi</i> (Hopkins)	N. America	16	0.81	0.06	0.0	0.06	0.06
	<i>Corthylus punctatissimus</i> Zimmermann	N. America	3	1.00	0.0	0.0	0.0	0.0
	<i>Euwallacea validus</i> Eichhoff	Asia	9	0.44	0.33	0.0	0.22	0.0
	<i>Hypothenemus dissimilis</i> (Zimmermann)	N. America	658	0.51	0.26	0.14	0.06	0.02
	<i>Hypothenemus eruditus</i> Westwood	N. America	133	0.61	0.25	0.11	0.03	0.0
	<i>Phloeotribus limnaris</i> (Harris)	N. America	1	0.0	1.00	0.0	0.0	0.0
	<i>Pityophthorus</i> sp. Eichhoff	na	1	0.0	1.00	0.0	0.0	0.0
	<i>Scolytus rugulosus</i> (Müller)	Eurasia	1	0.0	1.00	0.0	0.0	0.0
	<i>Xyleborinus alni</i> (Niisima)	Asia	23	0.26	0.35	0.22	0.13	0.04
	<i>Xyleborinus saxesenii</i> (Ratzeburg)	Eurasia	37	0.51	0.08	0.14	0.24	0.03
	<i>Xyleborus atratus</i> Eichhoff	Asia	15	0.53	0.27	0.13	0.0	0.07
	<i>Xylosandrus crassiusculus</i> (Motschulsky)	Asia	1	1.00	0.0	0.0	0.0	0.0
	<i>Xylosandrus germanus</i> (Blandford)	Asia	1959	0.57	0.13	0.16	0.08	0.06
	<i>Xylosterinus politus</i> (Say)	N. America	14	0.79	0.14	0.07	0.0	0.0
2014	<i>Anisandrus maiche</i> Stark	Asia	9	0.22	0.11	0.0	0.44	0.22
	<i>Anisandrus sayi</i> (Hopkins)	N. America	17	0.82	0.0	0.06	0.06	0.06
	<i>Euwallacea validus</i> Eichhoff	Asia	14	0.64	0.21	0.0	0.14	0.0
	<i>Hypothenemus dissimilis</i> (Zimmermann)	N. America	281	0.31	0.19	0.24	0.21	0.05
	<i>Hypothenemus eruditus</i> Westwood	N. America	25	0.44	0.44	0.04	0.08	0.0
	<i>Micracis swainei</i> Blackman	N. America	3	0.33	0.33	0.33	0.0	0.0
	<i>Monarthrum fasciatum</i> (Say)	N. America	1	0.0	0.0	0.0	1.00	0.0
	<i>Monarthrum mali</i> (Fitch)	N. America	6	0.67	0.0	0.33	0.0	0.0
	<i>Pityophthorus</i> sp. Eichhoff	na	1	0.0	1.00	0.0	0.0	0.0
	<i>Xyleborinus alni</i> (Niisima)	Asia	10	0.40	0.20	0.0	0.30	0.10
	<i>Xyleborinus saxesenii</i> (Ratzeburg)	Eurasia	32	0.72	0.06	0.09	0.13	0.0
	<i>Xyleborus atratus</i> Eichhoff	Asia	20	0.70	0.05	0.10	0.15	0.0
	<i>Xyleborus pelliculosus</i> Eichhoff	Asia	14	0.79	0.0	0.0	0.14	0.07
	<i>Xylosandrus crassiusculus</i> (Motschulsky)	Asia	5	0.40	0.40	0.0	0.20	0.0
	<i>Xylosandrus germanus</i> (Blandford)	Asia	2083	0.70	0.13	0.10	0.06	0.02
	<i>Xylosterinus politus</i> (Say)	N. America	5	0.60	0.20	0.20	0.0	0.0

Table 2. Mean \pm SE captures of *X. germanus* at various distances through mid-summer in Ohio 2013 and 2014

Year	Date	n	Mean \pm SE <i>X. germanus</i> captured ^a				
			-13 m	13 m	25 m	50 m	100 m
2013	17 April	9	0	0	0	0	0
	25 April	11	1.9 \pm 0.8a	0.4 \pm 0.3b	0.3 \pm 0.2b	0.4 \pm 0.2b	0.1 \pm 0.1b
	2 May	11	24.6 \pm 4.5a	8.5 \pm 1.8b	7.4 \pm 1.9bc	2.4 \pm 0.7c	3.8 \pm 1.8c
	8 May	10	19.0 \pm 5.0a	3.2 \pm 1.0b	3.7 \pm 1.2b	1.6 \pm 1.3b	0.6 \pm 0.3b
	16 May	10	14.2 \pm 3.3a	1.9 \pm 0.6b	1.4 \pm 0.6b	3.5 \pm 1.2b	1.2 \pm 0.5b
	30 May	8	32.9 \pm 4.5a	8.9 \pm 2.3b	19.6 \pm 6.8ab	8.2 \pm 2.0b	4.5 \pm 1.2b
	5 June	10	4.0 \pm 0.9a	2.1 \pm 0.7b	3.3 \pm 1.5b	2.9 \pm 1.4b	1.5 \pm 0.7b
	20 June	10	5.7 \pm 2.6a	2.1 \pm 0.5ab	1.8 \pm 0.8ab	1.6 \pm 0.7b	1.1 \pm 0.5b
	25 July	10	19.3 \pm 5.7a	3.2 \pm 1.3b	4.4 \pm 2.2b	0.5 \pm 0.2cd	0.3 \pm 0.1d
	2014	17 April	10	0.1	0.0	0.0	0.0
23 April		10	0.5 \pm 0.2a	0.0a	0.2 \pm 0.2a	0.1 \pm 0.1a	0.1 \pm 0.1a
8 May		10	1.0 \pm 0.7a	0.0a	0.0a	0.0a	0.0a
14 May		7	36.1 \pm 10.6a	8.7 \pm 2.4ab	8.6 \pm 3.0bc	3.7 \pm 1.1bc	1.4 \pm 0.4c
22 May		10	19.5 \pm 9.5a	2.7 \pm 0.5bc	3.4 \pm 1.4b	2.4 \pm 1.4bc	1.0 \pm 0.7c
29 May		10	19.5 \pm 6.1a	3.0 \pm 1.3b	2.8 \pm 0.7b	1.4 \pm 1.2b	0.5 \pm 0.3b
5 June		10	8.6 \pm 2.1a	0.3 \pm 0.3b	0.8 \pm 0.4b	1.0 \pm 0.7b	0.1 \pm 0.1b
12 June		7	2.3 \pm 0.5a	0.2 \pm 0.3b	0.2 \pm 0.3b	0.6 \pm 0.6b	0.2 \pm 0.1b
24 July		10	68.7 \pm 14.1a	12.8 \pm 6.2b	5.8 \pm 2.1bc	3.1 \pm 2.4bc	1.6 \pm 0.7c

Means within rows followed by the same letter are not significantly different (Tukey's HSD, $\alpha = 0.05$). Data were $\log(X + 1)$ transformed for analysis, with untransformed data presented.

^aThe distances are positions of traps in relation to the nursery-woodlot interface, with -13 m in adjacent woodlots and 13, 25, 50, and 100 m within nurseries.

programs that include protective sprays and removal of attacked trees. Consequently, resident ambrosia beetle populations within nurseries should be relatively low. These results support the hypothesis that wooded habitats adjacent to nurseries are primary or important

sources of ambrosia beetles infesting those nurseries in spring. Furthermore, the lack of interactions between nursery and distance indicates that relative activity was similar among trap positions at each nursery, regardless of the variability in the agro-ecosystems.

Table 3. Statistics for comparing *X. germanus* captures at the various trap locations (distances) within nurseries and adjacent wooded areas in 2013 and 2014, which were analyzed by sample date

Year	Date	Distance			Distance × Nursery interaction		
		<i>F</i>	df	<i>P</i>	<i>F</i>	df	<i>P</i>
2013	25 April	7.06	4, 30	<0.001	2.45	16, 30	0.017
	2 May	13.62	4, 30	<0.001	0.67	16, 30	0.797
	8 May	10.18	4, 25	<0.001	0.58	16, 25	0.870
	16 May	12.84	4, 24	<0.001	1.82	16, 24	0.090
	30 May	8.19	4, 19	<0.001	0.91	12, 19	0.557
	5 June	7.28	4, 23	<0.001	2.46	16, 23	0.024
	20 June	3.36	4, 25	0.025	0.68	16, 25	0.782
25 July	31.72	4, 24	<0.001	5.33	16, 24	<0.001	
2014	23 April	2.09	4, 30	0.107	0.80	12, 30	0.652
	8 May	1.81	4, 30	0.153	0.30	12, 30	0.985
	14 May	9.29	4, 20	<0.001	0.45	8, 20	0.874
	22 May	17.83	4, 30	<0.001	0.93	12, 30	0.528
	29 May	16.37	4, 30	<0.001	0.71	12, 30	0.732
	5 June	19.30	4, 30	<0.001	0.63	12, 30	0.796
	20 June	6.96	4, 20	0.001	0.96	8, 20	0.490
	24 July	25.72	4, 29	<0.001	1.37	12, 29	0.236

The experiment was set up as a GRBD and analyzed with a treatment by nursery interaction effect in the model, and data were log(*X* + 1) transformed for analysis.

Table 4. Parameter estimates and statistics for logistic analysis of the relationship between the presence of *X. germanus* at the various distances through late May and cumulative degree-days (10°C) from 1 January or *X. germanus* flight activity in adjacent wooded areas (derived from captures in a plot’s woodlot [–13 m] trap)

Model ^a	Distance (m)	<i>n</i>	Parameter	df	Estimate	Standard error	Wald chi-square	<i>P</i> > chi-square	
DD	–13	115	<i>B0</i>	1	–3.07524	0.66822	21.16	<0.001	
			<i>B1</i>	1	0.03651	0.00712	26.32	<0.001	
	13	116	<i>B0</i>	1	–3.10781	0.58637	28.09	<0.001	
			<i>B1</i>	1	0.02364	0.00439	29.05	<0.001	
	25	116	<i>B0</i>	1	–3.58577	0.65020	30.36	<0.001	
			<i>B1</i>	1	0.02755	0.00492	31.36	<0.001	
	50	116	<i>B0</i>	1	–2.46345	0.49670	24.60	<0.001	
			<i>B1</i>	1	0.01413	0.00321	19.45	<0.001	
	100	115	<i>B0</i>	1	–2.6740.	0.51845	26.63	<0.001	
			<i>B1</i>	1	0.01343	0.00318	17.81	<0.001	
	<i>X. germanus</i> flight activity in woodlots	13	115	<i>B0</i>	1	–1.63723	0.33312	24.11	<0.001
				<i>B1</i>	1	0.15631	0.03109	25.30	<0.001
25		115	<i>B0</i>	1	–1.79594	0.35257	25.91	<0.001	
			<i>B1</i>	1	0.17928	0.03494	26.32	<0.001	
50		115	<i>B0</i>	1	–2.11764	0.36818	33.06	<0.001	
			<i>B1</i>	1	0.12379	0.02368	27.35	<0.001	
100		114	<i>B0</i>	1	–2.01936	0.34948	33.41	<0.001	
			<i>B1</i>	1	0.08184	0.01749	21.90	<0.001	

^a The basic form of the model was $p = \frac{e^{(B0+B1*X)}}{1+e^{(B0+B1*X)}}$, where *p* is the probability of capturing *X. germanus*, *X* is degree-days, or *X. germanus* flight activity in woodlots represented by captures of *X. germanus* in –13-m traps, *B0* and *B1* are parameters to be estimated. Data for 2013 and 2014 were combined for these analyses.

Table 5. Probability of capturing *X. germanus* with corresponding predicted degree-days (10°C) or *X. germanus* captures (flight activity) in adjacent woodlots (–13 m traps) derived from logistic regression analysis for each distance

Model	Probability of capturing <i>X. germanus</i> (%)	Degree-days or captures in woodlot traps				
		–13 m	13 m	25 m	50 m	100 m
DD 10°C	25	54	85	91	98	118
	50	85	132	131	176	200
	90	146	228	210	330	370
<i>X. germanus</i> flight activity in woodlots ^a	25	na	4	4	9	12
	50	na	11	11	18	25
	90	na	25	23	35	52

^a Derived from total *X. germanus* captured in a plot’s woodlot (–13 m) trap.

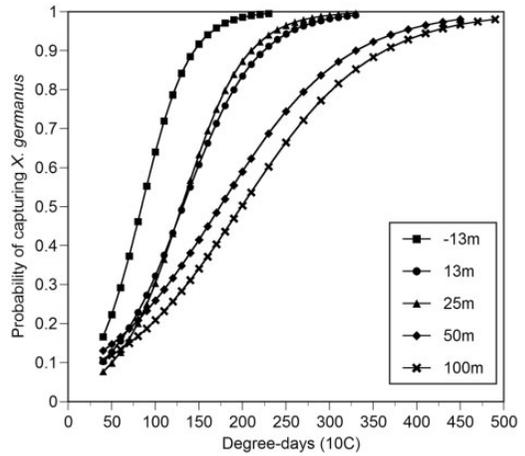


Fig. 2. Logistic regression analysis of the relationship between flight activity of *X. germanus* at the various distances, represented by the probability of capturing *X. germanus* in ethanol-baited bottle traps, in relation to degree-days (10°C) accumulated from 1 January.

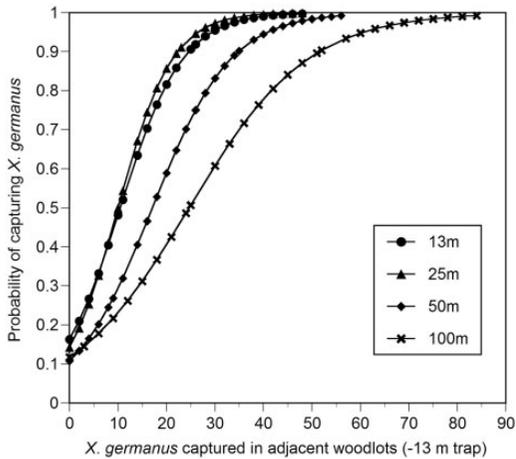


Fig. 3. Logistic regression analysis of the relationship between flight activity of *X. germanus* within nurseries, represented by the probability of capturing *X. germanus* in ethanol-baited bottle traps, in relation to captures in corresponding woodlot traps (–13-m traps of the same plot).

The relationships between degree-days and *X. germanus* flight activity indicated that *X. germanus* occurred in wooded areas adjacent to nurseries ahead of locations within nurseries. Furthermore, higher levels of flight activity were observed in woodlands before *X. germanus* were found in nursery interior traps compared to when first detections were seen in traps closer to the perimeter. These results provide further evidence that beetles overwinter in areas outside the nursery, dispersing toward the nursery interior over time as more of the population becomes active. Timing and levels of *X. germanus* flight activity, as measured by trap detections, were similar at 13 and 25 m from the nursery border, occurring earlier than activity measured at 50 and 100 m. The relationships between flight activity of *X. germanus* in woodlots adjacent to nurseries and presence of beetles at 13 and 25 m into nurseries were similar and occurred at lower activity levels than at 50 and 100 m. Heidenreich (1964) proposed that *X. germanus* was capable of flying 200–300 m to locate a suitable host, while Peer and Taborsky (2005) estimated their dispersal distance ranges up to 100 m. In the current study, *X. germanus* were captured 100 m from presumed emergence sites (woodlands), indicating they can fly at least 100 m. However, numbers of beetles were relatively low 100 m into nurseries compared to 13 and 25 m.

Movement of *X. germanus* into nurseries appears to occur over time and the probability of their occurrence in nurseries appears to be strongly associated with the proximity of adjacent woodlots. Because the probability of beetles occurring increases as the distance to wooded habitats decreases, and taking into consideration factors such as stress and possibly host preference, trees near perimeters of nurseries appear to be at greater risk of attack than those in a nursery's interior. Trees in closer proximity to woodlots would be exposed to greater pressure from colonizing beetles than those

farther into the nursery. In terms of managing *X. germanus* in nurseries, growers could spray the blocks nearest to adjacent wooded areas first. Reding et al. (2013b) demonstrated degree-days and plant phenology could be used to time trunk sprays for *X. germanus* in Ohio. In addition, growers could possibly reduce the risk of seasonal attack on the most ambrosia beetle susceptible trees by placing them as far from adjacent wooded areas as possible.

Since ambrosia beetles move into nurseries from surrounding habitats, strategies that involve intercepting or deflecting beetles away from valuable trees might also present an opportunity for their management in nurseries. These strategies could exploit the efficient host-seeking capabilities of ambrosia beetles by attracting them away from saleable trees. Ethanol-baited traps could be positioned around the perimeter of nurseries to intercept beetles as they move into nurseries (Prokopy et al. 1990). Trees injected with ethanol could be used as trap trees to intercept or divert beetles away from valuable trees (Ranger et al. 2010). Repeated experiments have shown that injecting trees with ethanol induces attacks by ambrosia beetles, while adjacent noninjected trees are not attacked (Ranger et al. 2010, 2012; Reding et al. 2013a). Ornamental nurseries usually have trees designated for culling that could be injected with ethanol to use as trap trees. These tactics could reduce attack pressure on nursery trees to the point that efficacy of trunk sprays is enhanced. In a “push–pull” strategy for managing ambrosia beetles, traps and trap trees could be used as “pull” components, while repellents applied to valuable nursery trees would act as “push” components (Borden et al. 2006, Gillette et al. 2012).

Acknowledgments

We thank Betsy Anderson for technical assistance identifying Scolytinae, and the cooperating nurseries. This research was supported in part by funding from USDA-ARS Research Project 3607-22000-012-00D and the USDA Floriculture and Nursery Research Initiative. Mention of proprietary products or companies is included for the reader's convenience and does not imply any endorsement or preferential treatment by USDA-ARS.

References Cited

- Adelman, S. 1969. The generalized randomized block design. *Am. Stat.* 23: 35–36.
- Analytical Software. 2003. *Statistix 8 user's manual*. Analytical Software, Tallahassee, FL.
- Borden, J. H., A. L. Birmingham, and J. S. Burleigh. 2006. Evaluation of the push-pull tactic against the mountain pine beetle using verbenone and non-host volatiles in combination with pheromone-baited trees. *For. Chron.*, 82: 579–590.
- Cade, S. C., B. F. Hrutford, and R. I. Gara. 1970. Identification of a primary attractant for *Gnathotrichus sulcatus* isolated from Western hemlock logs. *J. Econ. Entomol.* 63: 1014–1015.
- French, J.R.J. and R. A. Roeper. 1972. Interactions of the ambrosia beetle *Xyleborus dispar* (Coleoptera: Scolytidae), with its symbiotic fungus *Ambrosiella hartigii* (Fungi Imperfecti). *Can. Entomol.* 104: 1635–1641.

- Gillette, N. E., C. J. Mehmehl, S. R. Mori, J. N. Webster, D. L. Wood, N. Erbilgin, D. R. Owen. 2012. The push-pull tactic for mitigation of mountain pine beetle (Coleoptera: Curculionidae) damage in lodgepole and whitebark pines. *Environ. Entomol.* 41: 1575–1586.
- Graham, K. 1968. Anaerobic induction of primary chemical attractancy for ambrosia beetles. *Can. J. Zoo.* 46: 905–908.
- Hale, F. A. 2007. Entomological research priorities for nursery and landscape ornamentals, pp. 17–21. In B. L. James (ed.), *Proceeding 52nd Annual Southern Nursery Association Research Conference*, Atlanta, GA.
- Heidenreich, E. 1964. Ökologische Bedingungen für Primärbefall durch *Xylosandrus germanus*. *J. Appl. Entomol.* 54: 131–140.
- Hoffman, C. H. 1941. Biological observations on *Xylosandrus germanus* (Bldfd.). *J. Econ. Entomol.* 34: 38–42.
- Hudson, W., and R. Mizell. 1999. Management of Asian ambrosia beetle, *Xylosandrus crassiusculus*, in nurseries, pp. 198–201. In B. L. James (ed.), *Proceeding 44th Annual Southern Nursery Association Research Conference*, Atlanta, GA.
- Kelsey, R. G., and G. Joseph. 2001. Attraction of *Scolytus unispinosus* bark beetles to ethanol in water-stressed douglas-fir branches. *For. Ecol. Manag.* 144: 229–238.
- Kimmerer, T. W., and T. T. Kozlowski. 1982. Ethylene, ethane, acetaldehyde, and ethanol production by plants under stress. *Plant Physiol.* 69: 840–847.
- Klimetzek, D., J. Köhler, J. P. Vité, and U. Kohnle. 1986. Dosage response to ethanol mediates host selection by “secondary” bark beetles. *Naturwissenschaften* 73: 270–272.
- Kühnholz, S., J. H. Borden, and A. Uzunovic. 2001. Secondary ambrosia beetles in apparently healthy trees: Adaptations, potential causes and suggested research. *Integr. Pest Manag. Rev.* 6: 209–219.
- Moeck, H. A. 1970. Ethanol as the primary attractant for the ambrosia beetle *Trypodendron lineatum* (Coleoptera: Scolytidae). *Can. Entomol.* 102: 985–995.
- Montgomery, M. E., and P. M. Wargo. 1983. Ethanol and other host-derived volatiles as attractants to beetles that bore into hardwoods. *J. Chem. Ecol.* 9: 181–190.
- Oliver, J. B., and C. M. Mannion. 2001. Ambrosia beetle (Coleoptera: Scolytidae) species attacking chestnut and captured in ethanol-baited traps in middle Tennessee. *Environ. Entomol.* 30: 909–918.
- Peer, K., and M. Taborsky. 2005. Outbreeding depression, but no inbreeding depression in haplodiploid ambrosia beetles with regular sibling mating. *Evolution* 59: 317–323.
- Prokopy, R. J., S. A. Johnson, and M. T. O'Brien. 1990. Second-stage integrated management of apple arthropod pests. *Entomol. Exp. Appl.* 54: 9–19.
- Quinn, G. P., and M. J. Keough. 2002. *Experimental design and data analysis for biologists*. Cambridge University Press, New York, NY.
- Rabaglia, R. J., S. A. Dole, and A. I. Cognato. 2006. Review of American Xyleborina (Coleoptera: Curculionidae: Scolytinae) occurring north of Mexico, with an illustrated key. *Ann. Entomol. Soc. Am.* 99: 1034–1056.
- Ranger, C. M., M. E. Reding, A. B. Persad, and D. A. Herms. 2010. Ability of stress-related volatiles to attract and induce attacks by *Xylosandrus germanus* (Coleoptera: Curculionidae, Scolytinae) and other ambrosia beetles. *Agric. For. Entomol.* 12: 177–185.
- Ranger, C. M., M. E. Reding, P. B. Schultz, and J. B. Oliver. 2012. Ambrosia beetle (Coleoptera: Curculionidae) responses to volatile emissions associated with ethanol-injected *Magnolia virginiana* L. *Environ. Entomol.* 41: 636–647.
- Ranger, C. M., M. E. Reding, P. B. Schultz, and J. B. Oliver. 2013a. Influence of flood-stress on ambrosia beetle host-selection and implications for their management in a changing climate. *Agric. For. Entomol.* 15: 56–64.
- Ranger, C. M., P. C. Tobin, M. E. Reding, A. M. Bray, J. B. Oliver, P. B. Schultz, S. D. Frank, and A. B. Persad. 2013b. Interruption of semiochemical-based attraction of ambrosia beetles to ethanol-baited traps and ethanol-injected trap trees by verbenone. *Environ. Entomol.* 42: 539–547.
- Ranger, C. M., P. C. Tobin, and M. E. Reding. 2015. Ubiquitous volatile compound facilitates efficient host location by a non-native ambrosia beetle. *Biol. Invasions* 17: 675–686.
- Reding, M., J. Oliver, P. Schultz, and C. Ranger. 2010. Monitoring flight activity of ambrosia beetles in ornamental nurseries with ethanol-baited traps: Influence of trap height on captures. *J. Environ. Hort.* 28: 85–90.
- Reding, M. E., P. B. Schultz, C. M. Ranger, and J. B. Oliver. 2011. Optimizing ethanol-baited traps for monitoring damaging ambrosia beetles (Coleoptera: Curculionidae, Scolytinae) in ornamental nurseries. *J. Econ. Entomol.* 104: 2017–2024.
- Reding, M. E., J. Oliver, P. Schultz, C. M. Ranger, and N. Youssef. 2013a. Ethanol injection of ornamental trees facilitates testing insecticide efficacy against Ambrosia beetles (Coleoptera: Curculionidae: Scolytinae). *J. Econ. Entomol.* 106: 289–298.
- Reding, M. E., C. M. Ranger, J. B. Oliver, and P. B. Schultz. 2013b. Monitoring attack and flight activity of *Xylosandrus* spp. (Coleoptera: Curculionidae: Scolytinae): The influence of temperature on activity. *J. Econ. Entomol.* 106: 1780–1787.
- Underwood, A. J. 1997. *Experiments in ecology: Their logical design and interpretation using analysis of variance*. Cambridge University Press, Cambridge, United Kingdom.
- Weber, B. C., and J. E. McPherson. 1983. Life history of the ambrosia beetle *Xylosandrus germanus* (Coleoptera: Scolytidae). *Ann. Entomol. Soc. Am.* 76: 455–462.
- Weber, B. C., and J. E. McPherson. 1984. Attack on black walnut trees by the ambrosia beetle *Xylosandrus germanus* (Coleoptera: Scolytidae). *For. Sci.* 30: 864–870.
- Wood, S. L. 1982. The bark and ambrosia beetles of North and Central America (Coleoptera: Scolytidae), a taxonomic monograph. *Gt. Basin Nat. Mem.* 6: 1–1359.
- Zar, J. H. 1999. *Biostatistical analysis*. Prentice Hall, Upper Saddle River, NJ.
- Zhang, S., H. E. Burkhart, and R. I. Amateis. 1996. Modeling individual tree growth for juvenile loblolly pine plantations. *For. Ecol. Manag.* 89: 157–172.

Received 7 April 2015; accepted 1 June 2015.