

## Flight Capacities and Diurnal Flight Patterns of the Ambrosia Beetles, *Xyleborus glabratus* and *Monarthrum mali* (Coleoptera: Curculionidae)

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### Abstract

We compared the flight activity of *Xyleborus glabratus* Eichhoff, vector and symbiont of the causal agent of laurel wilt disease (*Raffaelea lauricola*), with a native species *Monarthrum mali* (Fitch) using flight mills. Flight mills were operated either for 24 h or for three 3-h time intervals. During the 3-h interval experiment, the shortest time to flight initiation for *X. glabratus* occurred at 1600–1900 hours. The average flight time and total flying distance during 1600–2100 hours were also higher than those quantified during the other two recording times investigated. However, total flight duration and proportion of fliers was highest at 1000–1300 hours. We compared several flight parameters. About 64.0% of tested *X. glabratus* flew <20 m. During 24-h recording periods, *M. mali* flew longer distances than *X. glabratus*. Over 50.0% of *M. mali* flew over 100 m on the flight mill. *Xyleborus glabratus* flight activity was greatest between 1200 and 1800 hours, while *M. mali* flew most frequently between 1500 and 2100 hours. *Monarthrum mali* flew more than five times more frequently than *X. glabratus*, and their longest single flight distance ( $37.5 \pm 12.5$  m) and total flight distance ( $213.7 \pm 85.5$  m) were greater than those of *X. glabratus*. These data will be useful for development of species-specific control and monitoring protocols for these ambrosia beetles based on greater understanding of their flight capacities and associated invasion distance.

**Key words:** laurel wilt, redbay ambrosia beetle, flight mill, flight capacity

Ambrosia beetles and other wood-associated insects are of increasing concern owing to transport outside of their native Asian range via modern global commerce and travel (Harrington et al. 2011). Ambrosia beetles (Curculionidae: Scolytinae and Platypodinae) and their larvae feed on wood-digesting symbiotic fungi within galleries in the xylem tissue of generally dying or dead wood (Haack 2001). Ecologically, this contributes to the decomposition of wood in compromised or already dying trees. However, movement of ambrosia beetles and exposure to new hosts, in some instances, can be detrimental to agricultural and forestry production in newly invaded habitats. The most concerning ambrosia beetle species in the United States currently is the invasive redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff (Coleoptera: Scolytidae), because it is vector of the fungus that causes laurel wilt disease. *Xyleborus glabratus* was first introduced into the southeastern United States in 2002 likely by movement of previously infested wood products (Kendra et al. 2013). Since its introduction into the United States, it has devastated populations of redbay (*Persea borbonia*) trees, a dominant component of Coastal Plain forest communities in the southeastern United States.

Adult *X. glabratus* are small (2 mm long), brown-black in color, with accordingly small white legless larvae. *Xyleborus glabratus* is currently the most concerning of the 50 species of exotic scolytids established in the United States (Haack 2001) because it is the known vector of the lethal fungal phytopathogen *Raffaelea lauricola* causing laurel wilt. In April of 2012, laurel wilt was found in Florida avocado (Lauraceae: *Persea americana*) groves (Mayfield et al. 2008). This has been a major concern to the industry because plants in the family Lauraceae are at a high risk of becoming infected with the beetle's fungal symbiont and there is a high density of alternate hosts (Mayfield et al. 2008).

The beetles carry fungal spores within mycangia located at the base of their mandibles (Fraedrich et al. 2008). The fungus is quickly spread throughout the plant and eventually blocks the xylem completely, resulting in rapid plant death. The beetles interbreed within the plant and exhibit haplo-diploid sex determination that skews the sex ratio toward female (Rabaglia 2002). The adult female beetles are the only insects capable of leaving the tree and migrating to other hosts; male adult beetles are smaller, haploid, and flightless. Although these beetles are likely

most widely spread by movement of wood and wood product throughout the United States, adult female beetles are able to fly, and their capacity for natural migration between hosts is currently unknown.

Insect flight and dispersal capabilities can be measured in many ways. Insect flight range and dispersal capacity can be addressed in the field using mark–release–recapture (MRR; *Avalos et al.* 2014). However, *Abbas et al.* (2006) and *Chinchilla et al.* (1993) suggest that external stimuli such as pheromones or abiotic factors like wind may affect results and their interpretation. Analysis of flight behavior and dispersal capacities of another coleopteran, *Rhynocophorus ferrugineus* (Olivier), with MRR was challenging (*Avalos et al.* 2014). In addition, ambrosia beetles spend most of their life within their host wood, and are only present in the external environment for a short period of time, when they forage for a new host. Therefore, an MRR strategy might be challenging to implement for ambrosia beetles. To resolve conflicting outcomes under field conditions, laboratory experiments using a flight mill compliment evaluations of an insect's flight capabilities and behavior. Although these are unnatural circumstances, the technique has been used successfully to study flight behaviors of many economically important insect pests, including *Cactoblastis cactorum* (Berg) (Lepidoptera: Pyralidae) (*Sarvary et al.* 2008), *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) (*Hughes and Dorn* 2002), *Aphis glycines* Matsumura (Hemiptera: Aphididae) (*Zhang et al.* 2008), *Cylas formicarius* (Summers) (Coleoptera: Brentidae) (*Moriya and Hiroyoshi* 1998), and *Conotrachelus nenuphar* (Herbst) (Coleoptera: Curculionidae) (*Chen et al.* 2006). The technique is particularly effective for estimating the physiological upper limits of flight capacity.

To effectively implement monitoring and control techniques, it is essential to understand the dispersal activity and movement behavior of ambrosia beetles. A better understanding of *X. glabratus* dispersal capabilities will help in implementing monitoring protocols. *Hulcr et al.* (2011) confirmed short-range attraction of *X. glabratus* to volatiles from its symbionts in laboratory bioassays. Also, progress has been made toward chemical identification of fungal attractants and their potential practical use as a lure in the field (*Kuhns et al.* 2014). Recent investigations of potential attractants or repellents for monitoring and management of *X. glabratus*, respectively, have been carried out in the field and laboratory (*Martini et al.* 2015, *Hughes et al.* 2017). Flight periodicity and seasonal flight patterns of *X. glabratus* have helped optimize trap design and placement (*Brar et al.* 2012). Attractants such as a manuka oil or cubeb oil have been used in trapping and surveying this species for quarantine and management purposes (*Hughes et al.* 2015, *Johnson et al.* 2014). Cubeb oil and one of its constituents,  $\alpha$ -copaene, have been identified as particularly effective attractants for *X. glabratus* (*Kendra et al.* 2014, 2015). However, the effective trapping range or distance from which beetles are attracted to these lures in the field is currently unknown.

In the current investigation, we explored the flight duration, velocity, and flight distance capabilities of *X. glabratus*. As a comparison, we also investigated the North American ambrosia beetle, *Monarthrum mali* Fitch, a species that promotes the spread of an established fungus within Lauraceous trees.

## Materials and Methods

### Experimental Insects

*Xyleborus glabratus* and *M. mali* emerged and were collected from infested swamp bay (*Persea palustris* (Raf.) Sarg.) trees with signs of ambrosia beetle establishment. Logs with signs of laurel wilt were

obtained from Wekiwa Springs State Park (WSSP, Apopka, FL — 28° 42'40.93" N, 81° 27'45.85" W) and Ichetucknee Springs State Park (ISSP, Fort White, FL—29° 58'2.47" N, 82° 46'33.82" W). They were placed into ventilated plastic bins (76 by 50 by 36 cm) at  $25 \pm 1$  °C,  $45 \pm 15\%$  relative humidity, and exposed to natural light in a secure rearing facility. Mason jars were screwed into holes cut in the bins and contained moist Kimwipe (Kimtech, Rosswell, GA). Only the mason jars were exposed to light to attract beetles into the jars. Beetles were collected from the jars and the surface of logs daily. All beetles used in flight mill studies were female and of unknown mating status. *Monarthrum mali* was used for comparison because it was present in the same logs with *X. glabratus* and the intraplant spread of *R. lauricola* in nature is unknown. However, promiscuous lateral transfer of *R. lauricola* by nonsymbiotic ambrosia beetle species has been documented (*Carrillo et al.* 2014).

### Flight Mill Apparatus and Procedure

The flight mill apparatus used in this study was described thoroughly in *Martini et al.* (2014). The pivot arm assembly was composed of a 13-cm fiber optic horizontal axis fixed to a pivot consisting of a metal fiber. The pivot was positioned vertically under a magnet and another magnet was placed about 2.5 cm below to hold the metal fiber perpendicularly. At one end of the horizontal fiber optic rod, a beetle was attached using nontoxic, washable glue (Elmer's products, Columbus, OH). An aluminum minute flag was attached to the other end to both activate a photo-sensor and record one full revolution of the arm and balance the weight of the beetle. The light source was provided by a linear fluorescent 54-W bulb (F54W/T5/865/ECO, GE lighting, Nela Park, OH). Beetles were chilled on an ice pack prior to attachment. All experiments were carried out under the conditions described for rearing above. Beetles were tested either for a complete 24-h period or at one of the three time interval treatments: 1) 1000–1300 hours, 2) 1300–1600 hours, and 3) 1600–1900 hours. These two approaches were complementary because beetles were unlikely to reach their physiological limits during 3-h time intervals, although their flight capacity may have declined over time during the 24-h measurement interval. However, the 24-h survey allowed more precise estimation of the average beetle flight distance during one diel period. The three interval windows chosen were based on previously reported activity of *X. glabratus* in the field (*Brar et al.* 2012) and the activity observed during the 24-h observation period.

The data collection system was adapted from *Attisano et al.* (2015). Briefly, four flight mills with sensors were concurrently connected to a circuit and a data logger (DATAQ Instruments, Model DI-149 HS, Akron, OH). Data were acquired from each data logger using a custom-made four-channel acquisition system, and flight signals were transformed into waveforms using WinDAQ Waveform Browser software (DATAQ Instruments).

### Experimental Design and Analysis

Because our flight mill apparatus was four-channel, we recorded flight data from four individual beetles per replicate. All experiments were carried out over 10 replicates. In the experiment examining flight patterns of *X. glabratus* at different recording times, we tested 108 females. Also, 36 *X. glabratus* females were tested in the 24-h recording experiment. In the case of *M. mali*, 92 females were examined at the three distinct time intervals and 33 females were tested during the 24-h recordings. For 24-h experiments, all recordings were initiated at 1000 hours.

**Table 1.** Flight capacity of the redbay ambrosia beetle, *X. glabratus*, quantified on flight mills for 24 h

Flight parameters	N	Mean $\pm$ SE
No. of flights ( <i>n</i> )	25	11.8 $\pm$ 2.2
Avg flight distance (m)	21	5.0 $\pm$ 1.6
Longest single flight (m)	28	10.0 $\pm$ 4.3
Avg flight velocity (m/s)	32	1.0 $\pm$ 0.1
Max flight velocity (m/s)	37	2.0 $\pm$ 0.3
Avg flight time (s)	31	8.4 $\pm$ 0.0
Total flight time (s)	36	68.5 $\pm$ 18.3
Time elapsed to first flight (s)	22	2204.7 $\pm$ 512.1
Total flight distance (m)	18	17.6 $\pm$ 4.6

Flight duration (s), distance (m), and velocity (m/s) were quantified using WinDAQ waveform software. A one-way analysis of variance (ANOVA) was used to analyze data. Beforehand, we assessed data for equal variance and normal distribution. We separated the means into three groups by time interval. The means were analyzed using Tukey's honest significant difference (HSD) test, with significance level of  $P < 0.05$ . Data between the two species were compared using *t*-tests. All analyses were performed using IBM SPSS Statistics 22.

## Results

### Flight Capacity of *X. glabratus* on the Flight Mill During the 24-h Observation Period

Nine parameters of *X. glabratus* flight capacity are summarized in Table 1. Beetles displayed an average  $\pm$  standard error of mean ( $\pm$ SEM) velocity of  $1.00 \pm 0.1$  m/s and average ( $\pm$  SEM) maximum velocity of  $2.04 \pm 0.3$  m/s. Over a 2-h period, beetles flew for  $68.5 \pm 18.0$  s and  $\sim 17.6 \pm 4.6$  m (Table 1). Less than 64.0% of *X. glabratus* flew 20 m during the 24-h recording period (Fig. 1A).

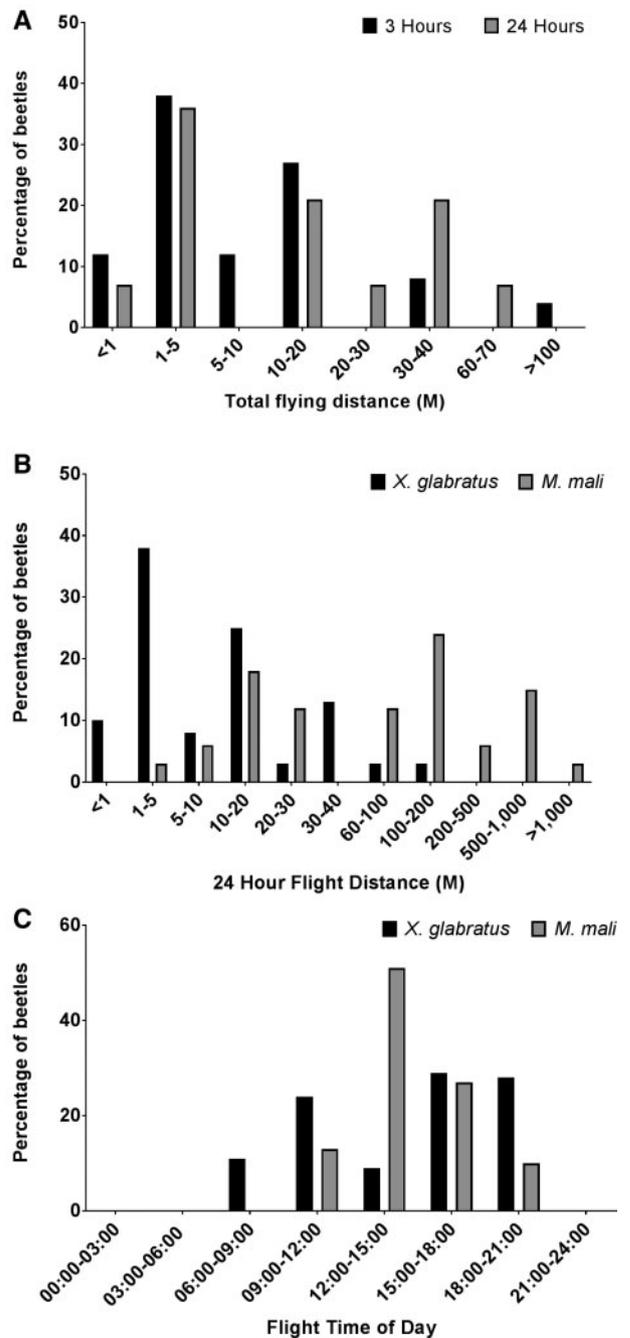
### Flight Patterns of *X. glabratus* at Different Recording Intervals

Daily variation in flight activity of *X. glabratus* was approximated by recording beetle flight during three different intervals throughout the photoperiod. In total, 108 *X. glabratus* were tested. Of those tested,  $\sim 60.3\%$  failed to fly and were excluded from analyses of flight performance. With the exception of latency to initial flight and total flight duration, there were no statistical differences in flight characteristics of *X. glabratus* during the three time intervals tested (Table 2). Flight was initiated sooner during 1600–1900 hours than during the other intervals tested, suggesting that this interval was within the period of natural flight activity of *X. glabratus*.

The average flight distance and longest single flight were highest during the 1600–1900 hours recording interval. Average flight time and total flying distance during this period were also higher than those observed at the other recording intervals; however, there were no statistical differences ( $\alpha = 0.05$ ) between the number of flights occurring at the three different recording intervals. The majority of flights by *X. glabratus* occurred between 1000 and 1300 hours (Table 2). Approximately 88.0% of *X. glabratus* flew  $< 20$  m (Fig. 1A), and a small proportion flew  $> 100$  m during the 3-h recording intervals.

### Comparison of Flight Capacities and Patterns Between *X. glabratus* and *M. mali*

*Monarthrum mali* performed significantly ( $t = 4.082$ ,  $df = 39.93$ ,  $P = 0.0002$ ) more flights during 24 h of recording than *X. glabratus* (Fig. 2A). Compared with the results for *X. glabratus*, *M. mali* flew



**Fig. 1.** A comparison of *X. glabratus* and *M. mali* flight characteristics using a flight mill. (A) Percentage of redbay ambrosia beetles, *X. glabratus*, classified by total flight distance on flight mill for 3- and 24-h recording time intervals. (B) Percentage of *X. glabratus* and *M. mali* beetles flying various distances during a 24-h recording interval. (C) Daily flight activity of *X. glabratus* and *M. mali* as measured by flight mill recordings conducted at various intervals during the photoperiod.

longer distances. Over 50% of *M. mali* tested in this study flew  $> 100$  m during a 24-h recording period (Fig. 1B). In addition,  $\sim 18\%$  of *M. mali* flew 500–1,000 m, with 5% flying  $> 1,000$  m (Fig. 1B). The stronger flight capability of *M. mali* suggests greater dispersal distance than that expected by *X. glabratus*.

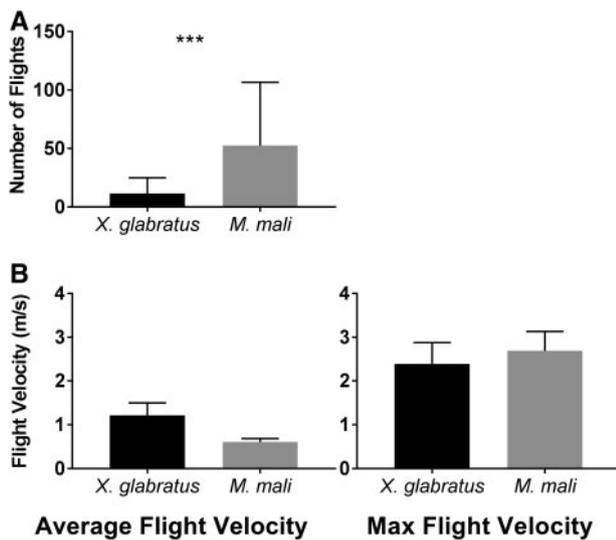
*Xyleborus glabratus* appeared most active between 1500 and 2100 hours. However, *M. mali* appeared to perform flights with greatest frequency between 1200 and 1800 hours (Fig. 1C).

**Table 2.** Daily activity of the redbay ambrosia beetle, *X. glabratus*, during 3-h recording intervals on flight mills

Flight parameters	Mean $\pm$ SEM			$P^a$
	1000–1300 hours ( $n = 20$ )	1300–1600 hours ( $n = 20$ )	1600–1900 hours ( $n = 24$ )	
Percentage of flyers	55.0a	30.0a	37.5a	0.253
No. of flights ( $n$ )	8.5 $\pm$ 2.7a	6.0 $\pm$ 1.5a	3.6 $\pm$ 1.5a	0.288 <sup>ns</sup>
Single flight distance (m)	3.2 $\pm$ 1.4a	1.3 $\pm$ 0.1a	5.2 $\pm$ 3.5a	0.561 <sup>ns</sup>
Longest single flight distance (m)	4.8 $\pm$ 1.8a	2.9 $\pm$ 0.9a	15.2 $\pm$ 10.3a	0.538 <sup>ns</sup>
Avg velocity (m/s)	0.7 $\pm$ 0.2a	0.7 $\pm$ 0.1a	0.6 $\pm$ 0.2a	0.898 <sup>ns</sup>
Max velocity (m/s)	2.2 $\pm$ 0.6a	1.5 $\pm$ 0.4a	1.0 $\pm$ 0.4a	0.252 <sup>ns</sup>
Single flight duration (s)	4.4 $\pm$ 1.1a	2.0 $\pm$ 0.5a	6.3 $\pm$ 2.7a	0.246 <sup>ns</sup>
Total flight duration (s)	67.9 $\pm$ 13.7a	10.4 $\pm$ 1.9b	28.6 $\pm$ 10.6ab	0.029*
Time elapsed to first flight (s)	924.6 $\pm$ 136.1b	3226.7 $\pm$ 584.0a	316.6 $\pm$ 54.4b	<0.001*
Total flight distance (m)	14.4 $\pm$ 3.3a	7.8 $\pm$ 2.2a	21.7 $\pm$ 17.9a	0.716 <sup>ns</sup>

<sup>a</sup> Means with different letters within rows indicate significant differences at  $\alpha = 0.05$  (one-way ANOVA, post hoc tests by Tukey HSD).

\* $0.01 < P < 0.05$ , ns  $P > 0.05$ .



**Fig. 2.** Comparison of flight number (A) and average and maximum flight velocity (B) between *X. glabratus* and *M. mali* during 24 h of recording on flight mills. ¶ indicates a significant difference in mean comparison between the two beetle species; <sup>ns</sup>  $P > 0.05$ ; \*  $0.01 < P < 0.05$ ; \*\*  $0.001 < P < 0.01$ ; \*\*\*  $P < 0.001$ .

Maximum flight velocity did not differ between the two species ( $t = 0.458$ ,  $df = 33.83$ ,  $P = 0.6499$ ; Fig. 2B); however, average flight velocity of *X. glabratus* was marginally higher than that of *M. mali* ( $t = 2.026$ ,  $df = 15.02$ ,  $P = 0.0609$ ; Fig. 2B).

There were no statistical differences in average flight distance between the two species ( $t = 1.8998$ ,  $df = 40.76$ ,  $P = 0.0648$ ; Fig. 3B). However, the longest single flight distance and total flight distance by *M. mali* were significantly greater than those of *X. glabratus* ( $t = 3.219$ ,  $df = 32.8$ ,  $P = 0.0029$ ;  $t = 3.536$ ,  $df = 32.3$ ,  $P = 0.0013$ , respectively; Fig. 3B). On an average, *M. mali* performed longer flights than *X. glabratus* ( $t = 3.886$ ,  $df = 34.68$ ,  $P = 0.0004$ ), and total flight time was greater in *M. mali* than *X. glabratus* ( $t = 4.271$ ,  $df = 33.24$ ,  $P = 0.0002$ ; Fig. 3B).

## Discussion

This is the first investigation to report on the flight capacity of both *X. glabratus* and *M. mali* under controlled conditions using a flight mill and is currently the best estimate of their physiological flight

capacities. There were significant differences in flight capacity and patterns between these two species. The flight activity of *X. glabratus* appeared greatest between 1600 and 1800 hours, while *M. mali* exhibited greatest flight activity earlier in the photophase (1400–1600 hours). Over a 24-h period, the flight distance of *X. glabratus* was limited to 20 m, while *M. mali* was capable of routinely flying >100 m during an equivalent interval. Because the beetles used in the study were newly collected just after emergence from wood, we hypothesize that they were physiologically prepared for movement from the host tree at the initiation of recordings. These results suggest that *M. mali* disperse farther than *X. glabratus*; however, both species have relatively limited dispersal capabilities without wind or anthropogenic assistance. However, with respect to aggregated host trees growing in clumped distribution within forests or within monocultures of cultivated agricultural species such as avocado, it appears that natural movement by *X. glabratus* could rapidly spread the fungal causal agent of laurel wilt from an epicenter of inoculum with detrimental ecological and economic consequences.

Measurement of flight capability using a flight mill is an approximation of physiological capability under controlled conditions, and previous experiments indicate that flight mill data must not be overly extrapolated without caution. Other beetle species have been assessed with this technique with varying success and compared with direct observations under field conditions. In a previous investigation using another beetle species, *Rhynocophorus ferrugineus* Olivier, up to 54% of tested beetles exhibited short-distance flights covering <100 m on the flight mill (Avalos et al. 2014). However, *R. ferrugineus* exhibited much stronger flight capacity under field conditions, with recorded flight distances >5,000 m (Avalos et al. 2014). Comparatively, the flight capacity of *X. glabratus* appeared limited, as measured by our flight mill recordings. Despite their overall similarity in size and biology, *M. mali* appeared to be much more capable of dispersal than *X. glabratus*, exhibiting flight approximately five times more frequently and routinely moving a distance an order of magnitude greater. It is, however, possible that both *X. glabratus* and *M. mali* may exhibit greater flight capacity under natural conditions, and this warrants further investigation.

Seasonal differences in flight velocity have been reported for weevils. Red palm weevil exhibited a higher average and maximum flight velocity in summer than during other times throughout the season (Hoddle et al. 2015). Scolytinae exhibit species-specific patterns of flight related to light intensity, temperature, and humidity (Rudisky

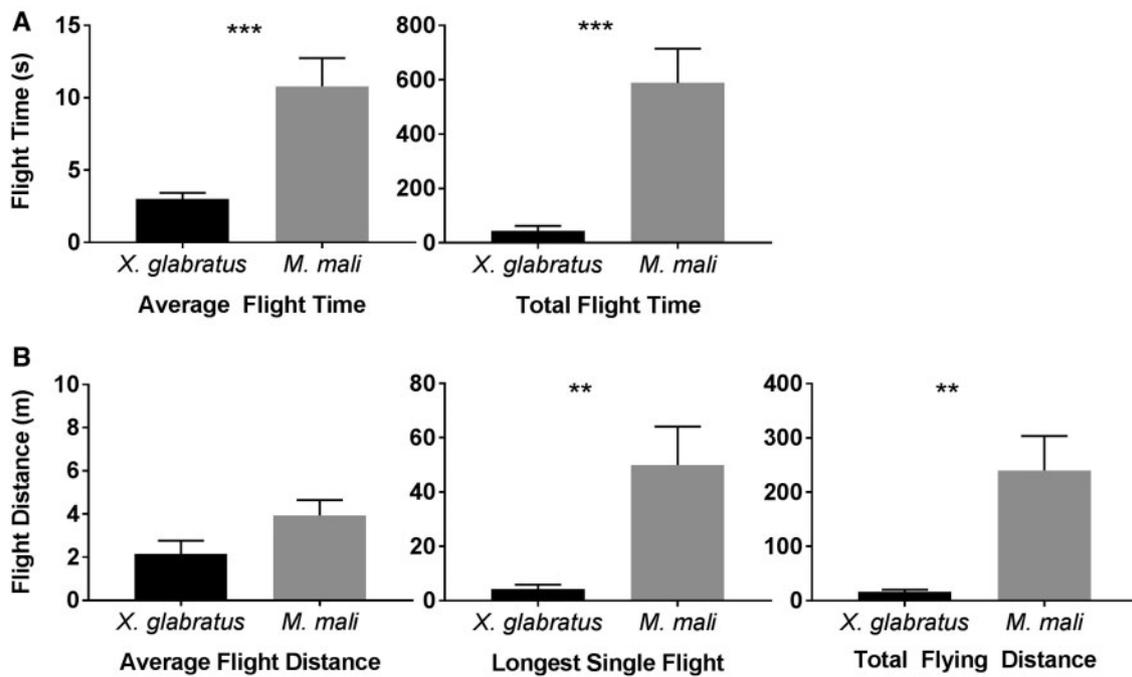


Fig. 3. Comparison of flight distance (A) and time (B) between *X. glabratus* and *M. mali* during 24 h of flight recording (\* indicates a significant difference in mean comparison between the two beetle species; <sup>NS</sup>  $P > 0.05$ ; \*  $0.01 < P < 0.05$ ; \*\*  $0.001 < P < 0.01$ ; \*\*\*  $P < 0.001$ ).

and Schneider 1969, Liu and Mclean 1993). Temperature is one of the most important factors affecting insect flight behavior; most beetles tend to fly to oviposition sites or shelter faster as temperature increases. Our flight mill results are congruent with results from a previous field investigation of beetle phenology and monitoring in which *Xyleborus glabratus* Eichhoff, *Xyleborus affinis* Eichhoff, and *Xyleborus ferrugineus* F. were observed flying during late afternoon and early evening in central Florida (Brar et al. 2012, Kendra et al. 2012). *Xyleborus glabratus* was observed initiating flight to host plant volatiles earlier than the two other species, with most beetles captured between 1400 and 1800 hours, while *X. affinis* and *X. ferrugineus* were typically observed after 1800 hours. However, the flight window of some ambrosia beetle species, such as *Xyleborinus andrewesi* Blandford (Okins and Thomas 2010), appears to overlap with that of *X. glabratus*. In general, flight periodicity of ambrosia beetles will likely vary seasonally. For example, *Xylosandrus mutilatus* Blandford captures in ethanol-baited traps are highest in spring when attacks on saplings are low and captures of adults are lowest in fall, when attacks on sapling are high (Stone and Nebeker 2007).

Accurate quantification of the dispersal potential of insect pests is critical during the initial stages of invasion because management and eradication are favored when populations are relatively low and localized (Tobin et al. 2014). Our data estimate the dispersal potential of *X. glabratus* and *M. mali*. At this point, it is unclear if determining the true dispersal of these two ambrosia beetles in the field is tractable. Our investigation suggests that *X. glabratus* is unlikely to move several kilometers without wind assistance or anthropogenic movement. The effect of wind within a dense forest habitat might be limited to exceptional weather events given that these beetles primarily fly below 2 m in height and below the tree canopy (Brar et al. 2012). However, a localized infestation could spread rapidly within a forest or crop monoculture following an introduction of an initial inoculum source. Understanding the flight capabilities of *X. glabratus* may allow for more effective implementation of management and monitoring tools developed for this high-risk pest (Brar et al. 2012, Maner et al. 2013).

In avocado, occurrence of *X. glabratus* is rare and transmission of *R. lauricola* is likely caused by alternative vectors such as *Xyleborus volvulus* F. and *Xyleborus bispinatus* Eichhoff that acquire *R. lauricola* spores by lateral transfer within infected dead trees (Carrillo et al. 2014). Future investigations should focus on the flight capabilities of these two species to better understand the spread of laurel wilt in avocado groves.

Based on our flight mill results, most *X. glabratus* exhibited ~20 m of movement (total flight distance =  $17.6 \pm 4.6$  m; Table 1) during 24-h bouts. We crudely estimate potential spread up to 250 m within forests during a period of 2 wk. This distance of spread may also apply to the potential movement of the laurel wilt disease causal pathogen to healthy trees from infected areas. Monitoring traps in the field will be necessary to prove the validity of these estimates. A trapping investigation determined that increasing trap distance up to 300 m from a source *X. glabratus* population had little effect on beetle captures (Hanula et al. 2016). Baiting traps with an attractant lure has greater impact on capture of *X. glabratus* than trap spacing (Hanula et al. 2016). Unexpectedly, more *X. glabratus* were not captured in closer proximity to the source population, and there was no clear gradient of diminishing beetle abundance with increasing distance from the infested area (Hanula et al. 2016). An effective trap spacing to attract *X. glabratus* to host odor sources using eight-unit funnel traps baited with cubeb oil lure for *X. glabratus* is  $< 1$  m (Hanula et al. 2016).

Spacing of monitoring traps may impact captures of *X. glabratus* depending on the trap and lure type used, and further investigation is warranted for optimizing detection efforts in quarantine areas. *Xyleborus glabratus* females emerge from natal trees and initiate flight in search of other appropriate host trees. At this time, how far they can fly before initiating boring is an open question. Our laboratory data indicate that flights  $> 10.0 \pm 4.3$  m per day in distance may be rare. These results may be useful for estimating spacing intervals for *X. glabratus* monitoring traps in quarantine and management areas, but need further field validation.

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## References

- Abbas, M.S.T., S. B. Hanounik, A. S. Shahdad, and S. A. Al-Bagham. 2006. Aggregation pheromone traps, a major component of IPM strategy for the red palm weevil, *Rhynchophorus ferrugineus* in date palms (Coleoptera: Curculionidae). *J. Pest. Sci.* 79: 69–73. [TQ2][TQ3]
- Attisano, A., J. T. Murphy, A. Vickers, and P. J. Moore. 2015. A simple flight mill for the study of tethered flight in insects. *J. Vis. Exp.* 106: e53377. doi:10.3791/53377.
- Avalos, J. A., A. M. Campoy, and A. Soto. 2014. Study of the flying ability of *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae) adults using a computer-monitored flight mill. *Bull. Entomol. Res.* 104: 462–470.
- Brar, G. S., J. L. Capinera, S. McLean, P. E. Kendra, R. C. Ploetz, and J. E. Peña. 2012. Effect of trap size, trap height and age of lure on sampling *Xyleborus glabratus* (Coleoptera: Curculionidae: Scolytinae), and its flight periodicity and seasonality. *Fla. Entomol.* 95: 1003–1011.
- Carrillo, D., R. E. Duncan, J. N. Ploetz, A. F. Campbell, R. C. Ploetz, and J. E. Peña. 2014. Lateral transfer of a phytopathogenic symbiont among native and exotic ambrosia beetles. *Plant Pathol.* 63: 54–62.
- Chen, H., C. Kaufmann, and H. Scherm. 2006. Laboratory evaluation of flight performance of the plum curculio (Coleoptera: Curculionidae). *J. Econ. Entomol.* 99: 2065–2071.
- Chinchilla, C. M., A. C. Oehlschlager, and L. M. Gonzales. 1993. On the management of red ring disease in oil palm through pheromone based trapping of *Rhynchophorus palmarum*. In *Pipoc Porim International Palm Oil Congress "Update and vision,"* 20–25 September 1993. Kuala Lumpur, Malaysia.
- Fraedrich, S.W.S., T.T.C. Harrington, R. J. Rabaglia, M. D. Ulyshen, A. E. Mayfield, III, J. L. Hanula, J. M. Eickwort, and D. R. Miller. 2008. A fungal symbiont of the redbay ambrosia beetle causes a lethal wilt in redbay and other Lauraceae in the southeastern United States. *Plant Dis.* 92: 215–224.
- Haack, R. A. 2001. Intercepted scolytidae (Coleoptera) at U.S. ports of entry: 1985–2000. *Integr. Pest Manage. Rev.* 6: 253–282.
- Hanula, J. L., A. E. Mayfield, L. S. Reid, and S. Horn. 2016. Influence of trap distance from a source population and multiple traps on captures and attack densities of the redbay ambrosia beetle (Coleoptera: Curculionidae: Scolytinae). *J. Econ. Entomol.* 109: 1196–1204.
- Harrington, T. C., H. Y. Yun, S. S. Lu, H. Goto, D. N. Aghayeva, and S. W. Fraedrich. 2011. Isolations from the redbay ambrosia beetle, *Xyleborus glabratus*, confirm that the laurel wilt pathogen, *Raffaelea lauricola*, originated in Asia. *Mycologia* 103: 1028–1036.
- Hoddle, M. S., C. D. Hoddle, J. R. Faleiro, H.A.F. EL-Shafie, D. R. Jeske, and A. A. Sallam. 2015. How far can the red palm weevil (Coleoptera: Curculionidae) fly? Computerized flight mill studies with field-captured weevils. *J. Econ. Entomol.* 108: 2599–2609.
- Hughes, J., and S. Dorn. 2002. Sexual differences in the flight performance of the oriental fruit moth, *Cydia molesta*. *Entomol. Exp. Appl.* 103: 171–182.
- Hughes, M., X. Martini, E. Kuhns, J. Cole, A. Mafra-Neto, L. L. Stelinski, and J. A. Smith. 2017. Evaluation of repellents for the redbay ambrosia beetle, *Xyleborus glabratus*, vector of the laurel wilt pathogen. *J. Appl. Entomol.* In press.
- Hughes, M. A., J. Smith, R. Ploetz, P. Kendra, A. E. Mayfield, J. Hanula, J. Hulcr, L. Stelinski, S. Cameron, J. Riggins, et al. 2015. Recovery plan for laurel wilt on redbay and other forest species caused by *Raffaelea lauricola* and disseminated by *Xyleborus glabratus*. National Plant Disease Recovery System, Homeland Security Presidential Directive Number 9 (HSPD-9).
- Hulcr, J., R. Mann, and L. L. Stelinski. 2011. The scent of a partner: Ambrosia beetles are attracted to volatiles from their fungal symbionts. *J. Chem. Ecol.* 37: 1374–1377.
- Johnson, C., R. Cameron, J. Hanula, and C. Bates. 2014. The attractiveness of Manuka oil and ethanol, alone and in combination, to *Xyleborus glabratus* (Coleoptera: Curculionidae: Scolytinae) and other Curculionidae. *Fla. Entomol.* 97: 861–864.
- Kendra, P. E., W. S. Montgomery, J. Niogret, M. A. Deyrup, L. Guillen, and N. D. Epsky. 2012. *Xyleborus glabratus*, *X. affinis*, and *X. ferrugineus* (Coleoptera: Curculionidae: Scolytinae): electroantennogram responses to host-based attractants and temporal patterns in host-seeking flight. *Environ. Entomol.* 41: 1596–1605.
- Kendra, P. E., Montgomery, W. S., Niogret, J. & Epsky N. D. (2013). An Uncertain Future for American Lauraceae : A Lethal Threat from Redbay Ambrosia Beetle and Laurel Wilt Disease (A Review). *American Journal of Plant Sciences*, 4, 727–738.
- Kendra, P. E., W. S. Montgomery, E. Q. Schnell, J. Niogret, M. A. Deyrup, and N. D. Epsky. 2014. Evaluation of seven essential oils identifies cubeb oil as most effective attractant for detection of *Xyleborus glabratus*. *J. Pest. Sci.* 87: 681–689.
- Kendra, P. E., J. Niogret, W. S. Montgomery, M. A. Deyrup, and N. D. Epsky. 2015. Cubeb oil lures: Terpenoid emissions, trapping efficacy, and longevity for attraction of redbay ambrosia beetle (Coleoptera: Curculionidae: Scolytinae). *J. Econ. Entomol.* 108: 350–361.
- Kuhns, E. H., Y. Tribuiani, X. Martini, W. L. Meyer, J. Peña, J. Hulcr, and L. L. Stelinski. 2014. Volatiles from the symbiotic fungus, *Raffaelea lauricola*, are synergistic with Manuka lures for increased capture of Redbay ambrosia beetle, *Xyleborus glabratus*. *Agric. Forest Entomol.* 16: 87–94.
- Liu, Y., and J. A. Mclean. 1993. Observations on the biology of the ambrosia beetle *Gnathotrichus retusus* (Lee). *Can. Entomol.* 101: 1248–1255.
- Maner, M. L., J. L. Hanula, and S. K. Braman. 2013. Gallery productivity, emergence, and flight activity of the redbay ambrosia beetle (Coleoptera: Curculionidae: Scolytinae). *Environ. Entomol.* 42: 642–647.
- Martini, X., A. Hoyte, and L. L. Stelinski. 2014. Abdominal color of the Asian citrus psyllid (Hemiptera: Liviidae) is associated with flight capacities. *Ann. Entomol. Soc. Am.* 107: 842–847.
- Martini, X., M. A. Hughes, J. A. Smith, and L. L. Stelinski. 2015. Attraction of redbay ambrosia beetle, *Xyleborus glabratus*, to leaf volatiles of its host plants in North America. *J. Chem. Ecol.* 41: 613–621.
- Mayfield, A. E., J. E. Peña, J. H. Crane, J. A. Smith, C. L. Branch, E. D. Ottoson, and M. Hughes. 2008. Ability of the redbay ambrosia beetle (Coleoptera: Curculionidae: Scolytinae) to bore into young avocado (Lauraceae) plants and transmit the laurel wilt pathogen (*Raffaelea* sp). *Fla. Entomol.* 91: 485–487.
- Moriya, S., and S. Hiro Yoshi. 1998. Flight and locomotion activity of the sweetpotato weevil (Coleoptera: Brentidae) in relation to adult age, mating status and starvation. *J. Econ. Entomol.* 91: 439–443.
- Okins, K. E., and M. C. Thomas. 2010. New North American record for *Xyleborinus abdrevesi* (Coleoptera: Curculionidae: Scolytinae). *Fla. Entomol.* 93: 133–134.
- Rabaglia, R. J. 2002. XVII. Scolytinae Latreille 1807, pp. 792–805. In R. H. Arnett, Jr., M. C. Thomas, P. E. Skelley, and J. H. Frank (eds.), *American beetles*, vol. 2: Polyphaga: Scarabaeoidea through Curculionoidea. CRC Press, Boca Raton, FL.
- Rudisky, J. A., and I. Schneider. 1969. Effect of light intensity on the flight pattern of two *Gnathotrichus* (Coleoptera: Scolytidae). *Can. Entomol.* 125: 73–83.
- Sarvary, M. A., S. D. Hight, J. E. Carpenter, S. Bloem, K. A. Bloem, and S. Dorn. 2008. Identification of factors influencing flight performance of field-collected and laboratory-reared, overwintered, and non-overwintered cactus moths fed with field-collected host plants. *Environ. Entomol.* 37: 1291–1299.
- Stone, W. D., and T. F. Nebeker. 2007. Distribution and seasonal abundance of *Xylosandrus mutilates* (Coleoptera: Curculionidae). *J. Entomol. Sci.* 42: 409–412.
- Tobin, P. C., J. M. Kean, D. M. Suckling, D. G. McCullough, D. A. Herms, and L. D. Stringer. 2014. Determinants of successful arthropod eradication programs. *Biol. Invasions* 16: 401–414.
- Zhang, Y., L. Wang, K. Wu, K.A.G. Wyckhuys, and G. E. Heimpel. 2008. Flight performance of the soybean aphid, *Aphis glycines* (Hemiptera: Aphididae) under different temperature and humidity regimens. *Environ. Entomol.* 37: 301–306.