Lateral transfer of a phytopathogenic symbiont among native and exotic ambrosia beetles

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Different ambrosia beetle species can coexist in tree trunks, where their immature stages feed upon symbiotic fungi. Although most ambrosia beetles are not primary pests and their fungal symbionts are not pathogenic to the host tree, exceptional situations exist. Notably, Xyleborus glabratus carries a phytopathogenic symbiont, Raffaelea lauricola, which causes laurel wilt, a lethal disease of some Lauraceae species. Both X. glabratus and R. lauricola are natives of Asia that recently invaded much of the coastal plain of the southeastern USA. This study examined ambrosia beetles that breed in susceptible trees in Florida (USA), including avocado (Persea americana), redbay (P. borbonia) and swampbay (P. palustris). Raffaelea lauricola was recovered from six of eight ambrosia beetle species that emerged from laurel wilt-affected swampbay trees, in addition to X. glabratus. Controlled infestations with cohorts of the six species other than X. glabratus revealed that each could transmit the pathogen to healthy redbay trees and two could transmit the pathogen to healthy avocado trees; laurel wilt developed in five and one of the respective beetle × host interactions. These results indicate flexibility in the lateral transfer of a non-native ambrosial fungus to other ambrosia beetles, and for the first time documents the transmission of a laterally transferred phytopathogenic symbiont by new ambrosia beetle species. Additional work is needed to determine whether, or to what extent, the new beetle × R. lauricola combinations play a role in spreading laurel wilt.

Keywords: beetle–fungus symbiosis, invasive species, lateral transfer, laurel wilt, Raffaelea lauricola

Introduction

Ambrosia beetles (Coleoptera: Curculionidae: Scolytinae and Platypodinae) are fungus farmers (Farrell et al., 2001). They have obligate nutritional relationships with fungi that grow in their natal galleries in host tree xylem (Six, 2012). Their larval stages feed upon these fungi until they reach the adult stage, which in turn carries the fungal symbionts from tree to tree in specialized structures called mycangia. Mycangia are found in either or both sexes in the platypodinae ambrosia beetles, but occur only in females of the scolytinae ambrosia beetles. The scolytinae females start new colonies/broods and are responsible for gallery establishment and maintenance (Six, 2012).

A given beetle species is usually associated with one or more primary fungal symbionts that are transmitted vertically from one generation to the next (Baker & Norris, 1968; Kolarík & Hulcr, 2009; Gibson & Hunter, 2010; Harrington & Fraedrich, 2010). However, symbionts are not transmitted directly from mother to offspring; rather, they grow independently in natal galleries from which offspring obtain symbionts via feeding. This period of independent growth represents a weak link in the transmission process and provides an opportunity for horizontal transmission of symbionts (Six, 2012). Multiple species of ambrosia beetles can coexist in a single host plant, in which a beetle species could interact with another beetle’s brood gallery and its associated fungi (Kendra et al., 2011). Although specific symbionts have been found in two or more beetle species (Batra, 1967; Gebhardt et al., 2004), the lateral movement of a fungal symbiont from one ambrosia beetle species to another is not well studied.

Typically, ambrosia beetles infest dead or stressed trees, and their fungal symbionts are saprobes that colonize the lining of natal galleries and surrounding tissues; they are usually not phytopathogens. However, an increasing number of phytopathogens have been identified among these usually benign fungi (Hulcr & Dunn, 2011). For example, Raffaelea lauricola, a symbiont of the invasive Asian species Xyleborus glabratus (Coleoptera: Curculionidae: Scolytinae), causes laurel wilt, a new disease that has decimated vast areas of native trees in the Lauraceae in the southeastern USA (Fraedrich et al., 2008) and threatens the avocado industry in south Florida (Ploetz et al., 2011a). Although X. glabratus clearly plays a significant role as this pathogen’s vector (Hanula et al., 2008; Harrington & Fraedrich, 2010), not much is known about the interaction of R. lauricola with other ambrosia beetle species or their potential role in spreading laurel wilt.

Lateral transfer of R. lauricola to scolytinae other than X. glabratus has previously been noted in four species (Xyleborinus (X.) saxesseni (Coleoptera: Curculionidae: Scolytinae), Xyleborus affinis, Xylosandrus (Xa.)
crassiusculus and Xyleborus ferrugineus) (Harrington & Fraedrich, 2010; Harrington et al., 2010; Ploetz et al., 2011a). However, information on the frequency and prevalence of these associations, or on their potential significance, has not been published. In Florida, at least 14 ambrosia beetle species have emerged from laurel wilt-affected (R. lauricola-infected) redbay and avocado. In a recent study, X. glabratus was abundant in redbay, but seldom recovered from avocado (Carrillo et al., 2012).

Given the rarity of X. glabratus in laurel wilt-affected avocado trees and the detection of R. lauricola in other scolytinae that infest avocado and redbay trees, it can be hypothesized that beetles other than X. glabratus could be vectors of R. lauricola. To test this hypothesis, this study aimed to: (i) determine the presence and prevalence of R. lauricola in scolytinae species that emerged from laurel wilt-affected swampbay, (ii) assay transmission of the pathogen by the different scolytinae species to healthy avocado and redbay trees, and (iii) assess the development of laurel wilt in these trees.

Materials and methods

Wood samples (>10 cm in diameter × 50 cm long) were collected from laurel wilt-affected swampbay trees in a natural area in Miami Dade County, Florida, USA (25°43′37.96″N 80°28′36.16″W), where previous work had documented the presence of X. glabratus and R. lauricola. Wood was placed inside emergence chambers (166 L Brute container 2643, Rubbermaid®, with Mason jars attached to collect the emerging beetles) and held at 14-10-h light: darkness, 80% relative humidity (RH) and 25 °C in the Containment Facility of the University of Florida, Tropical Research and Education Center (TREC), Homestead, Florida, USA. The presence of R. lauricola in wood was determined with a semiselective medium (CSMA+) as described previously (Ploetz et al., 2012).

Ambrosia beetles (Coleoptera: Curculionidae: Scolytinae) that emerged from R. lauricola-infected wood were collected daily and identified. Identities of a subset of these beetles were confirmed by either Drs M. Thomas or K. Okins (Florida Department of Agriculture and Consumer Services (FDACS), Division of Plant Industry, Gainesville, Florida, USA). Nine ambrosia beetle species were assayed for R. lauricola: Xyloborus volvulus, X. glabratus, X. affinis, X. ferrugineus, Ambrosiodmus devecula, Ambrosiodmus lecontei, Xyleborinus gracilis, Xi. saxeseni and Xa. crassiusculus. Voucher specimens for each species were deposited in the Florida State Collection of Arthropods, FDACS, Gainesville, Florida, USA.

Recovery of R. lauricola from ambrosia beetles

Beetles were surface disinfested for 15 s in 70% ethanol and washed three times in sterile deionized water before the part of the body that contained mycangia was separated from the rest of the body and macerated in sterile glass tissue grinders (Pyrex no. 7727-07). For Xi. saxeseni and Xa. crassiusculus, which have metanotal and mesonotal mycangia, the abdomen and the whole body were tested, respectively, whereas assays of the remaining beetles, which have mandibular mycangia, used only the heads. The macerate was serially diluted one, 10 and 100 times, and aliquots of the dilutions were plated on CSMA+ medium. After 7–10 days under ambient light in the laboratory, colonies of R. lauricola were putatively identified based on their characteristic appearance on this medium (Harrington et al., 2010); numbers of colony-forming units (CFU) of the fungus were then calculated for individual beetles. The identity of a subset of single-conidium isolates from these colonies was confirmed as R. lauricola with two diagnostic microsatellite markers, CHK and IFW, which were amplified in PCR-based assays (Fig. 1). Each locus was shown previously to distinguish R. lauricola from 21 closely related species of Raffaelea and Ambrosiella, and the assay has been used to identify R. lauricola and to diagnose laurel wilt in four independent laboratories (T. Dreden & J. Smith, University of Florida, Gainesville, USA, personal communication). Vouchers of representative isolates from different beetle species and trees affected by laurel wilt in these experiments were deposited at the Centraalbureau voor Schimmelcultures (CBS Fungal Biodiversity Centre, Utrecht, The Netherlands).

Transmission of R. lauricola to, and the development of laurel wilt in, healthy avocado and redbay trees

Cohorts of the seven beetle species from which R. lauricola was recovered were used to infest healthy trees of the laurel wilt-susceptible avocado cv. Simmonds (clonal scions grafted on seedling rootstocks, 3–4 years’ old, 2 m tall, 4 cm diameter at the trunk base) and redbay (3-year-old seedlings, 1-5 m tall, 3 cm diameter at the trunk base) under glasshouse conditions (80 ± 15% RH, 25 ± 4°C, drip irrigation). For each beetle species, a total of five avocado and five redbay trees were infested over a period of 2 months (i.e. as sufficient numbers of beetles became available). A total of 80 trees were tested, comprising 10 trees infested with each of the seven beetle species and 10 non-infested trees used as control treatments.

Forty females of a given species were released in 25 × 15 cm sleeves of white cotton fabric affixed to trunks. The ends of sleeves were tied around trunks with 5 mm thick tagging tape. At 15 cm and 65 cm from the base of the trees, additional strips of tagging tape, impregnated with Tangle-foot®, were used to prevent entry of crawling arthropods into sleeves. Velcro strips, sewn into the sleeves, enabled access to the enclosed stem and, after closure, containment of the released beetles.

Trees were inspected for the development of laurel wilt on a weekly basis, as described previously (Ploetz et al., 2011b, 2012). Wilted trees were monitored until leaves had dried and the trunk started to show basipetal necrosis, at which time they were inspected in detail. Wilted trees were initially inspected with a hand lens to ensure that no beetle entry holes were present outside the sleeves. No evidence for this was found and subsequent evaluations were restricted to the area that was enclosed in the sleeve. The portion of the trunk that was enclosed by the sleeve was then removed, inspected for beetle boring, and dissected to determine how many boring attempts resulted in penetration of the bark and resulted in gallery construction in the xylem. Gallery length and life stages of the beetles that were found in galleries were recorded, as were the numbers of dead beetles in the sleeve. After 3 months, non-infested control trees and trees that did not wilt after infestation with a given beetle species were inspected and dissected as described above. Wood samples from the portion of the trunk that was enclosed by the sleeve were plated on CSMA+ medium. The identity of a subset of single-conidium isolates from these colonies was confirmed as R. lauricola with microsatellite markers as above. Trees infested with X. glabratus were considered positive controls and non-infested trees were considered negative controls.
Statistical analysis

The PROC GLIMMIX procedure (SAS v. 9.3) was used to assess differences in the probabilities that individuals of the tested beetle species carried *R. lauricola*, and the Steel–Dwass method (SAS v. 9.3) was used for non-parametric paired comparisons of mean CFU of *R. lauricola* in the different beetle species. Due to variance heterogeneity and non-normality of data, boring attempts, gallery formation, average gallery length, recovery of *R. lauricola* and development of laurel wilt symptoms in avocado and redbay trees infested with the different ambrosia beetle species were analysed with Kruskal–Wallis tests (SAS v. 9.3).

Results

Recovery of *R. lauricola* from ambrosia beetles

A total of 473 adult females of the nine scolytinae species that were recovered from the swampbay samples (25 to 118 individuals for a given species) were assayed for *R. lauricola*. *Raffaelea lauricola* was not detected in *A. devexulus* and *A. lecontei*, but was isolated from at least one individual of each of the seven other beetle species that were assayed (Table 1). The identity of a subset of single-conidium isolates was confirmed with the two microsatellite markers, CHK and IFW (Table 2). Great variation was observed in the proportion of individuals that carried the fungus and the CFU detected in each (Table 1). The probability of carrying *R. lauricola* was significantly higher for *X. glabratus* than for *X. ferrugineus*, *X. volvulus* and *Xi. gracilis* which, in turn, were significantly more likely to carry the pathogen than *X. affinis*, *Xi. saxeseni* and *Xa. crassiusculus* (d.f. = 6,401; F = 12.92; P < 0.0001; Table 1). The mean number of *R. lauricola* CFUs per beetle was more than one order of magnitude higher in *X. glabratus* than in the other beetle species, whereas CFUs detected from *X. ferrugineus*, *X. volvulus* and *Xi. gracilis* were significantly greater than those found in *X. affinis*, *Xi. saxeseni* and *Xa. crassiusculus* (d.f. = 6,401; F = 12.92; P < 0.0001; Table 1).

Transmission of *R. lauricola* to, and the development of laurel wilt in, avocado and redbay trees

No differences in the mean number of boring attempts or the number and length of galleries were detected in redbay versus avocado trees infested with *X. glabratus* (Table 3). All trees that were infested with *X. glabratus* were infected by *R. lauricola* and developed symptoms of laurel wilt (Fig. 2). *Xyleborus affinis* bored a similar number of times in redbay and avocado, but the numbers and lengths of its galleries were significantly greater.
in redbay (Table 3). After infestation with X. affinis, three of the five tested redbay trees were infected by R. lauricola and developed laurel wilt, but none of the five avocado trees were infected or developed the disease (Fig. 2). Xyloborus volvulus also bored a similar number of times in redbay and avocado, with significantly greater numbers and lengths of its galleries in redbay (Table 3). All of the redbay trees that were infested with X. volvulus were infected by R. lauricola and developed laurel wilt, whereas three of the five tested avocado trees were infected, two of which developed laurel wilt (Fig. 2). Similar numbers of boring attempts, and numbers and lengths of galleries were observed on redbay and avocado trees that were infested with X. ferrugineus (Table 3). Four of five redbay trees infested with X. ferrugineus were infected with R. lauricola, three of which developed laurel wilt, whereas one symptomless avocado tree was infected with R. lauricola (Fig. 2). For both X. gracilis and X. saxeseni, significantly greater boring attempts, galleries, and gallery lengths were observed in redbay than in avocado (Table 3). Both X. gracilis and X. saxeseni transmitted R. lauricola to redbay, but not to avocado. All redbay trees infested with X. gracilis were infected by R. lauricola and developed laurel wilt, whereas four redbay trees infested with X. saxeseni were infected by R. lauricola, three of which developed laurel wilt (Fig. 2). Finally, on Xa. crassiusculus-infested trees more boring attempts, gallery numbers, and gallery lengths were observed on redbay than on avocado (Table 3). In contrast to observations with the other beetles, the pathogen was recovered from only one redbay, but three of these trees wilted. However, typical
Table 3 Behaviour of ambrosia beetle species that attacked healthy avocado and redbay trees under no-choice conditions

<table>
<thead>
<tr>
<th>Species</th>
<th>Avocado</th>
<th>Redbay</th>
<th>$\chi^2$ (1, n = 10)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xyleborus glabratus</td>
<td>14.4 ± 2.6a</td>
<td>14.8 ± 3.4a</td>
<td>0.01</td>
<td>0.91</td>
</tr>
<tr>
<td>No. boring attempts</td>
<td>10.0 ± 1.4a</td>
<td>13.8 ± 3.8a</td>
<td>0.51</td>
<td>0.463</td>
</tr>
<tr>
<td>No. of galleries</td>
<td>11.4 ± 1.3a</td>
<td>9.9 ± 1.8a</td>
<td>0.88</td>
<td>0.347</td>
</tr>
<tr>
<td>Gallery length (mm)</td>
<td>8.0 ± 0.8b</td>
<td>19.6 ± 6.1a</td>
<td>4.51</td>
<td>0.034</td>
</tr>
<tr>
<td>Xyleborus affinis</td>
<td>2.0 ± 0.7a</td>
<td>2.4 ± 0.9a</td>
<td>0.1</td>
<td>0.751</td>
</tr>
<tr>
<td>No. of bore attempts</td>
<td>0.2 ± 0.2b</td>
<td>2.2 ± 0.9a</td>
<td>4.05</td>
<td>0.044</td>
</tr>
<tr>
<td>No. of galleries</td>
<td>3.5 ± 0.9b</td>
<td>13.5 ± 2.6a</td>
<td>6.86</td>
<td>0.008</td>
</tr>
<tr>
<td>Gallery length (mm)</td>
<td>8.4 ± 2.8a</td>
<td>8.0 ± 1.4a</td>
<td>0.01</td>
<td>0.916</td>
</tr>
<tr>
<td>Xyleborus ferrugineus</td>
<td>2.0 ± 0.9b</td>
<td>6.8 ± 1.6a</td>
<td>4.03</td>
<td>0.046</td>
</tr>
<tr>
<td>No. of bore attempts</td>
<td>3.0 ± 1.1a</td>
<td>13.5 ± 2.6a</td>
<td>6.86</td>
<td>0.008</td>
</tr>
<tr>
<td>No. of galleries</td>
<td>0.6 ± 0.4a</td>
<td>16.0 ± 6.4a</td>
<td>1.72</td>
<td>0.189</td>
</tr>
<tr>
<td>Gallery length (mm)</td>
<td>3.7 ± 2.8a</td>
<td>22.5 ± 7.4a</td>
<td>2.97</td>
<td>0.085</td>
</tr>
<tr>
<td>Xyleborinus gracilis</td>
<td>11.0 ± 1.8a</td>
<td>6.4 ± 1.5b</td>
<td>3.66</td>
<td>0.05</td>
</tr>
<tr>
<td>No. of bore attempts</td>
<td>0.2 ± 0.2b</td>
<td>5.6 ± 1.4a</td>
<td>7.33</td>
<td>0.006</td>
</tr>
<tr>
<td>No. of galleries</td>
<td>0.8 ± 0.8b</td>
<td>9.4 ± 0.8a</td>
<td>7.25</td>
<td>0.007</td>
</tr>
<tr>
<td>Gallery length (mm)</td>
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<td>6.4 ± 0.9a</td>
<td>3.6</td>
<td>0.05</td>
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<tr>
<td>Xyleborinus saxeseni</td>
<td>0 b</td>
<td>5.6 ± 0.9a</td>
<td>7.75</td>
<td>0.005</td>
</tr>
<tr>
<td>No. of bore attempts</td>
<td>0 b</td>
<td>9.3 ± 1.4a</td>
<td>7.76</td>
<td>0.005</td>
</tr>
<tr>
<td>No. of galleries</td>
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<td>9.6 ± 4.9a</td>
<td>2.99</td>
<td>0.083</td>
</tr>
<tr>
<td>Gallery length (mm)</td>
<td>2.0 ± 0.4b</td>
<td>9.0 ± 4.8a</td>
<td>6.48</td>
<td>0.01</td>
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<tr>
<td>Xylosandrus crassiusculus</td>
<td>2.2 ± 1.4b</td>
<td>8.9 ± 2.4a</td>
<td>4.03</td>
<td>0.045</td>
</tr>
</tbody>
</table>

*Mean ± standard error of the mean (SEM). Means ± SEM followed by the same letter within rows are not significantly different at P < 0.05 in paired Kruskal-Wallis tests.

Discussion

The recent introduction of *X. glabratus* and *R. lauricola* into the eastern USA has resulted in lateral transfer of this phytopathogenic fungus to several other species of ambrosia beetles. Although lateral movement of phytopathogenic symbionts is known to occur in the related bark beetles (Gibbs, 1978; Massoumi Alamouti et al., 2009), the present study is the first to provide detailed information on the phenomenon in ambrosia beetles.

Before its detection in America, *X. glabratus* was associated with relatively few plant species in Asia (Bonin, Burma, Assam, Bengal, Bangladesh, India, Japan, Myanmar and Taiwan) (Wood, 1982; Rabaglia et al., 2006; Table 4). Compared to *X. glabratus*, the other beetle species in this study are highly polyphagous. Six of the species studied are considered to be New World endemics (Table 4): *X. affinis* and *X. ferrugineus* are native to tropical America (Wood, 1982; Rabaglia et al., 2006) and have continuous distributions throughout South America, Central America, the Gulf Coast and southeastern USA (Atkinson & Peck, 1994); *X. volvulus* is distributed throughout South and Central America, the Caribbean and south Florida (Wood, 1982); *X. gracilis* is distributed in tropical and subtropical areas in the Caribbean and South, Central and North America (Atkinson & Peck, 1994); and both *A. lecontei* and *A. devezensi* are Eurasian species which immigrated to the New World (Wood, 1982). *Xyleborinus saxeseni* has a worldwide distribution and is thought to be one of the first non-native scolytids introduced to America (Rabaglia et al., 2006), whereas *X. crassiusculus* is distributed in Africa and Asia and was introduced to North America (Rabaglia et al., 2006).

In this study, evidence for the acquisition of *R. lauricola* by six of the above species is presented, presumably...
Table 4 Distribution and host range of ambrosia beetle species examined in this study

<table>
<thead>
<tr>
<th>Ambrosia beetle species</th>
<th>Distributiona</th>
<th>Hostsb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xyleborus glabratus</td>
<td>Asia (N), NA (I)</td>
<td>Lauraceae (6), Dipterocarpaceae (1), Fagaceae (1), Fabaceae (1)</td>
</tr>
<tr>
<td>Xyleborinus saxesenii</td>
<td>NA (I), SA (I), Europe (I), Oceania (I), Africa, Asia (N)</td>
<td>Aceraceae (3), Anacardiaceae (1), Annonaceae (1), Apocynaceae (1), Betulaceae (3), Cornaceae (1), Cunoniaceae (1), Fabaceae (2), Juglandaceae (2), Magnoliaceae (6), Rosaceae (5), Salicaceae (1), Taxodiaceae (1), Tilliaceae (1), Ulmaceae (1)</td>
</tr>
<tr>
<td>Xyleborus affinis</td>
<td>NA (N), SA (N), CA (N), Caribbean (N), Africa (I), Asia (I), Europe (I), Oceania (I)</td>
<td>Agavaceae (1), Anacardiaceae (7), Annonaceae (2), Areceaeae (1), Betulaceae (1), Bignoniaceae (3), Burseraceae (2), Caesalpinaceae (3), Clusiaceae (2), Combretaceae (2), Cupressaceae (1), Cyrillaceae (1), Eleocharaceae (1), Euphorbiaceae (2), Fabaceae (3), Fagaceae (9), Hamamelidaceae (2), Juglandaceae (2), Lauraceae (3), Lecythidaceae (1), Melastomataceae (1), Meliaceae (2), Mimosaceae (8), Moraceae (2), Myricaceae (3), Palmaceae (1), Pinaceae (3), Poaceae (1), Rosaceae (1), Rubiaceae (1), Rutaceae (2), Sapindaceae (1), Sapotaceae (3), Sterculiaceae (1), Taxodiaceae (2), Ulmaceae (2), Verbenaceae (1)</td>
</tr>
<tr>
<td>Xyleborus ferrugineus</td>
<td>NA (N), SA (N), CA (N), Caribbean (N), Africa (I), Oceania (I)</td>
<td>Aceraceae (1), Agavaceae (1), Anacardiaceae (4), Apocynaceae (1), Araliaceae (1), Araliaceae (1), Bignoniaceae (3), Burseraceae (6), Caesalpinaceae (5), Clusiaceae (1), Combretaceae (1), Eleocharaceae (1), Fabaceae (7), Fagaceae (8), Lauraceae (3), Lecythidaceae (1), Leguminosae (1), Melastomataceae (1), Meliaceae (3), Mimosaceae (3), Moraceae (8), Musaceae (1), Nyctaginaceae (1), Nyssaceae (1), Pinaceae (4), Rutaceae (2), Sapindaceae (2), Sapotaceae (3), Sterculiaceae (1), Tilliaceae (3), Urticaceae (1), Verbenaceae (1)</td>
</tr>
<tr>
<td>Xyleborinus gracilis</td>
<td>NA, SA, CA, Caribbean, Africa</td>
<td>Araliaceae (1), Burseraceae (1), Clusiaceae (1), Combretaceae (1), Fabaceae (1), Lauraceae (1), Melaistemataceae (2), Mimosaceae (1), Moraceae (1), Sapotaceae (1), Sterculiaceae (1)</td>
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<tr>
<td>Xyleborus volvulus</td>
<td>SA, CA, NA, Caribbean, Africa, Asia, Oceania</td>
<td>Anacardiaceae (12), Apocynaceae (1), Araliaceae (1), Areceaeae (1), Burseraceae (18), Caesalpinaceae (5), Caricaceae (1), Casuarinaceae (1), Combretaceae (2), Eleocharaceae (1), Euphorbiaceae (3), Fabaceae (6), Lauraceae (2), Leguminosae (1), Meliaceae (2), Mimosaceae (5), Moraceae (9), Myricaceae (1), Palmaeae (1), Rubiaceae (1), Sapindaceae (2), Sterculiaceae (2), Taxodiaceae (1), Tilliaceae (1), Verbenaceae (1)</td>
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<td>Xylosandrus crassiusculus</td>
<td>NA (I), Africa, Asia</td>
<td>Anacardiaceae (1), Apocynaceae (1), Convolvulaceae (2), Cornaceae (1), Ebenaceae (1), Fabaceae (1), Fagaceae (1), Hamamelidaceae (3), Juglandaceae (3), Lauraceae (1), Magnoliaceae (2), Melastomataceae (1), Moraceae (5), Rosaceae (17), Sapindaceae (3), Sapotaceae (1), Ulmaceae (2), Verbenaceae (2), Vochysiaceae (1)</td>
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<td>Ambrosiodmus lecontei</td>
<td>NA (N), Caribbean (N)</td>
<td>Anacardiaceae (2), Aquifoliaceae (1), Burseraceae (1), Caesalpinaceae (3), Combretaceae (1), Compositae (1), Fabaceae (1), Juglandaceae (1), Lauraceae (2), Meliaceae (1), Mimosaceae (2), Phyllanthaceae (1), Pinaceae (2), Rosaceae (1), Rutaceae (2)</td>
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<tr>
<td>Ambrosiodmus devexulus</td>
<td>NA (N), Caribbean (N)</td>
<td>Anacardiaceae (1), Caesalpinaceae (1), Fabaceae (1), Hamamelidaceae (1), Lauraceae (1)</td>
</tr>
</tbody>
</table>


bHost ranges are from Atkinson (2012). Numbers in parentheses are numbers of host species reported in a family.

After *Xyleborus glabratus* was introduced to the USA in 2002, although lateral movement of symbionts among ambrosia beetles has been recognized for at least four decades (Batra, 1967), such a dramatic increase in the number of beetle species that have acquired a ‘new’ symbiont appears to be unprecedented, as there are no similar reports in the literature. Why this has occurred is not clear.

Although there may be a phylogenetic relationship between the different beetle species and the probability that they carry *R. lauricola* (three of the four highest probabilities in the study are for *Xyleborus* spp.), *R. lauricola* was not detected in species in the next most closely related genus (Cognato et al., 2011), *Ambrosiodmus*. The systemic colonization of host trees by *R. lauricola* may play a role in its relatively rapid acquisition by multiple species. Contact with another ambrosial fungus would occur when one beetle species came in contact with galleries of another beetle species. However, *R. lauricola* is not restricted to the galleries of *Xyleborus glabratus*; rather, it colonizes much of the host tree xylem and can be recovered from these tissues for more than a year after a tree dies (Spence, 2012). Thus, the probability that ambrosia beetles other than *X. glabratus* would come into contact with *R. lauricola* should be far greater than in typical situations in which an ambrosial fungus has a restricted distribution in a tree.

Although an increase in the species and numbers of beetles that are vectors of *R. lauricola* might affect the
spread of laurel wilt, it is clear that more data are needed. For example, information on the efficiency of the new vectors and their attraction to healthy hosts in natural environments would affect this outcome but is not available. In addition, the proportion of a beetle population in which \( R. \) lauricola is found and the number of pathogen propagules that individual beetles carry should influence host infection and the development of laurel wilt, as observed in the present study. Although the present assays examined only mycangia, propagules on the exoskeleton of the beetles (phoretic transmission) may also play an important role in the lateral movement of these fungi, as has been shown for some bark beetles (Webber & Gibbs, 1989; Webber, 2004). In the present study, low numbers of \( R. \) lauricola CFUs were detected in surface-disinfested bodies (mycangia) of \( X. \) affinis and \( X. \) saxeseni, yet, when redbay plants were confronted with non-disinfested cohorts of these species, relatively high rates of pathogen transmission and laurel wilt development occurred. Additional research is warranted on these topics.

Several outcomes are possible with new symbiont × ambrosia beetle associations. The fungus could benefit from transport to new host trees, especially if its primary vector is rare, and/or if the new vector attacks plants that the primary vector cannot. \( Xyleborus \) glabrat\( \text{us} \) is known to attack mostly lauraceous plants, but it has also been reported from a few other species in the Fagaceae, Fabaceae and Dipterocarpaceae (Rabaglia et al., 2006; Fraedrich et al., 2008; Peña et al., 2012; Table 4). In contrast, the other ambrosia beetles in the present study are polyphagous and can breed in a wide variety of hosts (Atkinson & Peck, 1994; Table 4). Thus, \( R. \) lauricola could benefit from the expanded host range afforded by the new, potential vectors described in this study. The recent recovery of \( R. \) lauricola from live oak (\( Quercus \) virginiana) in Florida in which \( X. \) glabrat\( \text{us} \) was not detected (J. Smith, Forestry & Conservation Department, University of Florida, USA, personal communication), suggests that vector-mediated host range expansion for \( R. \) lauricola may already occur.

In these situations, laterally transferred fungi could have a range of relationships with new beetles. Host range expansion, as described above, might benefit the fungus but not affect the beetle (i.e. they could have a commensalistic relationship), or the new relationship could benefit both partners (mutualistic) if the new fungus provided enhanced nutrition for the beetle or if the fungus were pathogenic on the new host trees and, thereby, gave the beetle a competitive advantage over other ambrosia beetle species (i.e. provided greater opportunities for brood development). Alternatively, the fungus could negatively affect the beetle either by displacing nutritionally superior symbionts or by being directly antagonistic to the beetle. Little is known about these possibilities because of the inherent difficulties in working with obligate nutritional symbioses. For example, although six \( \text{Raffaelea} \) spp. have been recovered from the mycangia of \( X. \) glabrat\( \text{us} \), nothing is known about their relative importance or roles as a food sources for this or other ambrosia beetles (Harrington & Fraedrich, 2010). Greater understanding is needed for how and why different ambrosia beetles obtain new symbionts.

\( \text{Leach (1940) established four principles to determine whether an insect is a vector of a phytopathogen. The first states that the insect must be closely associated with diseased plants. Based on a prior study (Carrillo et al., 2012) and the results of the present study, the scolytinae species examined were consistently associated with laurel wilt-affected trees in Florida.} \)

\( \text{Leach’s second principle states that a vector must interact with healthy plants. Most ambrosia beetles are thought to colonize dead, stressed or dying trees, and occasionally attack live trees (Kühnhölz et al., 2001). Ambrosia beetles of the genus Xyleborus typically infest trees of low vigour, or which have been cut, damaged or wind-thrown (Roep et al., 1980). However, Rabaglia et al. (2006) reported that} \ X. \text{affinis} \text{and} \ X. \text{ferrugineus} \text{can cause economic damage in moist, lowland areas of the neotropics. There are reports of} \ X. \text{affinis} \text{attacking healthy sugarcane and Dracaena massangeana (Merkl} \text{& Tusnádi, 1992; Granda Giro, 2003), and of} \ X. \text{ferrugineus} \text{boring into healthy pecan trunks and twigs (Aguilar-Pérez et al., 2007).} \text{Xyleborinus saxeseni} \text{is regarded as one of the most damaging species in the tribe Xyleborini (Rabaglia et al., 2006), and there are reports of it attacking healthy chestnut (Oliver} \text{& Mannion, 2001) and stressed peach trees (Kovach} \text{& Gorsuch, 1985). Lastly,} \text{Xa. crassiusculus} \text{can attack over 200 tree species and is an important pest of nursery grown trees (Frank} \text{& Sadof, 2011). In summary, despite the usual preference of ambrosia beetles for unhealthy or dead trees, several of the species that were examined in the present study can interact with healthy trees.} \)

\( \text{Because the present experiments were conducted under no-choice conditions, it is not possible to conclude that the new beetles from which} \ X. \text{lauricola} \text{was recovered are effective vectors in nature. However, under these conditions all beetle species attempted to bore into trees and there was a marked difference in host suitability, in that gallery number and length were significantly higher in redbay than avocado. More research is needed to determine the ability of these ambrosia beetles to attack healthy plants under natural conditions.} \)

\( \text{Leach’s third principle indicates that the pathogen must be associated with the insect. In this study,} \ R. \text{lauricola} \text{was consistently associated with four species (i.e. \geq 50\% of the assayed individuals) and was found less commonly in three others. Given the way in which these beetles were processed, it is presumed that the fungus was located in their mycangia. Whether or not phoretic, non-mycangial associations of} \ R. \text{lauricola} \text{occur with these insects should be examined.} \)

\( \text{Leach’s final principle states that disease should develop in healthy plants after they interact with} \text{...} \)
pathogen-infested insects. In this study, *R. lauricola* was transmitted to avocado by only two species besides *X. glabratus*, but it was transmitted to at least one red-bay tree by all of the species that were tested. Laurel wilt developed in most of the avocado and redbay plants that were infected by *R. lauricola*. However, disease did not develop in single infected avocado trees that were infested with *X. volvulus* and *X. ferrugineus*, and in single infected redbay trees that were infested with *Xa. crassiusculus*, *X. ferrugineus* and *Xi. saxeseni*. Although it is possible to kill both avocado and redbay plants with inoculum containing as few as 100 conidia, there is considerable variation in disease development at such low inoculum levels (i.e. some inoculated trees develop little or no disease) (M. Hughes, University of Florida, Gainesville, USA, personal communication). Considering the low numbers of *R. lauricola* CFUs that were detected in the above species, it is probable that insufficient levels of the pathogen were present in the infected, symptomless plants to cause disease.

In conclusion, this present study demonstrated that lateral transfer of the primary symbiont of *X. glabratus*, *R. lauricola*, has occurred in six additional invasive or native species of ambrosia beetle in Florida. Based on results from no-choice tests, some of these beetles can transmit this pathogen to avocado and/or redbay. However, more research is needed to determine whether these beetles attack healthy trees in natural and agroecosystems in Florida. New vectors could expand the host range of this pathogen and may influence the development of laurel wilt, especially on hosts that support little or no reproduction of *X. glabratus*.

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References


Kovach J, Gorsuch CS, 1985. Survey of ambrosia beetle species infesting South Carolina peach orchards and a taxonomic key for the most common species. *Journal of Agricultural Entomology* 2, 238–47.


