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Ecology, Biology, and Management of *Xylosandrus compactus* (Coleoptera: Curculionidae: Scolytinae) with Emphasis on Coffee in Hawaii

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ABSTRACT. The black twig borer, *Xylosandrus compactus* (Eichhoff) (Coleoptera: Curculionidae: Scolytinae) attacks >200 species of plants. This ambrosia beetle occurs on all the major islands of Hawaii and is a threat to some native plants and coffee plantations. Female beetles bore entry holes and excavate tunnels inside branches, which are inoculated with fungus to provide a food source for larvae. Two types of damages are described—1) superficial boring limited to the phloem and 2) cutting of the vascular tissue which subsequently reach the pith of the stem to make galleries. In this article, we discuss the life cycle, biology, plant damage characteristics, and management alternatives of *X. compactus*, focusing on coffee plants.

RESUMEN: El barrenador negro de las ramas, *Xylosandrus compactus* (Eichhoff) (Coleoptera: Curculionidae: Scolytinae) ataca más de 200 especies de plantas. Este escarabajo ambrosía se encuentra en todas las principales islas de Hawaii y es una amenaza para las plantas nativas y plantaciones de café. Las hembras del escarabajo hacen un orificio de entrada y desarrollan túneles dentro de las ramas que se inoculan con hongos para proporcionar alimento a las larvas. Dos tipos de daños se describen 1) orificio superficial limitado al floema y 2) el corte del tejido vascular que posteriormente llega a la médula del tallo para hacer galerías.

En este documento se discuten el ciclo de vida, biología, características de daño y alternativas de manejo para *X. compactus* enfocado en plantas de café.

Key Words: black twig borer, coffee, *Xylosandrus compactus*, ambrosia beetle

The potential damage caused by the invasion of exotic ambrosia beetles to Hawaii is among the most significant concerns for the coffee, forestry, and ornamental plant industries. Most of these invasive beetles are from temperate areas and find a suitable environment for reproduction and survival in Hawaii, with favorable climatic conditions, presence of a diversity of alternate hosts, and a lack of natural enemies of Scolytinae. Among the most economically important ambrosia beetles in Hawaii is the black twig borer, *Xylosandrus compactus* (Eichhoff) (Coleoptera: Curculionidae: Scolytinae). The black twig borer belongs to the tribe Xyleborini, also known as ambrosia beetles, which refers to the species that feed exclusively on fungi (ambrosia fungi) cultivated inside galleries constructed into the wood by the adult female beetles (mycetophagous; [Batra 1963](#), [Wood 1982](#), [Six 2012](#)). The adult female beetle makes an entry hole typically on the underside of twigs, which she then inoculates with a fungus. The fungus is the sole food source for the beetles ([Ngoan et al. 1976](#), [Hara and Beardsley 1979](#)). The physical and economic damage to infested plants could be caused by the tunneling action of the adult beetle, or the fungus that the beetle provides for the offspring.

X. compactus attacks >200 host plants, including native plants, shrubs, nursery plants, and landscape ornamentals ([Hara and Beardsley 1979](#), [Meshram et al. 1993](#), [Intachat and Kirton 1997](#), [Vasquez et al. 2002](#), [Matsumoto 2002](#), [Chong et al. 2009](#)). *X. compactus* was first found on Oahu in 1960 attacking pink tecoma, *Tabebuia heterophylla* Britton (syn. *T. pentaphylla* (L.) Hemsley) ([Beardsley 1964](#)), and it is now present on all the major islands of the state ([Hara and Beardsley 1979](#), [Bittenbender and Easton-Smith 1999](#)). This beetle is native to Asia and is mainly distributed in the subtropical and tropical areas and is adapted to a warm environment ([Hayato 2007](#)). It occurs widely in Japan, Vietnam, Indonesia, Malaya, Sri Lanka, Madagascar, south India, Seychelles, Mauritius, West Africa, Fiji, Cuba, and Brazil ([Venkataramaiah and Sekhar 1964](#), [Vasquez et al. 1996](#), [Oliveira et al. 2008](#)). In the United States, the black twig borer was first reported in

Fort Lauderdale, FL, in 1941 ([Wood 1982](#)) and has since spread throughout the southeast United States, along the coastal plain from Texas to North Carolina ([Ngoan et al. 1976](#)).

This review concentrates on the pest status of black twig borer in Hawaii, specifically as a pest of coffee. In recent years, the black twig borer appears to have become a more significant and predictable pest of coffee in Hawaii, particularly in the Kona area, and when alternate host plants of the beetles surround the coffee plantations. When infestation levels become high, sanitation is a major concern to growers, as the removal of large amounts of bearing branches from coffee plants significantly reduces yield potential for the current and several ensuing years. Coffee is the fifth most important agricultural crop in Hawaii, with an annual state revenue of US\$34.5 million (Hawaii Department of Agriculture [[HDOA](#)] 2013), and Hawaii is the only state that grows coffee commercially in the United States. Coffee is grown not only in the Kona area of the Big Island of Hawaii but also on large plantations on Oahu, Molokai, Maui, and Kauai ([Bittenbender and Easton-Smith 1999](#)). The black twig borer is a significant concern among Hawaiian coffee growers and managers of native Hawaiian forests on several islands, which has prompted a search for pest management alternatives. In this pest profile, we summarize the ecology, biology, and management options in coffee.

Description of Life Stages and Cycle

Adult. The teneral female adult is light brown and turns shiny black 3–4 d after eclosion from the pupal case. The body is cylindrical and stout; length is 1.4–1.8 mm, and width is 0.7–0.8 mm ([Fig. 1](#)). The male adult is smaller than the female, is light brown, and in 3–4 d turns reddish brown. The body length is 0.8–1.3 mm, and width is 0.42–0.46 mm.

Only adult females cause damage to plants, and males are flightless. The female bores an entry hole and excavates tunnels inside the branches ([Ngoan et al. 1976](#), [Hara 1977](#)).



Fig. 1. Dorsal view of a *X. compactus* adult female (~1.7 mm long and 0.8 mm width). Photos by Elsie B. Greco.

Mother beetles remain in the entry tunnel of their brood chamber throughout the brood development and emerge the galleries 23–29 d after initial boring and 4–6 d before the female progeny emerge (Hara 1997). It has been reported that females do not excavate new galleries after they have reared one brood. Females of the new generation left parental galleries after an average of 29 d following establishment of their galleries, and bore into a new host twig. Adult females exit the gallery by the same entry hole, to establish a new gallery, and emergence typically occurs in the afternoon hours between noon and 5:00 pm (Ngoan et al. 1976, Hara 1977).

They reproduce by arrhenotokous parthenogenesis, in which females produce males from unfertilized eggs while fertilized eggs produce female progeny. Males remain in the brood galleries and are rarely observed outside the plant. Mating is primarily sibling mating within the galleries. Pupation and mating of brood adults occurs in the infested plant material. Field populations have a male to female sex ratio of 1:9 (Hara 1977).

Oviposition occurs 4–7 d after the female bores into a twig. Eggs are laid in a loose cluster inside the gallery, and they hatch 3–5 d after being laid (Hara and Beardsley 1979).

In laboratory conditions, the total egg production per female ranged from 2 to 16 (Hara 1977), and the mean number of eggs per gallery found of infested coffee branches from the field ranged from 2 to 23 ($N = 2,913$; Burbano 2010).

The complete life cycle of *X. compactus* from egg to adult occurs in an average of 28.5 d at 23 to 27°C and 50 to 60% relative humidity (Hara 1977). Females live up to 58 d while males remain in the galleries with a life span of ~6 d (Ngoan et al. 1976).

Eggs are oval, white, and translucent with a smooth surface (Fig. 2A). Hara (1977) reported that the measurement of 15 eggs ranged from 0.53 by 0.26 mm to 0.59 by 0.30 mm, with an average of 0.55 by 0.28 mm, and the incubation period varied from 3 to 5 d. The body of larva is creamy white and legless (Fig. 2B); head capsule is white when first laid changing later to a pale-brown color; abdomen is pointed posteriorly in young larvae but rounded in fully mature larva (Ngoan et al. 1976, Hara and Beardsley 1979). Two larval instars were identified in laboratory rearing (Ngoan et al. 1999), while three instars were recorded from individuals collected in the field (Hara 1977). Pupae—the length of the pupal stage is similar to the adult stage, body creamy white and exarate (Fig. 2C). The range duration of egg, larva, and pupae was 4–6, 7–8, and 8–9 d, respectively, at $25 \pm 2^\circ\text{C}$ (Ngoan et al. 1976).

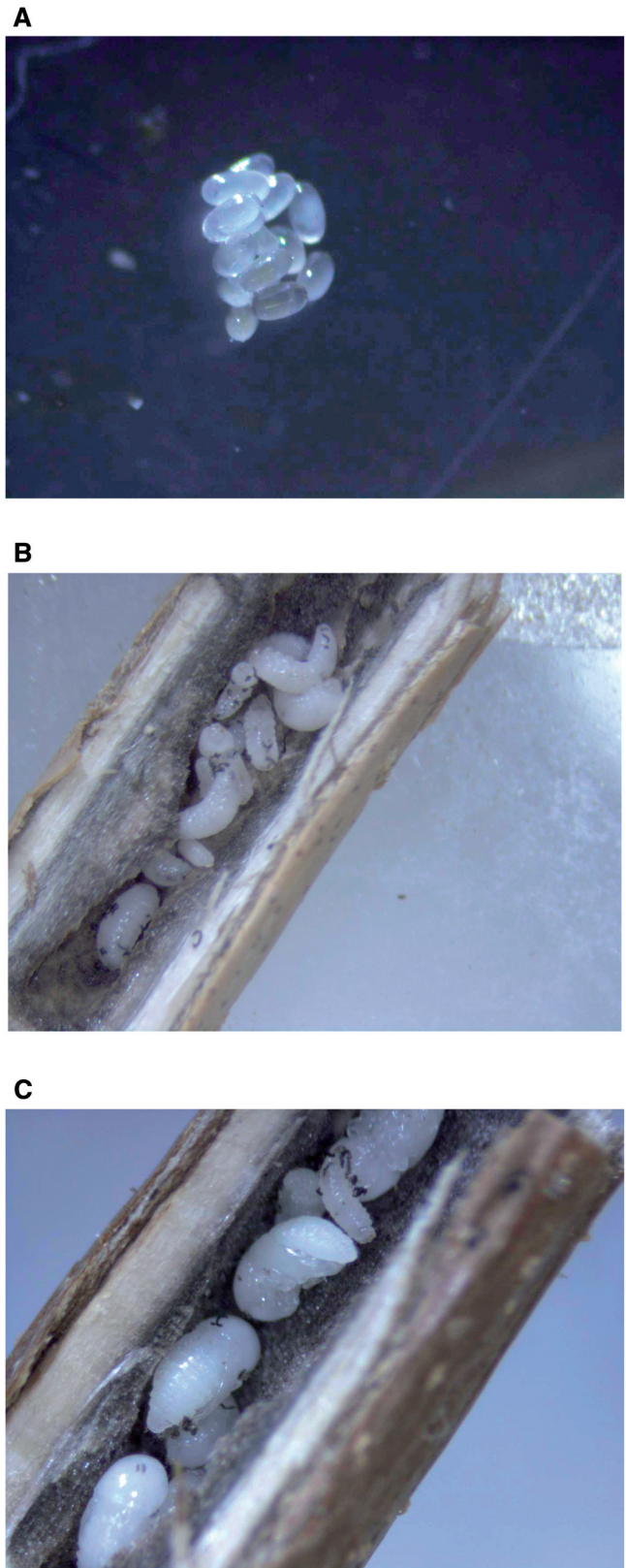


Fig. 2. Eggs (A), larvae (B) and pupae of *X. compactus* (C).

Crop Damage Characteristics

Beetles of the subfamily Scolytinae are among the most damaging insects in the world. Their cryptic life cycle inside the host plant makes these insects difficult to control (Rudinsky 1962). Most ambrosia



Fig. 3. Entry hole made by *X. compactus* in coffee branches (Photo by Riann H.A.S. Wakefield, Wakefield and Sons coffee farm).

beetles bore into the wood of unhealthy, stressed, or dying trees (Kajimura and Hijii 1994, Jones and Johnson 1996). However, *X. compactus* is one of the few ambrosia beetles that attacks both healthy plants and plants that are under stress conditions caused by drought, pruning, or recent transplanting (Hara and Beardsley 1979, Jones and Johnson 1996, Hayato 2007). Extent of damage on coffee is related to orchard proximity to alternate host plants and lack of sanitation of infested material within orchards (Jones and Johnson 1996, E.B.G., unpublished data). There are two potential mechanisms through which the black twig borer can cause severe damage and even the death of the host plant—1) mechanical damage and 2) the introduction of the ambrosia fungus, which may be phytopathogenic (Hara and Beardsley 1979, Daehler and Dudley 2002). There are two types of physical damage. One type of damage occurs where the hole is superficial and limited to the phloem; in this case, the female starts boring an entry hole but rejects the plant, and although the tunnel is not completed, wilting is observed on the terminal leaves of the branch (Burbano 2010, Vasquez and Martinez 1999).

The second type of physical damage occurs where females bore an entrance hole and initiate cutting of the vascular tissue (Fig. 3). They subsequently reach the pith of the stem and excavate it out along the twig on either side of the initial entrance tunnel to make a brood chamber where the eggs are laid (Fig. 4); subsequently, wilting, necrosis, and defoliation is observed in branches (Ngoan et al. 1976, Mannakkara and Alawathugoda 2005, Burbano 2010).

Nelson and Davis (1972) reported that physical damage done by *X. compactus* to twigs of Koa haole (*Leucaena leucocephala* Benth), guava (*Psidium guajava* L.), Vervain (*Stachytarpheta jamaicensis* L. Vahl), and Christmasberry (*Schinus terebinthifolius* Raddi) is minor; however, any boring activity, even shallow starts, can kill the twig support the damage found in coffee branches.

The time required for a female to bore an entrance tunnel is 3.7–5.3 h (Ngoan et al. 1976). Initially, first leaves of infested branches



Fig. 4. Mature (black) and teneral (light brown) females of *X. compactus* inside the tunnel of a coffee branch.

on coffee plants turn light green within hours of attack. Wilted leaves and bark beyond the affected area turn brown or black after few days of beetle attack (Fig. 5; Ngoan et al. 1976, Jones and Johnson 1996, Daehler and Dudley 2002, Burbano 2010). The dieback of twigs is the result of the mechanical damage of vessels caused by beetle boring (Daehler and Dudley 2002). During the introduction of the ambrosia fungus, a necrosis in the bark and a desiccated zone in the xylem are observed, suggesting the invasion of associated fungi into the twig tissue, which may move through the xylem of the tree, obstructing the flow of water and nutrients (Fig. 6; Hayato 2007).

Black twig borer has been reported attacking flowering dogwood twigs with an outside diameter of 1–7 mm and larger branches with an outside diameter of 8–22 mm (Ngoan et al. 1976), where one female can kill a small twig and larger branches may be infested by up to 20 black twig borer females. In avocado, unsuccessful boring attempts were observed in branches larger than 15 mm of diameter and tree trunks up to 200 mm in diameter (Hara 1977); however, in Florida successfully bored holes were observed in avocado branches of 4–52 mm in diameter; infestation varied considerably among varieties and damage was not observed in very young growth (Wolfenbarger 1973). Vasquez-Moreno et al. (2002) studied the influence of *X. compactus* on different varieties of coffee and reported significant higher number of holes in branches of variety Robusta (*Coffea canephora*). The quality of the sap, water content in the wood, and texture of tissues are the most important factors in relation to the attack of *X. compactus* and could be related to the preference of this beetle for certain coffee varieties (Vasquez-Moreno et al. 2002).

During 2007–2008, data were collected from coffee plants in the Kona area, Hawaii, and are summarized here. Eight coffee farms were sampled monthly and 2,913 infested branches were dissected to determine black twig borer infestation levels and to obtain data on the biology of this beetle.

X. compactus was observed attacking healthy and weak trees that showed stress caused by lack of water and fertilizer. Infested branches were observed principally from the middle to the top of the coffee trees (1.5–2.5 m height).

Black twig borer females were found inside vertical branches, lateral branches, and coffee berries (Fig. 7; Greco and Wright 2012). However, lateral branches were usually the preferred targets of females in Hawaii coffee. Vertical branches had black twig borer entry holes, but branch wilting was rarely observed, so damage was apparently rare in these branches, probably because vertical branches are larger in diameter than lateral branches and the hardness of the tissue might make them less attractive. Several entry holes were observed in single lateral branches, and most of them were occupied by several developmental stages of black twig borer.

The diameter of attacked lateral branches ranged from 0.48 to 6.47 mm (average = 3.09 mm), and the females were most abundant in

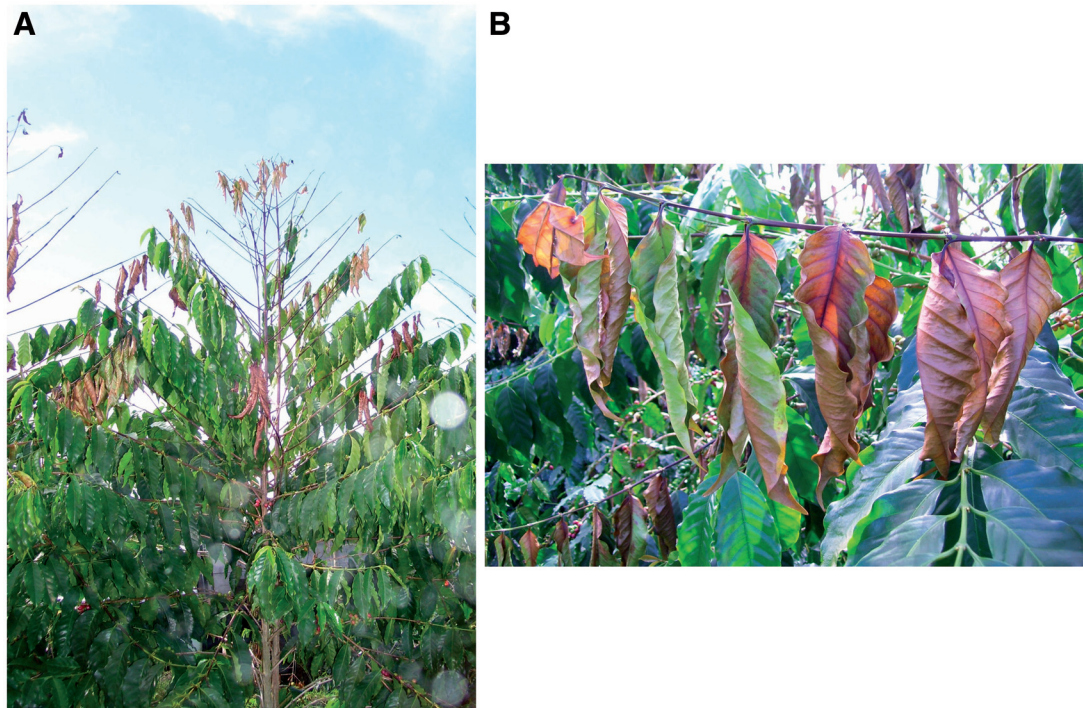


Fig. 5. Lateral coffee branches attacked by *X. compactus* (left), first leaves of infested coffee branches turn wilted and brown (right).



Fig. 6. Necrosis and desiccated zone are observed on the bark (Photo by Ray Anders).

medium-thickness twigs, and the larval densities were correspondingly highest in those twigs (Fig. 8A and B).

The number of successful galleries per branch ranged from 1 to 14 (average = 1.14), and the number of adult females in examined brood galleries ranged from 1 to 41 (average = 4.22). Sharing of galleries by colonizing adult females has not been reported in the literature (Hara 1977, Mannakkara and Alawathugoda 2005), but multiple adult females sharing galleries in the same twig with all the immature stages have been observed and distinct generations could not be distinguished (Burbano 2010).

Ngoan et al. (1976) reported that the number of adult black twig borer inside branches of flowering dogwood *Cornus florida* L. ranged from 1 to 40 (average = 11.9). The duration of boring activity and the number of eggs laid within galleries is influenced by the hardness of the tree tissue and conditions influencing the growth of the ambrosia fungus.

In Hawaii, black twig borers were present in coffee branches all year round; however, higher numbers of females, larvae, and pupae were observed in spring (May) and fall (August and November; Burbano 2010). Similar observations were reported in Florida, where highest population levels of *X. compactus* in dogwood twigs occurred from June through September (Ngoan et al. 1976). In Florida, black twig borer adults overwinter in flowering dogwood and emerge during late February, attack twigs in March, and brood production begins in April. In Kona, Island of Hawaii, on the other hand, the highest populations occur from April to September and flight activity is more or less restricted to the period October to March (Burbano 2010).

Reaction of Plants to Beetle Damage. Hara (1977) described different types of symptoms characteristic of infestation after black twig borer attack. Avocado plants exude a sap from the entry hole, and as the sap dries, a white powdery material identified as calcium oxalate remains surrounding the entry hole. This symptom has been observed in successful and unsuccessful attacks. Another type of reaction was observed in unsuccessful efforts to bore into stems of *Croton reflexifolius* Kunth. Branches larger than 5 mm in diameter were also observed with exuding sap. However, when successful boring occurred, no sap was exuded. Exuding sap was also reported in *Acacia koa* seedlings on stems larger than 10 mm in diameter. None of the entry holes with exuding sap had developing brood galleries (Hara 1977). Cankers of 10–210 mm long were observed in flowering dogwood branches of outside diameter 8–22 mm, with up to 13 beetle's entry holes per canker and up to 20 females per branch causing the death of the branch (Ngoan et al. 1976). Leaves of infested twigs turned dull green and wilted in about 1 wk and turned brown in 2 wk after initial entry of a female (Ngoan et al. 1976).

X. compactus was also reported attacking *Limonia acidissima* (L); however, females were unable to construct galleries due to the presence of gum exudation produced by the plant, and dead females were observed in the attempted entry holes (Mannakkara and Alawathugoda 2005). The presence of sap exudation can work as a repellent factor for *X. compactus* attack in healthy host plants, and plants under stressed conditions produced less sap, which facilitated successful attack by *X. compactus* (Hara 1977). This type of tree defense is common among

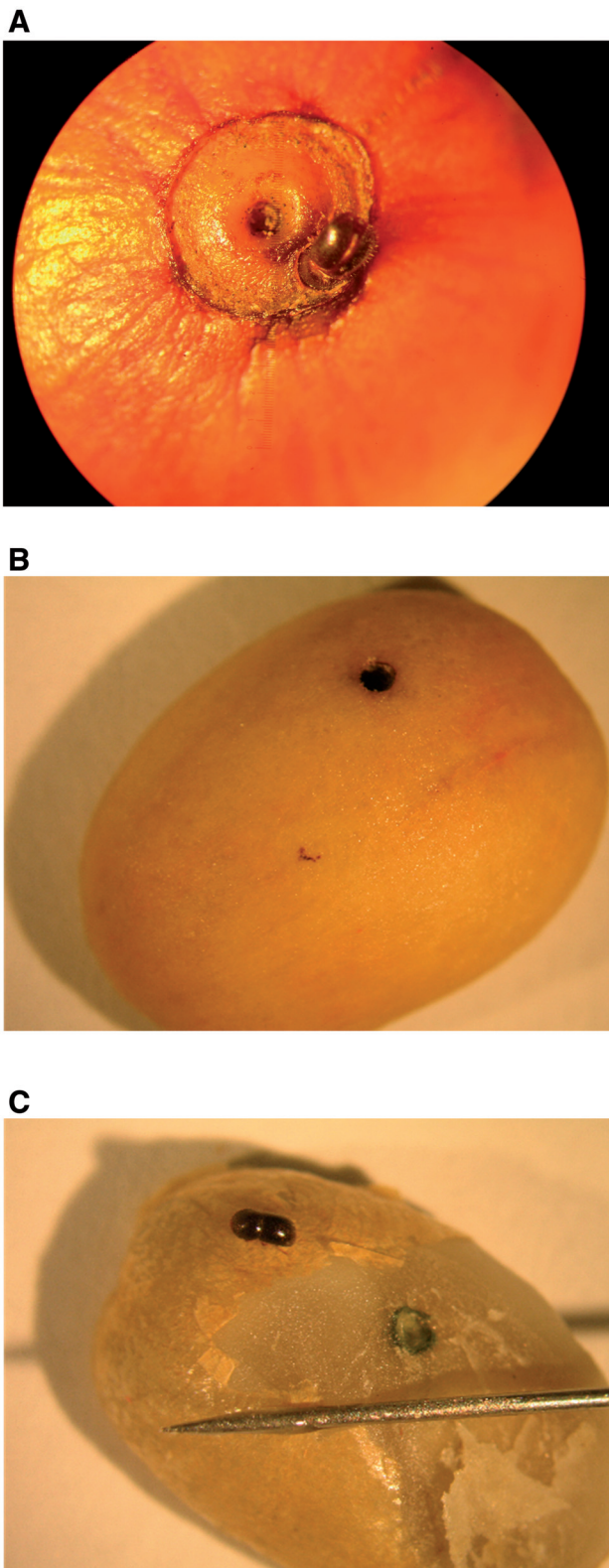


Fig. 7. *X. compactus* boring a hole in the blossom area of a coffee berry (A), damage in the parchment (B), and an adult female walking over a coffee seed (C).

plant responses to Scolytinae beetles; in fact, tree death can be predicted by the presence of dry frass coming out of the entrance hole (Hara 1977) or an exudation as a result of resistant trees (Rudinsky 1962). However, Chong et al. (2009) did not observe any pitching of sap in

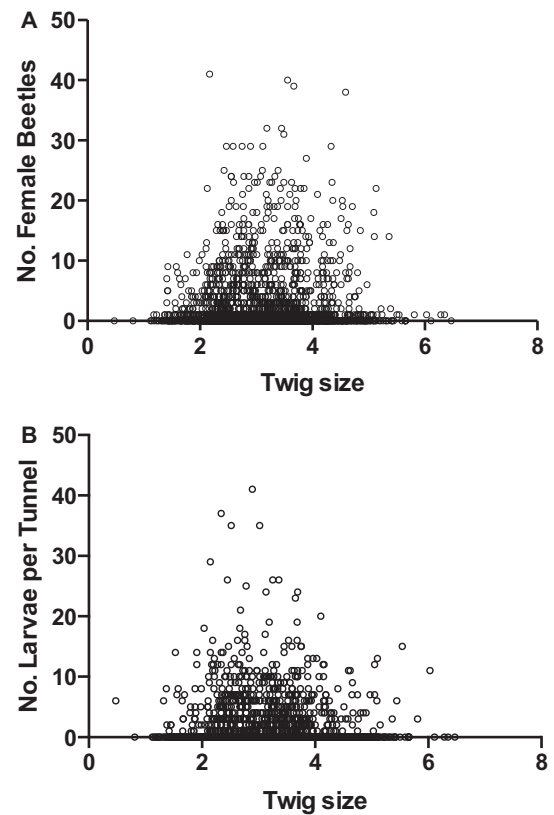


Fig. 8. Exploitation of twigs by (A) females and (B) larvae of *X. compactus*, related to twig diameter in mm ("size").

attacked southern magnolia trees in response to attack by *X. compactus*. No observations on sap exudation have been conducted in coffee. Similar responses and the effect on resistance of coffee trees to *X. compactus* attack should be studied.

Fungus and Beetle Association

Ambrosia beetles store and transfer the fungal propagules in specialized organs called mycangia (Hulcr and Dunn 2011). Mycangia are specialized structures that consist of pouches, sacs, or pubescent areas, and they can occur in numerous locations in and on beetles (Kajimura and Hijii 1994, Farrell et al. 2001, Six 2003). Some mycangia are equipped with glands or secretory cells that produce fatty acids, sterols, amino acids, and phospholipids secretions that influence the growth of fungal spores and perhaps also function to nourish mycelium during transport of the symbiotic fungus (Norris 1979, Beaver 1989). These glands also protect spores and mycelium from desiccation, and contamination until dispersal, and act selectively to suppress fungi not symbiotic with the beetle (Paine and Birch 1983, Kajimura and Hijii 1994).

The mycangium in *X. compactus* comprises a pair of dorsal pouches formed by the integumental membrane between the sclerotized mesonotum and the pronotum (Hara 1977). Once the fungal symbiont is inoculated into the galleries by the female beetles, the female lays her eggs. The female also transfers the fungus to the female offspring as they leave the gallery to colonize other plants (Norris 1979, Hulcr and Dunn 2011). The mutualistic association between the beetle and fungus is obligate and predictable, ensuring the continuity of insect–fungus association from generation to generation (Six 2003, Ploetz et al. 2013).

The nutrition of species like the black twig borer depends on the ambrosia fungus because they lack the enzymes in their digestive system to digest cellulose and lignin (Beryman 1989). This symbiotic association has been attributed to the dependence of the beetles on

fungal steroids necessary for egg hatching and larval development (Kok et al. 1970, Jordal 2002).

The symbiotic relationship between ambrosia beetles and their fungus farming, also known as ambrosia symbiosis, benefits both organisms in the following ways: 1) allows tree tissue predigestion by fungi which extract nutrients from host tissue and serve as the sole source of food for adult beetles and larvae, 2) the fungus weakens the wood, facilitating the excavation of the tunnel by developing larvae, 3) fungal mutualism in which fungus depends on the beetle to be inoculated and transported into a moisture- and nutrient-rich environment where it can survive, and 4) beetle avoids the attack of the defenses mechanisms present in the phloem (Batra 1967, Hulcr and Dunn 2011).

There are several species of fungi associated with *X. compactus* including *Fusarium solani* (Mart.) Snyder & Hans. (Hyphomycetes) and *Ambrosiella xylebori* Brader ex Arx and Hennebert (Hyphomycetes) as its primary ambrosia fungus (Hara 1977, Muthappa and Venkatasubbaiah 1981, Beaver 1989, Bhat and Sreedharan 1988, Hayato 2007, Daehler and Dudley 2002). Other species of fungi have also been isolated from body surface of adult beetles and mycangia, such as *Fusarium* sp., *Penicillium* sp., *Cladosporium* spp., and *Candida* sp. (Bhat and Sreedharan 1988, Hayato 2007). Kuo (2010) isolated several fungi from black twig borer galleries of different host plants, and *F. solani* was the most common fungal symbiont related as a source of food for the black twig borer. However, it is not certain if *F. solani* was the only source of food for *X. compactus*, as other fungi were also reported to be ambrosia fungi of *X. compactus* and their low isolation frequency suggested either contamination or incidental association related to abiotic factors that may influence the presence of fungi associated in the mycangia and be present during the isolation process (Muthappa and Venkatasubbaiah 1981; Bhat and Sreedharan 1988, Kuo 2010).

F. solani is an important phytopathogenic and toxigenic fungi that is frequently isolated from plants, soil, and animal substrata and is also associated with human infections (Daehler and Dudley 2002, Zhang et al. 2006, O'Donnell et al. 2008, Nalim et al. 2011, Hafizi et al. 2013).

F. solani has been applied widely to what is now known as the *F. solani* species complex (FSSC); however, molecular analysis demonstrated that FSSC contains at least 45 phylogenetically distinct species distributed among three major clades (Zhang et al. 2006, O'Donnell et al. 2008).

Most of the *F. solani* species have not been described formally; however, there are some studies that examine the existence of genetic variation in *F. solani* associated with ambrosia beetles (Balasundaran and Sankaran 1991, Rojas et al. 1999, Mendel et al. 2012, Ploetz et al. 2013). For instance, damage in avocado trees has been caused by this symbiotic species within Clade 3 of the FSSC, which is vectored by the ambrosia beetle *Euwallacea fornicates* Eichhoff (Coleoptera: Curculionidae: Scolytinae) (Mendel et al. 2012). Hulcr and Dumm (2011) also reported that *Fusarium* sp. is associated with *Xylosandrus crassiusculus*, which is an important pest of nursery production (Oliver and Mannion 2001). Identification of fungal associated with *X. compactus* should be determined in Hawaii islands at several elevations where coffee is grown. This study will contribute to a better understanding of *X. compactus* biology, interaction, and role among symbionts and explore other management techniques.

Host Plants

X. compactus attacks >224 plant species belonging to 62 families including agricultural crops, trees, and shrubs. Among the more commonly attacked nonnative host species are avocado (*Persea americana* Mill.), macadamia (*Macadamia integrifolia* Maiden and Betche.), mango (*Mangifera indica* L.), sycamore (*Platanus occidentalis* L.), dogwood (*Cornus florida* L.), orchids (e.g., *Cattleya skinneri* Lindl.), cinnamon (*Cinnamomum camphora* (L.) Nees and Eberm.), cherimoya (*Annona cherimola* Mill.), burutha (*Chloroxylon swietenia* DC.), cedrela (*Cedrela Mexicana* M. Roem), Enterolobium (*Enterolobium cyclocarpum* (Jacq.) Griseb), Khaya (*Khaya senegalensis* (Desr.)

A.Juss.), kobolela (*Bauhinia acuminata* L.), Kolon (*Adina cordifolia* (Roxb.) Ridsdale), kumbuk (*Terminalia arjuna* (Roxb.) Wight & Arn), Neem (*Azadirachta indica* A.Juss), Tamarind (*Tamarindus indica* L.), passion flower (*Passiflora edulis* Sims.), and southern magnolia (*Magnolia grandiflora* L.) (Ngoan et al. 1976, Mannakkara and Alawathugoda 2005, Chong et al. 2009). In Hawaii, *X. compactus* has been reported infesting coffee (*Coffea arabica* L.), cacao (*Theobroma cacao* L.), Brazilian pepper (*Schinus terebinthifolius* Raddi), koa haole (*Leucaena leucocephala* Benth), anthurium (*Anthurium andreaeanum* cv Rubrun), litchi (*Litchi chinensis* Sonn), longan (*Euphoria longan* Steud.), red ginger (*Alpinia purpurata* (Vieillard) K. Schumann), hibiscus (*Hibiscus rosa-sinensis* L.), and eucalyptus (*Eucalyptus sideroxylon* A. Cunn. Ex Woolls). In addition, some Hawaiian native species are also attacked by *X. compactus*, such as koa trees (*Acacia koa* A. Gray), hame (*Flueggea neowawraea* W.J. Hayden), mamaki (*Pipturus albidus* Hook. and Arn. A.Gray), kauila (*Colubrina oppositifolia* Brongn. ex H.Mann), lama (*Dyospyros* sp.), kawau (*Ilex anomala* Hook. & Arn.), uhiuhi (*Caesalpinia kavaiensis* H.Mann), *Olomea* (*Perrottetia sandwicensis* A. Gray), ohai (*Sesbania tomentosa* Hook. and Arn.), *Canavalia napaliensis* H. St. John, and Mann's Gardenia (*Gardenia mannii* H. St. John and Kuykendall) (Hara 1977). Many of these native Hawaiian plants are threatened or endangered, and attacks by black twig borer contribute damage to the plants that may impact their conservation status (Nelson and Davis 1972, Daehler and Dudley 2002).

Management

Cultural Control. To reduce black twig borer populations in coffee plantations, it is recommended to monitor the level of infestations and to remove as much beetle-infested material as possible from the field. Greco and Wright (2013) developed a sequential sampling procedure for black twig borer sampling in coffee. The sampling procedure provides a set-precision sampling plan to estimate mean infestation level by black twig borer. Estimating the mean density of infested branches with a precision level of 90%, 915 infested branches would need to be detected to make a decision with 40 plants sampled (Greco and Wright 2013). The infested branches should be pruned and destroyed; pruning can be done a few centimeters before the symptomatic area. If the pruned infested branches are not removed from the plantation, the black twig borer will remain active in the residues and reinfestation can occur. Use of chippers or shredders to destroy the pruned branches results in ~90% mortality of the beetles in the stem, so that the residue can be left on-site as long as branches are not left intact. Promotion of tree health and vigor will help in resisting infestation or recovering from attack (Jones and Johnson 1996).

Biological Control. Information on biological control agents of black twig borer is limited. Several natural enemies have been reported feeding on immature stages and adults of black twig borer, but none of them have been shown to provide sustained and effective control (Sreedharan et al. 1992).

Predators. Larvae of the predatory beetle *Callimerus* sp. (Coleoptera: Cleridae) were observed in tunnels of coffee branches *Coffea canephora* cv. *robusta* in India (Sreedharan et al. 1992). Under laboratory conditions, one larva of *Callimerus* sp. consumed an average of 18 larvae or pupae of black twig borer per day. *Callimerus* sp. pierces the body and then sucks the contents, leaving the exoskeleton behind. This predator feeds on all the immature stages of black twig borer and occasionally adults, but larvae are the preferred prey (Sreedharan et al. 1992). *Cryptamorpha desjardinsi* (Guérin-Méneville) (Coleoptera: Silvanidae) is a predator of the tropical nut borer in Hawaii (Jones 2002), and it has been observed on coffee trees, inside black twig borer tunnels and inside coffee berries feeding on larvae of the black twig borer and on larvae of the Mediterranean fruit fly *Ceratitidis capitata* (Diptera: Tephritidae) (Burbano 2010). This predator can be considered a potentially useful natural enemy for black twig borer.

Parasitoids. Several parasitoids have been reported in India. *Eupelmus* sp. (Hymenoptera: Eupelmidae) was found inside black twig borer tunnel in coffee plants in Kerala, India. Of 1,101 tunnels of *X. compactus* examined in branches of robusta coffee, 7.9% were occupied by the predatory *Eupelmus* sp. Although there are no studies on its impact on *X. compactus*, presence of this parasitoid was significantly higher during September and lower numbers were observed in January. This incidence ranged from 20.58% in September to 1.31% in January. This coincides with the higher and low levels of *X. compactus* populations during these months, respectively (Balakrishnan et al. 1989). *Tetrastichus xylebororum* (Eulophidae) and an undescribed bethylid (Hymenoptera: Bethylinidae) were reported to be associated with *X. compactus* on the island of Java in Indonesia (Balakrishnan et al. 1989). In Hawaii, three Braconidae were introduced for *X. compactus* control—*Dendrosoter enervatus* Marsh, *Dendrosoter protuberans* Nees, and *Ecphylyus* sp. However, parasitism has not been recorded from the field, and they are presumed not to have established (Bernarr Kumashiro personal communication, Hawaii Department of Agriculture).

Microbial Control. Another promising natural enemy of *X. compactus* is the entomopathogenic fungus *Beauveria bassiana*. *B. bassiana* was shown to infect all the life stages of *X. compactus* in India. Augmentative spray applications of spores of the fungus *B. bassiana* resulted in 21% infection of the beetles present in colonies of robusta coffee branches (Balakrishnan et al. 1994). *B. bassiana* is now registered in Hawaii, for the coffee berry borer *Hypothenemus hampei* Ferrari (Coleoptera: Curculionidae). Applications being made in the field for coffee berry borer control may be contributing to suppressing *X. compactus*.

Semiochemical Control. The use of semiochemicals to control ambrosia beetles by mass trapping has been widely studied (Moeck 1970, Czokajlo and Teale 1999, Oliver and Mannion 2001). Japanese beetle traps baited with vials filled with ethanol have been reported as a potential option to monitor abundance and flight activity of *X. compactus* (Burbano et al. 2012). The repellent verbenone (polyethylene bubblecaps filled with 800 mg neat S(-)-verbenone (Contech, Inc., Victoria, BC, Canada)) significantly reduced (by almost 50%) the number of *X. compactus* compared with control traps baited with ethanol, suggesting that this repellent may have some potential for *X. compactus* management (Burbano et al. 2012).

Chemical Control. Mangold et al. (1977) reported 83% mortality of all stages of *X. compactus* infesting flowering dogwood in Florida, using the organophosphate insecticide Chlorpyrifos (Dow Chemical Co., Midland, MI, USA). Two registered insecticides on coffee in Hawaii were tested in coffee branches infested with black twig borer in the Kona district (Jones and Johnson 1996), including the synthetic pyrethroid tau-fluvalinate (Mavrik, Adama Agricultural Solutions UK Ltd., UK) and the insect growth regulator from neem seed extract, azadirachtin (Azatin, OHP, Inc. Mainland, PA); each insecticide was combined with 25% horticultural mineral oil for application. Neither of the pesticides tested provided sufficient control of black twig borer population to reduce damage to coffee trees (Jones and Johnson 1996).

The translaminar neonicotinoid insecticide Provado (Bayer CropScience, North Carolina, USA) has been registered in Hawaii to control the green scale *Coccus viridis* (Green) (Hemiptera: Coccidae) in coffee plantations. Foliar applications of this insecticide have been tested on black twig borer attacking coffee, and it seems that infestation levels of coffee branches are reduced over time as a result of the treatment (E.B.G., unpublished data). Provado has since been replaced with AdmirePro, a systemic formulation.

In conclusion, studies on biology, ecology, management, and impact of *X. compactus* have been carried out in Hawaii (Hara and Beardsley 1979, Jones and Johnson 1996, Daehler and Dudley 2002, Burbano 2010). Effective control of *X. compactus* requires information on

seasonality of adult flights (the primary dispersal mechanism), the effectiveness of natural enemies, and the effectiveness of cultural practices (Jones and Johnson 1996). Effective sampling to characterize infestation levels is a valuable component of a *X. compactus* management program. Greco and Wright (2013) developed a sequential sampling plan to estimate extent of infestation in coffee. This sampling plan may be used in conjunction with nominal thresholds set by growers, to determine when action needs to be taken to manage *X. compactus* infestations. Management of *X. compactus* in coffee plantations in Hawaii can be improved by implementing effective monitoring, using baited traps to detect large mobilizations of female beetles. Sampling damage on coffee plants using a sequential sampling plan can provide estimates of *X. compactus* damage levels that may be used to make decisions on the need for pest management intervention. Biological control options are currently limited in Hawaii, although the use of *B. bassiana* applications directed at coffee berry borer (*H. hampei*) may contribute a currently unquantified level of mortality. Predators seem to play a minor role in the population dynamics of *X. compactus* in Hawaii coffee. Repellent semiochemicals, specifically verbenone, may have potential for use as repellents in coffee. Insecticidal control is currently not a viable option, with few labeled insecticides that show effectiveness. Physical removal of infested branches on coffee plants remains the most reliable means of managing this pest in coffee.

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References

- Balakrishnan, M. M., P. K. Vinodkumar, and C. B. Prakasan. 1989. Impact of the predator *Eupelmus* sp. (Hymenoptera: Eupelmidae) on the incidence of *Xylosandrus compactus*. *J. Coffee Res.* 19: 88–90.
- Balakrishnan, M. M., K. Sreedharan, and P. K. Bhat. 1994. Occurrence of the entomopathogenic fungus *Beauveria bassiana* on certain coffee pests in India. *J. Coffee Res.* 24: 33–35.
- Balasundaran, M., and K. V. Sankaran. 1991. *Fusarium solani* associated with stem canker and die-back of teak in southern India. *Indian For.* 117: 147–149.
- Batra, L. R. 1963. Ecology of ambrosia fungi and their dissemination by beetles. *Trans. Kans. Acad. Sci.* 66: 213–236.
- Batra, L. R. 1967. Ambrosia fungi: a taxonomic revision and nutritional studies of some species. *Mycologia* 59: 976–1017.
- Beardsley, J. W. 1964. The black twig borer, a potentially serious pest of coffee new to Hawaii. *Hawaii Farm Sci.* 13: 5–6.
- Beaver, R. A. 1989. Insect fungus relationships in the bark and ambrosia beetles, pp. 121–143. *In* N. Wilding, N. M. Collins, P. M. Hammond, and J. F. Weber (eds.), *Insect Fungus Interactions*. Academic, New York, NY.
- Berryman, A. A. 1989. Adaptive pathways in scolytid-fungus associations, pp. 145–159. *In* N. Wilding, N. M. Collins, P. M. Hammond, and J. F. Weber (eds.), *Insect Fungus Interactions*. Academic, New York, NY.
- Bhat, S. S., and K. Sreedharan. 1988. Association of *Ambrosiella xylebori* Brader, with the Shot-hole borer *Xylosandrus compactus* Eichhoff, a pest of robusta coffee. *J. Coffee Res.* 18: 54–57.
- Bittenbender, H. C., and V. Easton-Smith. 1999. Growing coffee in Hawaii. College of Tropical agriculture and human resources. University of Hawaii at Manoa.
- Burbano, E. 2010. Developing a monitoring tool to understand the seasonal dynamics and management techniques to estimate a sampling plan for *Xylosandrus compactus* (Eichhoff) in Hawaii. Ph.D. dissertation, University of Hawaii at Manoa, Honolulu.

- Burbano, E. G., M. G. Wright, N. E. Gillette, S. Mori, N. Dudley, T. Jones, and M. Kaufmann. 2012.** Efficacy of traps, lures and repellents for *Xylosandrus compactus* (Coleoptera: Curculionidae) and other ambrosia beetles on *Coffea arabica* plantations and *Acacia koa* nurseries in Hawaii. *Environ. Entomol.* 41: 133–140.
- Chong, J. H., L. Reid, and M. Williamson. 2009.** Distribution, host plants, and damage of the Black twig borer, *Xylosandrus compactus* (Eichhoff), in South Carolina. *J. Agric. Urban Entomol.* 26: 199–208.
- Czokajlo, D. and S. Teale. 1999.** Synergistic effect of ethanol to α -pinene in primary attraction of the larger pine shoot beetle, *Tomicus piniperda*. *J. Chem. Ecol.* 25: 1121–1130.
- Daehler, C. C., and N. Dudley. 2002.** Impact of the black twig borer, an introduced insect pest, on *Acacia koa* in the Hawaiian Islands. *Micronesica* 6: 35–53.
- Farrell, B. D., A. Sequeira, B. C. O'Meara, B. B. Normark, J. H. Chung, and B. H. Jordal. 2001.** The evolution of agriculture in beetles (Curculionidae: Scolytinae and Platypodinae). *Evolution* 55: 2011–2027.
- Greco, E. B., and M. G. Wright. 2012.** First report of exploitation of coffee beans by black twig borer (*Xylosandrus compactus*) and tropical nut borer (*Hypothenemus obscurus*) (Coleoptera: Curculionidae: Scolytinae) in Hawaii. *Proc. Hawaii. Entomol. Soc.* 44: 71–78.
- Greco, E. B., and M. G. Wright. 2013.** Dispersion and sequential sampling plan for *Xylosandrus compactus* (Coleoptera: Curculionidae) infesting Hawaii coffee plantations. *Environ. Entomol.* 42: 277–282.
- Hafizi, R., B. Salleh, and Z. Latiffah. 2013.** Morphological and molecular characterization of *Fusarium. Solani* and *F. oxysporum* associated with crown disease of oil palm. *Braz. J. Microbiol.* 44: 959–968.
- Hara, A. H. 1977.** Biology and rearing of the black twig borer, *Xylosandrus compactus* (Eichhoff) in Hawaii. Master thesis. University of Hawaii, Honolulu.
- Hara, A. H., and J. W. Beardsley, Jr. 1979.** The biology of the black twig borer, *Xylosandrus compactus* (Eichhoff), in Hawaii. *Proc. Hawaii. Entomol. Soc.* 18: 55–70.
- Hayato, M. 2007.** Note on the dieback of *Cornus florida* caused by *Xylosandrus compactus*. *Bull. For. For. Prod. Res. Inst.* 6: 59–63.
- (HDOA) Hawaii Department of Agriculture. 2013.** Hawaii farm facts. Coffee: marketing forecast lower but higher value expected for 2012/13 season. (http://www.nass.usda.gov/Statistics_by_State/Hawaii/Publications/Archive/xcof12.pdf)
- Huler, J., and R. R. Dunn. 2011.** The sudden emergence of pathogenicity in insect–fungus symbioses threatens naive forest. *Proc. R. Soc. Ser. B* 278: 2866–2873.
- Intachat, J. and L. G. Kirton. 1997.** Observations on insects associated with *Acacia mangium* in Peninsular Malaysia. *J. Trop. For. Sci.* 9: 561–564.
- Jones, V. P. 2002.** Macadamia integrated pest management. CTAHR, University of Hawaii at Manoa. p. 98.
- Jones, V. P., and M. W. Johnson. 1996.** Management of black twig borer on coffee. GACC Termination report, p. 6.
- Jordal, B. H. 2002.** Elongation Factor 1 α resolves the monophyly of the haplo-diploid ambrosia beetles Xyleborini (Coleoptera: Curculionidae). *Insect Mol. Biol.* 11: 453–465.
- Kajimura, H., and N. Hijii. 1994.** Reproduction and resource utilization of the ambrosia beetle, *Xylosandrus mutilatus*, in field and experimental populations. *Entomol. Exp. Appl.* 71: 121–132.
- Kok, L. T., D. M. Norris, and H. M. Chu. 1970.** Sterol metabolism as a basis for a mutualistic symbiosis. *Nature* 225: 661–662.
- Kuo, H. C. 2010.** Plant-fungus-beetle interactions: Case studies in Hawaiian endemic *Xyleborus* species and the black twig borer. Ph.D. dissertation, University of Hawaii at Manoa, Honolulu.
- Mangold, J. R., R. C. Wilkinson, and D. E. Short. 1977.** Chlorpyrifos sprays for control of *Xylosandrus compactus* in flowering dogwood. *J. Econ. Entomol.* 70: 789–790.
- Mannakkara, A., and R.M.D. Alawathugoda. 2005.** Black twig borer *Xylosandrus compactus* (Eichhoff) (Coleoptera: Scolytidae) damage for forest tree species. *Sri Lanka For.* 28: 65–75.
- Matsumoto, K. 2002.** Insect pests of Mahogany in Indonesia and Malaysia. *Trop. For.* 55: 29–36.
- Mendel, Z., A. Protasov, M. Sharon, A. Zveibil, S. Ben Yehuda, K. O'Donnell, R. Rabaglia, M. Wysoki, and S. Freeman. 2012.** An Asian ambrosia beetle *Euwallacea fornicatus* and its novel symbiotic fungus *Fusarium* sp. pose a serious threat to the Israeli avocado industry. *Phytoparasitica.* 40: 235–238.
- Meshram, P. B., M. Husen, and K. C. Joshi. 1993.** A new report of ambrosia beetle, *Xylosandrus compactus* Eichhoff. (Coleoptera: Scolytidae) as a pest of African mahogany, *Khaya* sp. *Indian For.* 119: 75–77.
- Moock, H. A. 1970.** Ethanol as the primary attractant for the ambrosia beetle, *Trypodendron lineatum* (Coleoptera: Scolytidae). *Canad. Entomol.* 102: 985–995.
- Muthappa, B. N., and P. Venkatasubbaiah. 1981.** Association of *Ambrosiella macrosore* with *Xylosandrus compactus*, the shot-hole borer of robusta coffee in India. *J. Coffee Res.* 11: 54.
- Nalim, F. A., G. J. Samuels, R. L. Wijesundera, and D. M. Geiser. 2011.** New species from the *Fusarium solani* species complex derived from perithecia and soil in the old world tropics. *Mycologia* 103: 1302–1330.
- Nelson, R. E. and C. J. Davis. 1972.** Black twig borer, a tree killer in Hawaii. USDA Forest Service Research Note PSW 274. U. S. Department of Agriculture. Berkeley, CA.
- Ngoan, N. D., R. C. Wilkinson, D. E. Short, C.S. Moses, and J. R. Mangold. 1976.** Biology of an introduced ambrosia beetle, *Xylosandrus compactus*, in Florida. *Ann. Entomol. Soc. Am.* 69: 872–876.
- Norris, D. M. 1979.** The mutualistic fungi of Xyleborini beetles. pp. 53–63. *In* L.R. Batra. *Insect-fungus symbiosis: nutrition, mutualism, and commensalism.* Allan-held, Osmun & Co., New York, NY.
- O'Donnell, K., D. A. Sutton, A. Fothergill, D. McCarthy, M. G. Rinaldi, M. E. Brandt, N. Zhang, and D. M. Geiser. 2008.** Molecular phylogenetic diversity, multilocus haplotype nomenclature, and in vitro antifungal resistance within the *Fusarium solani* species complex. *J. Clin. Microbiol.* 46: 2477–2490.
- Oliver, J. B., and C. M. Mannon. 2001.** Ambrosia beetle (Coleoptera: Scolytidae) species attacking chestnut and captured in ethanol baited traps in middle Tennessee. *Environ. Entomol.* 30: 909–918.
- Oliveira, C. M., C.A.H. Flechtmann, and M. R. Frizzas. 2008.** First record of *Xylosandrus compactus* (Eichhoff) (Coleoptera: Curculionidae: Scolytinae) on soursop, *Annona muricata* L. (Annonaceae) in Brazil, with a list of host plants. *Coleopterists Bull.* 62: 45–48.
- Paine, T. D., and M. C. Birch. 1983.** Acquisition and maintenance of mycangial fungi by *Dendroctonus brevicomis* LeConte (Coleoptera: Scolytidae). *Environ. Entomol.* 12: 1384–1386.
- Ploetz, R. C., H. Jiri, M. J. Wingfield, and Z. Wilhelm de Beer. 2013.** Destructive tree diseases associated with ambrosia and bark beetles: black swan events in tree pathology? *Plant Disease.* 95: 856–872.
- Rojas, G. M., J. A. Morales-Ramos, and T. C. Harrington. 1999.** Association between *Hypothenemus hampei* (Coleoptera: Scolytidae) and *Fusarium solani* (Moniliales: Tuberculariaceae). *Ann. Entomol. Soc. Am.* 92: 98–100.
- Rudinsky, J. A. 1962.** Ecology of Scolytidae. *Ann. Rev. Entomol.* 7: 327–348.
- Six, D. L. 2003.** Bark beetle-fungus symbioses, pp. 99–116. *In* K. Bourtzis and T. A. Miller. *Insect Symbiosis.* CRC Press, Boca Raton, FL.
- Six, D. L. 2012.** Ecological and evolutionary determinants of bark beetle-fungus symbioses. *Insects* 3: 339–366.
- Sreedharan, K., M. M. Balakrishnan, and P. K. Bhat. 1992.** *Callimerus* sp. (Coleoptera: Cleridae), a predator of the shothole borer, *Xylosandrus compactus* (Eichh.). *J. Coffee Res.* 22: 139–142.
- Vasquez, L. L., and G. A. Martinez. 1999.** Nivel de ataque y características de los danos ocasionados por *Xylosandrus compactus* (Eichhoff) en el café. *Revista de Protección Vegetal.* 14: 27–32.
- Vasquez, L. L., N. Tur, and S. Monteagudo. 1996.** Insectos de la familia Scolytidae (Coleoptera) que atacan al café en Cuba. *Revista de Protección Vegetal.* 11: 5–7.
- Vasquez Moreno, L. L., S. Monteagudo Toranzo, and R. Vera Lima. 2002.** Incidencia de *Xylosandrus compactus* (Coleoptera: Scolytidae) en diferentes variedades de *Coffea* en condiciones naturales. *Agrotecnia de Cuba.* 28: 68–73.
- Venkataramaiah, G., and P. Sekhar. 1964.** Preliminary studies on the control of the shot hole borer, *Xylosandrus compactus* (Eichhoff) *Xyleborus morstatti* (HGDN). *Indian Coffee.* 28: 208–210.
- Wolfenbarger, D. 1973.** Ataque del escarabajo *Xylosandrus compactus* (Eichhoff) al aguacate, con datos sobre su control. *Revista Peruana de Entomología* 16: 1–2.
- Wood, S. L. 1982.** The bark and ambrosia beetles of North and Central America (Coleoptera: Scolytidae), a taxonomic monograph. *Great Basin Nat. Memoirs* No. 6. Brigham Young University, Provo, UT, p. 1359.
- Zhang, S., D. G. Ahearn, J. A. Noble-Wang, R. D. Stulting, B. L. Schwam, R. B. Simmons, G. E. Pierce, and S. A. Jr. Crow. 2006.** Growth and survival of *Fusarium solani*-*F. oxysporum* complex on stressed multipurpose contact lens care solution films on plastic surfaces in situ and in vitro. *Cornea.* 25: 1210–1216.

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