Chapter 26
Polyphagous Shot Hole Borer and *Fusarium* Dieback in California

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Abstract The Polyphagous Shot Hole Borer (Coleoptera: Curculeonidae: Scolytinae), *Euwallacea* sp. near *fornicatus*, is an ambrosia beetle native to Asia that has been introduced into Israel, California, and South Africa. The beetle maintains a symbiotic relationship with three species of fungi that it vectors between host trees by carrying spores within a mandibular mycangium. These ambrosial fungi are inoculated into host trees and are the sole nutritional source for the adults and the larvae. Unfortunately for forest and resource managers, one of the fungi, *Fusarium euwallaceae*, is a moderately virulent pathogen and is responsible for causing a dieback disease in susceptible hosts. High levels of infestation of susceptible host trees have resulted in high levels of mortality. The currently recognized host range for the beetle-fungus complex includes more than 200 tree species that can be attacked by the beetle, more than 100 species that can support growth of the fungus, and 37 species that can be used as a reproductive host by the beetles. Many of these reproductive hosts are important agricultural crops, components of the California urban forest, or components of native riparian forest communities. Management is currently focused on monitoring using visual inspections or trapping, sanitation using solarization or chipping, and direct control using contact or systemic insecticides. Future management approaches will include planting resistant or unsuitable host trees and biological control. As more information about the biology and ecology of the insect-fungus complex is developed, it may be possible to develop strategies for limiting spread within and among regions of the world with Mediterranean climates.

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26.1 Wood Borers and Ambrosia Beetles

As international trade and movement of people increases, there are increased movements of insects to new environments. This has become a particular problem with wood borers and ambrosia beetles (Haack 2006). The emerald ash borer, a buprestid native to Asia, has killed hundreds of thousands of trees in central North America where it has been accidentally introduced and threatens to invade the Mediterranean forests of the west (Herms and McCullough 2014). The redbay ambrosia beetle was also introduced into southeastern North America where, in combination with a highly pathogenic fungus, is killing large numbers of native trees (Mayfield et al. 2013).

Scolytinae bark beetles have a wide spectrum of symbiotic associations with fungi (Paine et al. 1997; Six and Wingfield 2011). At one end of the spectrum are species that may be associated with fungi that contaminate the external surface of the body or with phoretic mites. At the other end of the continuum are beetles whose sole source of nutrition are the fungi vectored into new host trees. The ambrosia beetles may be associated with one or more symbiotic fungi which are cultivated on the walls of the beetle's galleries (Batra 1985). Fungi are carried between hosts in special ectodermal pouches known as mycangia that protect and culture the fungi (Batra 1963). The ambrosia beetles may colonize a range of host species and may also be associated with both living and dead or dying trees.

26.2 Polyphagous Shot Hole Borer Biology

The Polyphagous Shot Hole Borer (Scolytinae: *Euwallacea* sp. nr. *fornicatus*) (PSHB) is an invasive ambrosia beetle that has recently been found spreading throughout southern California (Eskalen et al. 2012). Based on morphological characteristics, the PSHB was initially identified as the Tea Shot Hole Borer (Scolytinae: *Euwallacea fornicatus*) (TSHB). However, Mendel et al. (2012) noted that *E. fornicatus* established in Israel exhibited previously undocumented host preferences. The two were distinguished as separate species based on DNA samples collected in California compared to those collected from tea plantations in Sri Lanka. There were significant differences in nuclear and mitochondrial DNA sequences which distinguished PSHB as a cryptic species (P. F. Rugman-Jones and R. Stouthamer, unpublished data). Until a full taxonomic evaluation and navigation of the numerous revisions that have occurred in the genus *Euwallacea* has been finished, the common name of Polyphagous Shot Hole Borer was adopted by Eskalen et al. (2013). The appellation "Polyphagous" refers to the broad range of trees attacked by the beetle rather than the different kinds of fungi eaten.

The first documentation of PSHB in California was in 2003 on black locust (*Robinia pseudoacacia*) (Eskalen et al. 2012). However, no fungal damage was recorded at the time. It was not until 2012 that nine avocado trees exhibiting branch

dieback were observed in Los Angeles County (Eskalen et al. 2012). The cultivars that were attacked consisted of Hass, Bacon, Fuerte, and Nabal (Eskalen et.al. 2012). Branch dieback is due to the disease *Fusarium* dieback which is caused by fungal invasion of the vascular elements of the tree, which prevents transport of water and nutrients to the branches (Eskalen et al. 2012; Freeman et al. 2013). Before this the only prior reports of damage caused by PSHB were on avocado in Israel (Mendel et al. 2012). Trees in Israel started showing symptoms of beetle attack in 2005 which includes a characteristic accumulation of white exudate around penetration site (Mendel et al. 2012). Because ambrosia beetles do not feed on the wood itself, the sawdust that is created during tunneling is cleaned out by the mother (Batra 1985) and often accumulates around the entrance to the gallery. Active galleries created by PSHB can often be found by the accumulation of sawdust on the bark of the tree along with discoloration around the gallery entrance (Fig. 26.1).

The mycangia of PSHB is located in a cuticular invagination associated with the mandibles. The beetle maintains a symbiotic relationship with three different fungal species that are carried within the fungus-bearing structure. The first is *Fusarium euwallaceae* which is the causal agent of *Fusarium* dieback (Freeman et al. 2013). The other two are an *Acremonium* and a *Graphium* species (Lynch et al. 2015).

Fig. 26.1 Water soaking and frass accumulation around polyphagous shot hole borer entry sites on the trunk of a coast live oak (*Quercus agrifolia*)

Sequences obtained from fungal isolates were deposited in Genbank under under accession numbers: JQ723753, JQ723760, JQ723756, and JQ723763 (Eskalen et al. 2012).

Female polyphagous shot hole borers are 1.8–2.5 mm in length and range from brown to black in color. Males are 1.5–1.67 mm in length, light brown to black in color, and lack wings (Fig. 26.2). Long distance dispersal and gallery formation is strictly limited to females. Males are only able to disperse by walking to adjacent galleries on the same host. Males are less common than females and galleries will usually only contain one to two males. The exception to this is in galleries created by unmated females. The beetles have a haplo-diploid sex determination system, which means that diploid fertilized eggs give rise to females and haploid unfertilized eggs give rise to males. Consequently, galleries created by unmated females will consist of only male progeny.

Galleries are only about as wide as the female beetle and are initially dug to a depth of about 15 mm into the tree. As the initial gallery is formed, the fungal symbionts are established on the walls using spores carried in the mycangia. If fungal growth is sufficient, the female will lay approximately five eggs at the end of the initial gallery before starting to expand the gallery further. The growing fungal mats are grazed upon by both larvae and adults throughout their entire occupation of the gallery (Fig. 26.3). Larvae remain in the area which they hatched and stay in a clumped distribution throughout the gallery, even when pupating. After pupation, both sexes reach a teneral adult stage that is characterized by lack of fully developed wings and lighter coloration.

While in the gallery, the beetles will mate with their siblings and continue to feed on the fungi growing on the walls. During this time, the mycangia of the females will be filled with fungal spores that will be transported to the next parental gallery. Adult beetles may remain within their natal gallery past maturation and disperse at irregular intervals. Dispersing females may either fly from their natal host to search for a new suitable host tree or they may recolonize the same host tree. The stimuli associated with

Fig. 26.2 Female polypgagous shot hole borer *Euwallacea sp. nr. Fornicatus*

Fig. 26.3 Cross section of a branch heavily colonized by the polyphagous shot hole borer. The gallery walls are lined with ambrosial fungal growth and the vascular tissue is stained

the decision to disperse or recolonize are currently very poorly understood but may possibly be associated with densities of occupied galleries and condition of the natal host.

Damage to host trees is characterized by different symptoms, depending on the species attacked. The tree may exhibit signs of *Fusarium* dieback in the branches (Fig. 26.4). Dieback symptoms include wilting branches, discolored leaves, and breaking of heavy branches (Mendel et al. 2012). These symptoms will be typically observed on primary branches as a result of the symbiotic fungi blocking water movement through the plant vascular system (Eskalen et al. 2013) (Fig. 26.5). However, PSHB can start galleries in branches as small as 2 cm in diameter and almost any age (Mendel et al. 2012). On the trunk of the tree the most common symptom of beetle invasion is the presence of staining or discoloration of the bark around the entry hole due to necrosis of the tissue (Eskalen et al. 2013). Some tree species will also respond to attack with gum deposition around the attack site. Infested avocado exhibits a unique response where large deposits of white and powdery exudate composed of the sugar perseitol form around the entry hole (Mendel et al. 2012).

Infested trees have been located in Los Angeles, San Diego, Riverside, and Orange County in southern California. Records of the beetles' movement are tracked using trap baited with an attractant lure (quercivorol) set up along the borders of the known infested areas in order to identify when the beetle has moved into new territory. Known host species are also visually inspected for signs of attack. The earliest mapped infestations in 2012 covered an area that included Los Angeles, Pasadena, Pomona, and Seal Beach (Eskalen et al. 2015. Distribution map). The following year, in 2013, the infestations had expanded its borders in each direction

Fig. 26.4 Dieback in boxelder (*Acer negundo*) heavily colonuised by the polyphagous shot hole borer and infected with the symbiotic *Fusarium euwallacea*

Fig. 26.5 Vascular staining associated with beetle galleries and infection by the symbiotic fungus

to include Brentwood, Altadena, Ontario, and Laguna Beach. During 2014 PSHB expanded its range northwest to Sunland above the Verdugo Mountains and east into Corona. This trend has continued in 2015 where the only new captures of PSHB are north and west in the lower Santa Susanna Mountains and Woodland Hills. Research is currently underway to determine the temperature development rates and thermal tolerances of the beetles to predict the potential limits of the infested areas.

Unfortunately, a different type of PSHB was discovered outside the previously infested area. The two types are distinguished by having different fungal complements and different mitochondrial DNA sequences (A. Eskalen and R. Stouthamer, unpublished data). The first type found in California has been named the Los Angeles type and the second type is named the San Diego type, based on the county that each were first recorded. The San Diego type has been mostly located around the city of Escondido with recent captures in the city of San Diego.

The infested areas of Los Angeles County include the Los Angeles Arboretum and the Huntington Library and Botanical Gardens. These botanical gardens contain a wide variety of identified tree species and cultivars. Trees in these collections were surveyed in order to estimate the range of possible hosts within California. Of the 335 tree species in 85 families that were examined 207 of them showed symptoms consistent with attack (Eskalen et al. 2013). More than 100 of the tree species were susceptible to colonization by *F. euwallaceae* (Eskalen et al. 2013), which indicates that even if the beetle doesn't reproduce inside that tree that it may still suffer the effects of *Fusarium* dieback. The number of trees species that supported reproductive success for PSHB was 19 species (Eskalen et al. 2013). That number has expanded to a list of 37 species. California native forest species that are threatened include box elder (*Acer negundo*), big leaf maple (*Acer macrophyllum*), California sycamore (*Platanus racemosa*), Gooding's black willow (*Salix goodingii*), red willow (*Salix laevigata*), white alder (*Alnus rhambifolia*), cottonwood (*Populus fremontii*), black cottonwood (*Populus trichocarpa*), Engelmann oak (*Quercus engelmannii*), valley oak (*Quercus lobata*), and coast live oak (*Quercus agrifolia*) (Eskalen et al. 2013). Of these trees, PSHB has a strong preference for box elder. However, work is currently underway to evaluate susceptibility and suitability of the reproductive hosts.

To estimate the potential impact PSHB could have on an urban forest, a comparison was made between a list of common street trees and the list of trees that support either or both fungus and beetle growth. It was determined that 48 % of street trees belong to a species that are suitable for fungal colonization and that 26 % of street trees are a suitable host for beetle development (Eskalen et al. 2013). Urban tree species on this list include Japanese maple, English oak, mimosa, mesquite, and camellia (Eskalen et al. 2013).

A similar comparison was made to estimate the threat of PSHB to agricultural crops. The fungus *F. euwallacea* was able to colonize avocado, eastern mulberry, olive, macadamia, Turkish hazelnut, loquat, peach, and grapevine (Eskalen et al. 2013). Of these crops only avocado supported beetle development (Eskalen et al. 2013). Trees of agricultural significance that were not attacked by PSHB include date palm, pomegranate, fig, apple, and citrus (Eskalen et al. 2013). Agricultural

trees that PSHB attacked but did not support fungal growth were cassava, Japanese persimmon, Japanese crabapple, and eastern black walnut (Eskalen et al. 2013).

Two reproductive hosts of exotic origin are of particular note. The first is castor bean (*Ricinus communis).* Castor bean is a favored reproductive host of the Los Angeles type (Eskalen et al. 2013) and is considered an obnoxious weed because of the toxic seeds and aggressive growth characteristics. The second is Tree of Heaven (*Alianthus altissima*). It is also considered an aggressive weedy tree species that will establish thick stands in disturbed habitats. Due to the widespread nature of these two weedy species, they may function as potential alternate hosts of PSHB that can facilitate reestablishment of the beetle in managed areas or allow for a population of beetles to move between areas if castor bean patches or *Alianthus* stands exist in between and act as corridors for invasion across the interfaces between urban, agricultural, and native forest communities.

26.3 Approaches for Management

The biology of the polyphagous shot hole borer limits potential options for management of the insect to reduce the number of affected trees. Females emerge from the natal galleries already inseminated, so there is no known sex pheromone for the insect. There does not appear to be an aggregation pheromone as has been identified for many other species of bark beetles. Consequently, survey and detection has been limited to visual inspections until very recently. The discovery of the response to quercivorol (p-menth-2-en-1-ol) has made it possible to trap beetles in the landscape. This discovery should make it possible to both delimit infestations and to monitor the movement of individuals. Because of the high risk of tree mortality, quarantine, detection, and restriction of movement of infested or potentially infested host material is critical to limiting tree loss.

Disposal of infested trees and wood residues provides challenge for forest managers. Sanitation is critical to reduce the population of beetles within an area, eliminate human-aided dispersal of the insects, and to prevent on-site emergence and reinfestation of trees. It is possible to chip or grind infested material to kill the beetles in the wood. Material chipped to sizes 2.5 cm or less prevented any emergence of adults. Chipping material to approximately 5 cm in size did not completely prevent emergence of the adults, but the population was reduced by more than 90 %. An alternative approach to chipping for sanitation is to use solarization. Covering infested log sections with 2 ml clear plastic in the summer months in southern California raised the temperatures within the log pile to more than 60 °C when the daily ambient temperatures had an average maximum of 32 °C and eliminated any signs of beetle activity within six weeks (Jones and Paine 2015). Unfortunately, solarization in the cooler fall and winter seasons has not proven to be effective.

It may be possible to use direct control with insecticides to reduce the risk of infestation of individual high value trees. Synthetic pyrethroid contact insecticides have been demonstrated to be effective at establishing a barrier to beetles attempting

to penetrate through the bark during colonization. There are systemic insecticides that have proven effective against other wood borers (McCullough et al. 2015), but these could be acting either on adults when they feed on foliage or on adults and larvae tunneling in the wood. Unlike the many other wood borers, the ambrosia beetles do not feed on the wood; rather, they only feed on the fungi. Consequently, it remains unclear whether they would contact the systemic insecticides in a way to acquire a toxic dose. However, their absolute reliance on fungi for nutrition may provide another opportunity for chemical control. It may be possible to apply a fungicide either systemically or in conjunction with a bark penetrant to kill the fungal symbionts and deprive the beetles of their source of nutrition. All of these options are the subject of ongoing investigations.

The identified list of susceptible or suitable hosts continues to change as the beetles encounter new potential host species. Although the range of potential hosts does change, it is clear that there are some species that are regularly infested (e.g., box elder) and others that are not (e.g., conifers). Thus, it is possible to generate a series of recommendations to landscape and forest managers of high risk tree species to either carefully monitor in established landscapes or to avoid when replanting. Careful host selection should be practiced to limit future risk from the ambrosia beetle.

The other option for long term management of the beetle is establishing biological control. Once it can be clearly established how many species of beetles have become established and where their native range is in Asia, it will be possible to conduct exploration in those areas for suitable natural enemies. Investigators have collected a number of candidate fungi, nematode, and arthropod natural enemies in preliminary trips and these opportunities will be pursued in the future. Unfortunately, because the ambrosia beetle species appear to be new to science, the amount of historical collection data for the beetles. Comparable historical data for the natural enemies is essentially nonexistent. Biological control remains an important option, but will not be established in a short time frame.

26.4 Risk to Mediterranean Forests

Although native range of the polyphagous shot hole borer appears to be in Asia, there is substantial risk to forest tree communities in Mediterranean environments. In fact, the beetle is currently found in three of the five continents with Mediterranean climates. It was first discovered infesting avocado groves in Israel (Mendel et al. 2012; Freeman et al. 2013) along the eastern rim of the Mediterranean Sea. Fortunately, the number of suitable host trees either in the urban landscape or in native forests is limited. Consequently, it has not been reported to have spread. However, because the beetle is well established there is a very significant risk of movement to other parts of the region. The California experience indicates that some species of *Quercus*, *Salix*, *Alnus*, and *Platanus* are highly susceptible (Fig. 26.6). Species in these plant genera are at high risk. Movement of the beetle

from currently infested areas with low host densities to areas with higher host densities could accelerate the spread of the insect throughout the Mediterranean Basin.

The beetle is also reported from South Africa, again from avocado. It is unclear how long the beetle has been in the southern part of the continent or whether it has moved from the areas dominated by summer rainfall the Mediterranean environments with winter precipitation. However, because the beetle is already present, the susceptible hosts in native and introduced host trees are at risk. There is the potential for both geographic spread and for the host range to expand as the beetles encounter new host species.

As noted previously, the polyphagous shot hole borer is well established in southern California. To date, the emphasis of research investigations has focused on the insect as a pest of commercial agriculture (avocados) or of landscape trees. However, there is also a critical need to understand the risk to native forest systems. The highly susceptible hosts that have been identified to date include very important constituents of the riparian forests and of native savannah or oak woodland ecosystems in California. Many of these are adjacent to urban developments that include susceptible urban forest tree species. The interface between the native and urban landscapes presents a very high risk for movement of the insects, something already observed in the southern California mountains. The valuable riparian forests in the

Fig. 26.6 Red willow (*Salix laevigata*) branch heavily infested by the polyphagous shot hole borer. The density of parental galleries structurally weakened the branch and contributed to structural failure in a wind storm

canyons have been colonized by the insect and trees at lower elevations adjacent to urban areas have been killed. It is not yet clear whether further spread will be restricted by low temperatures at higher elevations.

Because we do not know how the beetle/disease complex was introduced into any of the three currently infested areas, there is limited available analysis assessing risk for future introduction. If we knew how and from where, it would be possible to develop a monitoring strategy. However, we do know where it has currently been established and there is some information available regarding hosts at risk. Consequently, it now may be possible to evaluate risk of range expansion in invaded areas or risk of movement from invaded areas to new parts of the world.

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