INSECT PESTS OF COMMON *FICUS* SPECIES IN HAWAIʻI: HOSTS AND MANAGEMENT

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Abstract

A review on *Ficus* species, their importance as landscape trees, their major insect pests in Hawai‘i, a trunk injection system and its application in Hawaiian landscapes to protect trees was conducted. Ficus species are common landscape trees in Hawai‘i, among which Chinese banyan, *Ficus microcarpa,* and weeping banyan, *Ficus benjamina,* are most widely grown. To protect these trees from recent insect invaders, Chinese banyan stem gall wasp, *Josephiella microcarpae* Beardsley and Rasplus, leaf gall wasp, *Josephiella* sp., and lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan, we investigated the feasibility of a trunk injection system using systemic insecticides as a management option in the Hawaii urban landscape.

Key words: Chinese banyan, weeping banyan, trunk injection, systemic insecticides

Introduction

The genus *Ficus* (Moraceae) comprises about 1,000 species of trees, shrubs, vines, epiphytes and hemi-epiphytes of pantropical and subtropical origin (Wagner et al., 1999). *Ficus* species are of great ecological significance because of the large number of animals that feed on figs (Shanahan et al., 2001). A small number of reptiles and fish, and 1,274 bird and mammal species are known to eat figs (Shanahan et al., 2001). Sampling 15 different *Ficus* species from the rainforest and the coastal habitat of Papua New Guinea yielded 349 species of leaf chewing insects and 430 species of sap sucking insects (Basset and Novotny, 1999). Hence the *Ficus* species provide habitat for a large number of living organisms.

Ficus have unique symbiotic relationships with their pollinators. *Ficus* possess closed, urn-shaped inflorescences (called syconia) lined with tiny female flowers that are pollinated solely by tiny host plant specific fig wasps belonging to the family Agaonidae (Weiblen, 2002). Fig wasps are usually attracted to their specific host by developmental-stage specific volatiles released by the *Ficus* tree at the time of pollination, i.e. when it is ready for the pollinating agent to enter the fruit, oviposit and pollinate (van Noort et al., 1989; Grison-Pige et al., 2002). Each *Ficus* species is pollinated exclusively by one, or a small number of species of fig wasps (Weiblen, 2002; Zhang et al., 2014). The adult female fig wasp enters the fruit through a small hole called an ostiole, oviposits into the female flower, and completes its life cycle within the fruit. The female fig wasp also brings pollen from the natal fig in her pollen sac (Ramirez, 1970). Hence, the association of *Ficus* species with pollinating wasps is an obligate mutualism because neither partner can reproduce without the other (Weiblen, 2002; Cook et al., 2003).

In addition to their importance in natural systems, ficus trees are important landscape trees in Hawai‘i and other tropical and sub-tropical regions of the world. Chinese banyan, *Ficus microcarpa,* and weeping banyan, *Ficus benjamina* are very common landscape trees on the Hawaiian Islands.

Chinese banyan, Ficus microcarpa

The Chinese banyan, *Ficus microcarpa* L. (Rosales: Moraceae) is native from Ceylon to India, southern China, Ryukyu Islands, Australia, and New Caledonia (Wagner et al., 1999; Starr et al., 2003). *F. microcarpa* thrives in moist regions in its native range, where it is common up to 6,000 feet above mean sea level (Starr et al., 2003). Common names of *F. microcarpa* are Indian Laurel, Green Island, Green Gem, Green Spire, Green Emerald, Curtain fig, Green Mound, Tigerbark, Malayan Banyan, Tigerbark Fig etc. *F. microcarpa* is occasionally considered an invasive species in Hawai‘i, although it is grown as an ornamental landscape tree in public places, parks and natural areas, golf courses, roadsides, etc. *F. microcarpa* is considered a valuable landscape/shade tree species because of its height, attractive crown and leaves which drop gradually rather than synchronously, as in many other ficus trees (Ramirez and Montero, 1988). It was successfully introduced to Hawai‘i in 1921 (Candit, 1969; Ramirez and Montero, 1988).

Distribution and Habitat

Ficus microcarpa is widely distributed as an ornamental plant, and as a container tree, in the urban landscape setting of many tropical and subtropical regions throughout world. It has been introduced to the Hawaiian Islands- Oahu, Maui, Hawai‘i, Kauai, Molokai (Starr et al., 2003). It is now one of the common street trees on Hawaiian Islands. The University of Hawai‘i at Mānoa campus has a collection of more than 60 *F. microcarpa*. The *F. microcarpa* has the ability to disperse more often than some other *Ficus* species due to its small fruit size, which allows the fruit to be taken by a large number of dispersal agents. Its asynchronous fruiting cycle allows wasps to find fruits of different life stages, and it can be established with small founder populations, and a pollinating wasp find fruits throughout the year (Starr et al., 2003).

Ecology

Ficus microcarpa produces small fruits called syconia. The reproduction system of this species is unique. A host specific, symbiotic pollinating fig wasp, *Eupristina verticillata* Waterston (Hymenoptera: Chalcoidea: Agaonidae), effectuates pollination and reproduction of *F. microcarpa*. *Eupristina verticillata* was purposefully introduced to Hawai‘i in 1938 (Pemberton, 1939) to pollinate *F. microcarpa*. After the introduction of this pollinating wasp, *F. microcarpa* was able to propagate successfully and it has covered significant areas in Hawai‘i including forests, public and private areas. In Hawai‘i, *F. microcarpa* can be propagated readily from seeds (Starr et al., 2003). It can also be propagated from softwood cutting, hardwood cutting and air layering.

In addition to pollinating fig wasps, many non-pollinating fig wasps are also associated with these trees. Eight additional agaonid wasp species occurring in the fruit of *F. microcarpa* have been found in Hawai‘i, whereas at least 20 wasp species have already been reported in their native areas (Beardsley, 1998). These non-pollinating wasps may have negative effects on the reproductive success of both pollinating wasp and the host fig trees, and consequently on seed production (Cardona et al., 2013). A study in Tunisia showed a highly significant negative relationship between number of pollinating wasps and parasites in *Ficus microcarpa* (Kobbi et al., 1996). Hence, with increase in number of non-pollinating fig wasps, there could be competition between pollinating and non-pollinating fig wasps, resulting in poor reproductive success of pollinating wasp and ficus trees.

Weeping Banyan, Ficus benjamina

Weeping banyan, *Ficus benjamina* L. (Rosales: Moraceae), is an introduced species in Hawai'i. The native range of *F. benjamina* is considered to be India, southern China, Malaysia, Solomon Island and North Australia. Its common name includes Weeping fig, Benjamin's fig, Weeping banyan, Tropical-laurel, Java fig etc. It is pollinated by a host specific pollinating agaonid wasp, *Eupristina adempta* Wiebes (Hymenoptera: Chalcoidea: Agaonidae) (Ramirez and Montero, 1988).

F. benjamina is one of the large and attractive trees found in gardens, parks and other urban areas in Hawai‘i. The dense and round canopy, adroitly drooping branches; thick, shiny and evergreen leaves have made *F. benjamina* popular as a landscape tree. It is also grown as house plant and bonsai in tropical and sub-tropical climate. In particular, *F. benjamina* is one of the most severely infested plants by lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan, in Hawai’i. The lobate lac scale infestation has substantially reduced health and appearance of this tree due to sooty mold formation on young branches and leaves, and death of terminal branches.

Insect pests of ficus species

Ficus species are subject to attack by many insect pests. The common insect pests of ficus trees in Hawai'i are Chinese banyan leaf gall wasp, *Josephiella microcarpae*, Chinese banyan stem gall wasp, *Josephiella* spp., (Hymenoptera: Chalcidoidea: Agaonidae), lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan (Hemiptera: Coccoidea: Kerriidae), ficus whitefly, *Singhiella simplex* (Hemiptera: Aleyrodidae), cuban laurel thrips, *Gynaikothrips ficorum* Marchal (Insecta: Thysanoptera: Phlaeothripidae), and weeping fig thrips, *Gynaikothrips uzeli* Zimmerman (Insecta: Thysanoptera: Phlaeothripidae). The gall inducing wasps are host specific to *F. microcarpa,* whereas the lobate lac scale has a wide host range including native and endangered plant species of Hawai'i. The ficus whiteflies attack many species of *Ficus* but it is most commonly found infesting *F. benjamina* (Mannion et al., 2008; Avery et al., 2011). The cuban laurel thrips and weeping fig thrips usually attack *F. microcarpa* and *F. benjamina* respectively (Denmark et al., 2005). Although still can be found occasionally on ficus trees in Hawai'i, ficus whitefly and thrips are no longer considered major pests of ficus in Hawai'i. For example, the predator *Montandoniola moraguesi* Puton (Hemiptera: Anthocoridae) was introduced to Hawai'i in 1964, and it was successful to control cuban laurel thrips (Funasaki, 1966; Dobbs and Boyd, 2006; Held and Boyd, 2008).

Gall inducing wasps of Ficus microcarpa

Plant galls are masses of hypertrophied tissue, of very diverse form, produced by the plant in response to the presence of bacteria, fungi, mites, insects or other organisms (Davies, 1988). Gall forming insects are usually highly specific in their host plant, and the form of gall they produce. Plant galls may occur on any part of plants (leaves, stems, roots, flowers, and fruits) depending on the species of insect and plant involved. About 13,000 different species of insects are estimated to induce plant gall and numerous other species are yet to be discovered (Shorthouse et al., 2005).

A non-pollinating agaonid fig wasp, *Josephiella microcarpae* forms galls on the leaves of *F. microcarpa. J. microcarpae* was first found in Hawai'i in 1989, and described by John W. Beardsley and Jean-Yves Rasplus in 2001 (Beardsley and Rasplus, 2001). The adult leaf gall wasps are dark brown with pale yellow appendages and about 2.2 mm long. The male wasps are smaller in size (about 1.1 mm) than female wasps (Beardsley and Rasplus, 2001). The males also have shorter antennae than the females. The female wasp oviposits on the foliage. As the larva develops, the leaf tissue swells around each larva, and forms a gall. Larvae pupate inside the galled leaves both on the tree and on leaves that have fallen to the ground. When the adult wasp develops, it chews and makes a round hole on the lower portion of the leaf and exits.

Arborists collected an unidentified wasp from the galls on young stems of *F. microcarpa*, at the University of Hawaiʻi at Mānoa in July 2012. The wasp was found to cause leaf drop, dieback of young stems, and eventually death of the tree, if infestation is severe. The characteristics, life cycle, and mode of damages of the newly discovered stem gall wasp are similar to the *Josephiella*, but the species has not yet been fully described. Our laboratory and field observations suggested that the leaf gall wasps typically have a 3-4 month life cycle, whereas the stem gall wasps typically take 5-6 months to complete their life cycle. We studied the life span of stem and leaf gall wasps without food in lab conditions at 76ºF, immediately after collecting them from mature galls. On average, the stem gall wasps survived for 52 hours, leaf gall wasps survived for 79 hours, and maximum survival interval was 5 days and 21 hours for leaf gall wasps and 3 days and 8 hours for stem gall wasps. We conducted a cage study in the laboratory using Chinese banyan plants. The gall wasps were reared from infested samples from the field, and either leaf gall wasps or stem gall wasps or both were released in a cage with a plant. We observed that no leaf gall wasps attacked the stems and no stem gall wasps attacked on the leaves, indicating that the stem and leaf gall wasps are specific to stem and leaves of Chinese banyans respectively.

Lobate lac scale

The lobate lac scale, *Paratachardina pseudolobata* Kundo & Gullan (Kerriidae; Coccoidea; Hemiptera) is likely to be native to tropical Asia, although the exact native range is still unclear. It was first discovered in the United States in 1999 in southern Florida (Hamon, 2001). The lobate lac scale was first found on *Ficus benjamina* on Oahu, Hawai‘i in October, 2012. It has now become a severe pest infesting native and non-native plant species on urban landscapes of Oahu, Hawai‘i. It has not been officially reported on any other Hawaiian islands other than Oahu to date. However, given the frequency of interisland, Hawai’i-U.S. mainland, and international travel and movement of goods, and high scale population near Honolulu International Airport, lobate lac scale is likely to spread, and eventually disperse to neighboring islands in Hawai‘i, tropical and subtropical regions in the United States and throughout the Pacific region.

Lobate lac scale was initially mistakenly identified as *Paratachardina lobata* Chamberlin in the previous literatures. It was corrected as *Paratachardina pseudolobata* after the taxonomic revision of the genus *Paratachardina* (Kondo and Gullan, 2007).

The mature female lobate lac scales are about 2 mm long and 2 mm wide, with an x-shaped appearance and a deep maroon color. They have a hard, resinous protective armor covering their soft body underneath. The first instar measures approximately 0.4 mm in length and has a deep red color. The second instar molts to the adult. Development from instar to adult requires 15-19 weeks. The first instar lasts 8-11 weeks and the second instar lasts 7-8 weeks (Howard et al., 2010). The juveniles exit from the mother's shellac through the dorsal openings (Howard et al., 2010). The adults are wingless, immobile and attach tightly to twigs. This insect disperses at its crawler stage (either first or second instar) via air currents, birds, and other animals. Humans can unknowingly spread them by moving infested plants. Males have not been observed and thus lobate lac scale is considered parthenogenetic as are many other scale insects (Kundo and Gullen, 2007; Howards et al., 2010). The lobate lac scale infests the woody tissues of small, young twigs and branches of around pencil-size thickness and less frequently the older branches. Major effects on hosts include the formation of sooty molds (with unhealthy appearance), the dieback of twigs and branches, the thinning of foliage, and eventually the death of entire plants of some species. Lobate lac scales have not been found infesting leaves, petioles, flowers and the roots of plants.

Urban landscape pest management approach

Trees are an important component of urban landscapes because they provide shade and beauty around homes, schools, markets, streets, city parks and other natural areas. Landscape trees have psychological, aesthetic, social, historic, monetary and environmental values. Trees help the environment by providing oxygen, enhancing air quality, conserving water, soil and wildlife. With rapidly increasing urban populations, there is an increasing need for effective establishment and management of landscape trees in urban environments worldwide.

The Hawaiian Islands are well known for the beautiful tropical landscapes and trees are a major feature in many urban areas. There is a diversity of tree species in Hawaiian urban areas, sources from all over the world. There is a growing concern about invasive insect pests and their negative impact to the endemic plant species and the urban landscape of Hawaiʻi. In recent years, ficus trees in the urban areas have been under threat from new invasive insect pests, and thus require effective management. However, no effective non-chemical strategy has been developed to manage gall wasps and lobate lac scale on ficus trees. The integrated pest management (IPM) approach for urban landscape can be achieved by a combination of strategies. Regular scouting and monitoring can be taken to prevent significant problems. Insecticide application can be an option to manage invasive insect pests. Insecticides can be applied to trees in various ways such as spraying, soil drenching, and trunk injection. Out of these methods, trunk injection is usually considered one of the safer and more efficient ways to apply insecticides (Doccola and Wild, 2012). In addition, biological control could be explored for long term management.

Trunk Injection

Trunk injection is a way to deliver chemicals into trees for effectively managing the problems of insect, disease and nutrient deficiency. The sapwood, the outer region of the xylem in the tree, conducts water and minerals from the root system to the canopy. The chemical is injected into the sapwood so that it will move up through the rays (tree bundles of tubes). Systemic insecticides have been injected through trunk in a wide range of trees for the control of many insect pests. This approach was first used to control elm bark beetle (Norris, 1967). Trunk injection method usually requires relatively less chemical compared to conventional methods such as foliar spray, soil drenching, etc. Also there was a greater precision in chemical uptake when applied through trunk injection compared to soil application (Johnson and Rediske, 1965; Doccola and Wild, 2012). To apply tree injections effectively, one needs to thoroughly understand the methods of application, the chemistry of the insecticides, and tree health conditions (Doccola and Wild, 2012).

Trunk injection also limits environmental exposure of chemicals. It is simple, quick, and injected chemicals take relatively short time to reach all parts of treated trees, depending on the type of chemical and the tree species. A special injection tool is often used to deliver and seal the chemical directly into the trunk, where it is quickly taken up by the vascular system (xylem) and distributed throughout the tree.

Chemical spray on tree canopy may have limited coverage, and might cause pesticide drift problems. Unlike canopy sprays, trunk injection methods distribute the applied chemical throughout the tree, and limit exposure of chemicals in the environment. In addition, the trunk injection method reduces cost of pesticides, health concerns and potential environmental impacts (Norris, 1965; Docolla and Wild, 2012). In addition, it is considered to pose less negative impact on vertebrates, beneficial insects like predators and parasitoids, and other non-target organisms than other methods of application.

Imidacloprid and emamectin benzoate

Imidacloprid (1-[(6-chloro-3-pyridinyl) methyl]-N-nitro-2-imidazolidinimine) and emamectin benzoate are two systemic insecticides known to have some effective activity against gall-forming insects (Doccola et al., 2009). Imidacloprid is a systemic insecticide belonging to the neonicotinoid class. It moves rapidly through plant tissue after application, targets the nervous system of the target insects and disturbs nerve impulse transmission resulting in death of insects (Fossen, 2006).

Emamectin benzoate is a systemic insecticide derived from abamectin, a natural fermentation product of bacterium, *Streptomyces avermitilis*. It binds to neuron cells, disrupts nerve impulses, and causes a cessation of cell function and ultimately paralysis, and death of insect (USEPA, 2009). The primary route of toxicity for both of the insecticides (imidacloprid and emamectin benzoate) is through ingestion.

In previous studies, imidacloprid and emamectin benzoate have shown different effectiveness and longevity in different insect-plant systems. Trunk injected emamectin benzoate provided excellent activity against some insect pests. A study to evaluate the efficacy of systemic insecticides for preventing southern pine engraver beetle, *Ips* spp. (Coleoptera: Curculionidae), and wood borers (some species belong to genera *Monochamus, Acanthocinus* and *Stenocorus*) on loblolly pine found emamectin benzoate effective with significantly reduced colonization of insects (Grosman and Upton, 2006). Trunk injection of emamectin benzoate was effective in managing eastern tent caterpillars, *Malacosoma americanum* Fabricius (Lepidoptera: Lasiocampidae) in wild cherry trees (Potter et al., 2005). A single trunk injection with emamectin benzoate gave up to 100% control of emerald ash borer larvae, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), for 2-3 years in ash trees, *Fraxinus pennsylvanica* (Smitley et al., 2010; McCullough et al., 2011). In addition, emamectin benzoate is a strong candidate as a nematicide; it showed more activity than traditional trunk injecting compounds to control pine wilt disease, caused by pine wood nematode, *bursaphelenchus xylophilus* (Takai et al., 2000). The residual concentration of emamectin benzoate was sufficient to inhibit nematode in the shoots of Japanese black and red pine trees (*Pinus thunbergii* and *Pinus densiflora* respectively) for 3 years (Takai et al., 2004).

Imidacloprid has been used in trunk injection system to manage various insect pests. A study was conducted on *F. microcarpa* in Florida to observe the effectiveness of root drenching of imidacloprid, Organocide (containing fish and sesame seed oils and lecithin) and malathion combined with horticultural oil. The result showed imidacloprid was very effective with almost complete elimination of lobate lac scales within 103 days after treatment (Howard and Steinberg, 2005). A study by Doccola et al. (2009) to investigate effectiveness of trunk injected emamectin benzoate and imidacloprid against erythrina gall wasps, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae), on Wiliwili trees, *Erythrina sandwicensis* (Fabales: Fabaceae), found emamectin benzoate somewhat effective, whereas the imidacloprid was highly effective. Research on trunk injection of imidacloprid was conducted on Eastern hemlocks, *Tsuga canadensis* Carriere (Pinales: Pinaceae) to determine its effectiveness on hemlock woolly adelgid, *Adelges tsugae* Annand (Hemiptera: Adelgidae), and reduced *A. tsugae* populations for 3-4 years, with new shoot growth and better tree health (Eisenback et al., 2014). Mota-Sanchez et al. (2009) studied trunk injected radiolabelled ^{14}C- imidacloprid movement in North American ash trees, *Fraxinus* spp., and they found that imidacloprid moved slowly and steadily through the tree over time and accumulated in the leaves. Tanis et al. (2007) found higher concentration of imidacloprid on leaves and relatively low concentration in other plant organs such as the flower and fruit. Trunk injection with neonicotinoids, organophosphate and avermectin to control avocado thrips in California avocado groves showed imidacloprid to be the more suitable control option than other two chemical classes. In addition, imidacloprid had high chemical residue level in leaves; and in fruits, chemical residue level was below the detection limit (Byrne et al., 2014).

Although imidacloprid and emamectin benzoate are commonly used trunk-injectable systemic insecticides in trunk injection, their dose and effectiveness varies among different insect pests. Trunk injected imidacloprid has provided effective treatment against adelgids, aphids, leaf beetles, emerald ash borer, asian longhorned beetle, bronze birch borer, lacebugs, leafhoppers, leaf miners, mealybugs, psyllids, scale insects and whiteflies. Similarly, the trunk injected emamectin benzoate can provide effective treatment for pine coneworm, pine cone seed bug, tent caterpillar, gypsy moth, mimosa webworm, pine needle scale, red palm mite, sawfly, emerald ash borer, round headed borer, ips engraver beetles, mountain pine beetle, southern pine beetle, pinewood nematode etc. (Anonymous, 2015).

Phosphorous acid

Phosphorous acid is primarily used as a fungicide for the control of oomycetes. It is also considered to have some positive effects on plant physiology by stimulating the natural plant defense system and overall health in bringing the pest invasion under control (Smillie et al., 1989). Plant defense system constitutes various morphological, biochemical and molecular mechanisms to counter the effects of herbivore attack (War et al., 2012).

Pesticide distribution and residue activities

Based on previous studies, it has been shown that systemic insecticides take a few hours to weeks to distribute throughout the tree foliage and terminal shoots depending on chemicals and plants (Doccola and Wild, 2012). Injecting at the circumference of basal trunk with chemical pesticide yields most uniform distribution throughout the tree (Coppel and Norris, 1966; De Pietri-Tonelli et al., 1961). A recent study on injury caused by drilling holes found little evidence of significant damage, and healthy wood grew over the injected spots, and there was no any sign of pathogen infection, decay or other serious injury (Hahn et al., 2011). The optimum number of injection ports could help uniform distribution of injected chemicals (Acimovic, 2014).

The insecticides applied through trunk injection provide higher residual activity as compared to other methods such as spraying and drenching. Spraying and drenching methods are contingent on drifting, leaching, photolysis or microbial degradation. Studies have found pesticide residues persisted on the plant tissues up to few years depending on nature of chemical pesticides, and shown a long term activities against insect pests (Takai et al., 2004; Doccola et al., 2009; Smitley et al., 2010; Eisenback et al., 2014).

Conclusions

Ficus trees are important landscape trees in Hawaiʻi and other tropical and subtropical regions of the world. Recent attacks by emerging insect pests, Chinese banyan stem gall wasp, *Josephiella microcarpae*, leaf gall wasp, *Josephiella spp*. and lobate lac scale, *Paratachardina pseudolobata*, have resulted in poor tree health, unsightly form, and eventual fatalities amongst ficus trees. Injecting insecticides into these trees through trunk is a relatively new, convenient, environmentally conscious technology which has shown promising results in many studies.

Imidacloprid and emamectin benzoate are very commonly used systemic insecticides in the trunk injection system. Previous studies show that, imidacloprid and emamectin benzoate varies in their effectiveness and longevity of effectiveness in different insect-plant systems. Research efforts are needed to study the efficacy and longevity of efficacy of trunk injection systems with different insecticides on ficus trees in order to identify effective control strategies to mitigate damage of the recent insect invaders. Survey on host plant species of lobate lac scale in Hawai‘i is necessary to document the vulnerable plant species.

References

Acimovic S. G. (2014) Disease management in apples using trunk injection delivery of plant protective compounds (Doctoral dissertation, Michigan State University.

Anonymous. (2015) Arborjet online product catalog, Arborjet formulations: Tree-age and Ima-jet. http://www.arborjet.com/products/formulations (Accessed on October 22, 2015).

Avery P. B., Mannion C. M., Powell C. A., McKenzie C. L. and Osborne L. S. (2011) Natural enemies managing the invasion of the fig whitefly, Singhiella simplex (Hemiptera: Aleyrodidae), infesting a Ficus benjamina hedge. *Florida Entomologist*, *94*(3), 696-698.

Basset Y. and Novotny V. (1999) Species richness of insect herbivore communities on Ficus in Papua New Guinea. *Biological Journal of the Linnean Society*, 67(4), 477–499.

Beardsley W. J. (1998) Chalcid Wasps (Hymenoptera: chalcidoidea) Associated with Fruit of Ficus microcarpa in Hawai'i. *Proceedings of Hawaiian Entomological Society,* 33:19-34

Beardsley J. W. and Rasplus J.-Y. (2001) A new species of Josephiella (Hymenoptera: Agaonidae) forming leaf galls on *Ficus microcarpa* L. (Moraceae). *Journal of Natural History*, 35(1), 33–40.

Byrne F. J., Krieger R. I., Doccola J. and Morse, J. G. (2014) Seasonal timing of neonicotinoid and organophosphate trunk injections to optimize the management of avocado thrips in California avocado groves. *Crop Protection*, *57*, 20-26.

Cardona W., Kattan G. and de Ulloa P. C. (2013) Non-pollinating Fig Wasps Decrease Pollinator and Seed Production in *Ficus andicola* (Moraceae).*Biotropica*, *45*(2), 203–208.

Condit I. J. (1969) Ficus: the exotic species. University of California, Division of Agricultural Sciences, Berkeley, 363 pp

Cook J. M. and Rasplus J. Y. (2003) Mutualists with attitude. Coevolving fig wasps and figs. *Trends in Ecology and Evolution*, 18, 241–248.

Coppel H. C. and Norris D. M. (1966) Bark Penetration and Uptake of Systemic Insecticides from Several Treatment Formulations in White Pines. *Journal of Economic Entomology*, 59(4), 928–931.

Davies R. G. (1988) Outlines of Entomology (seventh edition), Chapman and Hall Publication.

Denmark H., Thomas R. and Funderburk E. (2005) Cuban Laurel Thrips, Gynaikothrips ficorum (Marchal)(Insecta: Thysanoptera: Phlaeothripidae). DPI Entomology Circular, 59.

De Pietri-Tonelli P., Barontini A. and Biondi G. (1961) Systemic migration and insecticidal activity of Dimethoate applied on tree trunks., 407–32 pp.

Dobbs T. T. and Boyd Jr D. W. (2006) Status and distribution of *Montandoniola moraguesi* (Hemiptera: Anthocoridae) in the continental United States. *Florida entomologist*, 89(1), 41-46.

Doccola J. J., Smith S. L., Strom B. L., Medeiros A. C., and von Allmen E. (2009) Systemically applied insecticides for treatment of erythrina gall wasp, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae). *Arboriculture & Urban Forestry*, *35*(4), 173-181.

Doccola J. J. and Wild P. M. (2012) Tree injection as an alternative method of insecticide application. Insecticides–Basic and Other Applications, ed. by Soloneski S and Larramendy M. InTech, Rijeka, Croatia, 61-78.

Eisenback B. M., Salom S. M., Kok, L. T. and Lagalante A. F. (2014) Impacts of trunk and soil injections of low rates of imidacloprid on hemlock woolly adelgid (Hemiptera: Adelgidae) and eastern hemlock (Pinales: Pinaceae) health. *Journal of economic entomology*, 107(1), 250-258.

Emamectin benzoate- United States Environmental Protection Agency (EPA) (2009) http://www.epa.gov/opp00001/chem_search/cleared_reviews/csr_PC-122806_13-Jan-09_a.pdf (Accessed on July 28, 2015).

Fossen M. (2006) Environmental fate of imidacloprid. California Department of Pesticide Regulation, 1-16.

Funasaki G. Y. (1966) Studies on the life cycle and propagation technique of *Montandoniola moraguesi* (Puton)(Heteroptera: Anthocoridae). *Proceedings of Hawaiian Entomological Society*, 19, 209–211.

Grison-Pige L., Bessiere J. M. and Hossaert-McKey M. (2002) Specific attraction of fig-pollinating wasps: role of volatile compounds released by tropical figs. *Journal of chemical ecology*, 28(2), 283-295.

Grosman D. M. and Upton W. W. (2006) Efficacy of systemic insecticides for protection of loblolly pine against southern pine engraver beetles (Coleoptera: Curculionidae: Scolytinae) and wood borers (Coleoptera: Cerambycidae). *Journal of economic entomology*, 99(1), 94-101.

Hahn J., Herms D. A. and McCullough D. G. (2011) Frequently Asked Questions Regarding Potential Side Effects of Systemic Insecticides Used To Control Emerald Ash Borer. University of Minnesota, Michigan State University, and The Ohio State University Extension Emerald Ash Borer Fact Sheet.

Hamon A. (2001) Pest alert: Lobate lac scale, *Paratachardina pseudolobata* (Chamberlin) (Hemiptera: Kerriidae). Florida Department of Agriculture and Consumer Services, Division of Plant Industry. http://www.freshfromflorida.com/Divisions-Offices/Plant-Industry/Plant-Industry-Publications/Pest-Alerts/Pest-Alerts-Lobate-Lac-Scale-Paratachardina-Pseudolobata (Last accessed September 25, 2015).

Held D. W. and Boyd Jr D. W. (2008) New records of *Gynaikothrips uzeli* (Zimmerman)(Thysanoptera: Phlaeothripidae) on *Ficus benjamina* in Texas and O'ahu, Hawai‘i, USA. *The Pan-Pacific Entomologist*, 84(2), 77-80.

Howard F. W., Pemberton R. W., Shroer S. and Hodges G. (2010) *Paratachardina pseudolobata* (Coccoidea: Kerriidae): Bionomics in Florida. *Florida entomologist*, 93, 1-7.

Howard F. W. and Steinberg B. (2005) Root drenches and topical insecticide treatments for control of the lobate lac scale, *Paratachardina lobata* (Chamberlin). *Proceedings of Florida State Horticultural Society*, 118, 314-318.

Johnson N. E. and Rediske J. H. (1965) Systemic pesticides in woody plants: translocation. *Bulletin of the Entomological Society of America*, *11*(3), 190-195.

Kobbi M., Edelin C., Michaloud G. and Chaieb M. (1996) Relationship between a mutualist and a parasite of the laurel fig, Ficus microcarpa L. *Canadian Journal of Zoology*, 74(10), 1831–1833.

Kondo T. and Gullan P. J. (2007) Taxonomic review of the lac insect genus *Paratachardina* Balachowsky (Hemiptera: Coccoidea: Kerriidae), with a revised key to genera of Kerriidae and description of two new species. *Zootaxa*, 1617, 1-41.

Mannion C., Osborne L., Hunsberger A., Mayer H. and Hodges G. (2008) Ficus whitefly: A new pest in South Florida. University of Florida, IFAS Extension Bulletin, August 2008.

McCullough D. G., Poland T. M., Anulewicz A. C., Lewis P. and Cappaert D. (2011) Evaluation of *Agrilus planipennis* (Coleoptera: Buprestidae) control provided by emamectin benzoate and two neonicotinoid insecticides, one and two seasons after treatment. *Journal of economic entomology*, 104(5), 1599-1612.

Mota-Sanchez D., Cregg B. M., McCullough D. G., Poland T. M. and Hollingworth R. M. (2009) Distribution of trunk-injected 14 C-imidacloprid in ash trees and effects on emerald ash borer (Coleoptera: Buprestidae) adults. *Crop protection*, *28*(8), 655-661.

Norris D. M. (1965) Systemic pesticides in woody plants: Uptake. *Bulletin of the Entomological Society of America*, 11(3), 187-190.

Norris D. M. (1967) Systemic insecticides in trees. *Annual review of entomology*, *12*(1), 127-148.

Pemberton C. E. (1939) Note on introduction and liberation of *Eupristina verticillata* Waterston in Honolulu. *Proceedings of the Hawaiian Entomological Society*, 10, 182.

Potter D. A., Foss L., Baumler R. E. and Held D. W. (2005) Managing eastern tent caterpillars Malacosoma americanum (F) on horse farms to reduce risk of mare reproductive loss syndrome. *Pest management science*, 61(1), 3-15.

Ramirez B. W. (1970) Host specificity of fig wasps (Agaonidae). *Evolution*, 680-691.

Ramirez B. W. and Montero S. J. (1988) *Ficus microcarpa* L., *F. benjamina* L. and other species introduced in the New World, their pollinators (Agaonidae) and other fig wasps. *International Journal of Tropical Biology and Conservation*, 36(2B), 441-446.

Shanahan M., So S., Gompton S. G. and Gorlett R. (2001) Fig-eating by vertebrate frugivores: a global review. *Biological Reviews*, 76(4), 529–572.

Shorthouse J. D., Wool D. and Raman A. (2005) Gall-inducing insects – Nature's most sophisticated herbivores. *Basic and Applied Ecology*, *6*(5), 407–411.

Smillie R., Grant B. R. and Guest D. (1989) The mode of action of phosphite: evidence for both direct and indirect modes of action on three *Phytophthora spp.* in plants. *Phytopathology*, 79(9), 921-926.

Smitley D. R., Doccola J. J. and Cox D. L. (2010) Multiple-year protection of ash trees from emerald ash borer with a single trunk injection of emamectin benzoate, and single-year protection with an imidacloprid basal drench. *Journal of Arboriculture*, 36(5), 206.

Starr F., Starr K. and Loope L. (2003) Ficus microcarpa. Chinese Banyan, Moraceae. http://www.hear.org/starr/hiplants/reports/pdf/ficus_microcarpa.pdf. (Accessed on July 28, 2015).

Takai K., Soejima T., Suzuki T. and Kawazu, K. (2000) Emamectin benzoate as a candidate for a trunk-injection agent against the pine wood nematode, *Bursaphelenchus xylophilus*. *Pest Management Science*, *56*(10), 937-941.

Takai K., Suzuki T. and Kawazu K. (2004) Distribution and persistence of emamectin benzoate at efficacious concentrations in pine tissues after injection of a liquid formulation. *Pest management science*, 60(1), 42-48.

Tanis S. R., Cregg B. M., Mota-Sanchez D., McCullough D. G., Poland T. M. and Hollingworth R. M. (2007) Distribution of trunk-injected 14C imidacloprid in Fraxinus trees: a test of the sectored-flow hypothesis. *Proceedings of the Emerald Ash Borer and Asian*

Longhorned Beetle Research and Technology Development Meeting, Cincinnati, Ohio Vol. 29, pp. 34-36.

van Noort S., Ware A. B. and Compton S. G. (1989) Pollinator-specific volatile attractants released from the figs of ficus burtt-davyi. *South African Journal of Science*, 85(5), 323-324.

Wagner W. L., Herbst D. R. and Sohmer S. H. (1999) Manual of the Flowering Plants of Hawai'i, Vols. 2 . University of Hawai'i and Bishop Museum Press.

War A. R., Paulraj M. G., Ahmad T., Buhroo A. A., Hussain B., Ignacimuthu S., and Sharma H. C. (2012) Mechanisms of plant defense against insect herbivores. *Plant signaling & behavior*, 7(10), 1306-1320.

Weiblen G. D. (2002) How to be a fig wasp. *Annual review of entomology*, 47(1), 299-330.

Zhang Y., Peng Y-Q., Compton S. G. and Yang, D-R. (2014) Premature Attraction of Pollinators to Inaccessible Figs of *Ficus altissima*: A Search for Ecological and Evolutionary Consequences. *PLoS ONE*, 9(1), e86735.

CHAPTER 2. Management of stem and leaf gall wasps, *Josephiella* spp., on Chinese banyan, *Ficus microcarpa*, in Hawai‘i

Abstract

Chinese banyan, *Ficus microcarpa,* is a popular landscape tree in many tropical regions of the world. Currently in Hawai‘i, these trees are severely infested by two host-specific insect pest species in the family Agaonidae (Hymenoptera: Chalcidoidea): the Chinese banyan leaf gall wasp, *Josephiella microcarpae*, and the stem gall wasp, *Josephiella* spp. (species currently being described). Infestations by these insects result in gall formation on young leaves and shoots, premature leaf drop, new shoot death, poor tree health and eventually death of the tree if infestation is severe. We evaluated the efficacy and longevity of the efficacy of two low-risk systemic insecticides, imidacloprid and emamectin benzoate, with or without phosphorous acid amendment, delivered through trunk injection to control these two wasp species using 45 Chinese banyans in Honolulu, Hawai‘i. Although both systemic insecticides had some effect against leaf gall wasp for up to 18 months post treatment, only emamectin benzoate had effect against stem gall wasp for up to 14 months post treatment. Phosphorous acid amendment did not provide any benefits for Chinese banyans to mitigate wasp infestations. In conclusion, trunk injection of emamectin benzoate could be a feasible management strategy to control stem and leaf gall wasps on Chinese banyans in Hawai‘i.

Key words*:* Chinese banyan; agaonid wasps; imidacloprid; emamectin benzoate; trunk injection

Introduction

Chinese banyan, *Ficus microcarpa* L. (Rosales: Moraceae), is native to diverse geographical locations ranging from Ceylon to India, southern China, Ryukyu Islands, Australia, and New Caledonia (Wagner et al., 1999; Starr et al., 2003). It is very widespread and commonly found in landscapes and as a container tree in many tropical and subtropical regions of the world. It has some other common names, such as Cuban laurel, Indian laurel, Green Island, Green gem, Green spire, Green emerald, Green mound, Malayan banyan, Ficus long island, Tigerbark fig, and Kin men fig. It is a popular landscape tree on islands of Hawaiʻi. It was introduced to Hawaiʻi in 1921 (Ramirez et al., 1988). Chinese banyan is easily dispersed due to its small fruit size, which allows the fruit to be taken by a large number of dispersal agents. It is pollinated by *Eupristina verticillata* Waterston (Hymenoptera: Agaonidae), which was purposefully introduced to Hawaiʻi in 1938 (Pemberton, 1939). Its fruiting cycle allows wasps to find fruits of different life stages, hence it can be established with small population size and allows pollinating wasp to find fruits throughout the year (Starr et al., 2003).

The non-pollinating agaonid fig wasp, *Josephiella microcarpae* Beardsley and Rasplus (Hymenoptera: Agaonidae), which forms galls on the leaves of *Ficus microcarpa,* was first found in Hawaiʻi in 1989 (Starr et al., 2003), and the species was described in 2001 (Beardsley and Rasplus, 2001). This wasp was also discovered in September, 1997 in California (Anonymous, 1998), and in Florida in early 2007 (Caldwell, 2008). It remains as a pest problem in certain areas of Florida (Caldwell, 2008). The adult leaf gall wasps are dark brown with pale yellow appendages, and about 2.2 mm long (female). The adult female wasp exhibits a preference for depositing eggs in very young terminal leaves, but not mature leaves. It stings on the foliage and inserts multiple eggs. As the larva develops, the leaf tissue swells around each larva, and forms the gall. Larvae pupate inside galled leaves both on tree and on ground. When the adult wasp emerges, it chews and makes round hole on lower portion of leaf and exits out. The male wasps are similar to female wasps except that they are smaller in size (about 1.1 mm), and female has longer antennae (8 segments) than that of male (7 segments) (Beardsley and Rasplus, 2001).

In July 2012, another non-native agaonid wasp was discovered in Honolulu (HDOA, 2012). This pest wasp causes gall formation on young branches, resulting in defoliation and ultimately death of young shoots. The characteristics and mode of damage of the newly discovered stem gall wasp are similar to the leaf gall wasp; however, stem gall wasps forming galls on the young twigs are more damaging to tree health than leaf gall wasps. The stem gall wasp is an undescribed species and has been discovered only in Hawaiʻi to date. Our laboratory and field observations suggest that the leaf gall wasps typically take 3-4 months whereas the stem gall wasps typically take 5-6 months to complete life cycle. We also studied the life span of stem and leaf gall wasps without food in lab condition at 76ºF, immediately after collecting them from mature galls. On average, the stem gall wasps survived for 52 hours, leaf gall wasps survived for 79 hours, and maximum survival interval was 5 days and 21 hours for leaf gall wasps and 3 days and 8 hours for stem gall wasps. We conducted a cage study in the laboratory using Chinese banyan plants. The gall wasps were reared from the infested samples from field, and either leaf gall wasps or stem gall wasps or both were released in a cage. We observed that no leaf gall wasps attacked the stems and no stem gall wasps attacked the leaves, indicating that the stem and leaf gall wasps are specific to stems and leaves of Chinese banyans respectively. We have not observed any predation or parasitism on this wasp species to date. Systemic insecticide treatments could be a viable management tactic at this stage.

Imidacloprid and emamectin benzoate are two low-risk systemic insecticides known to have some effect against gall-forming insects (Doccola et al., 2009). Imidacloprid, a neonicotinoid, moves through plant tissues after application and targets the nervous system and disturbs nerve impulse transmission resulting in death of insects (Fossen, 2006). Emamectin benzoate, also a systemic insecticide, is derived from abamectin, a natural fermentation product of a soil bacterium, *Streptomyces avermitilis*. Its mode of action includes binding of insect neuron cells, cessation of cell function, and ultimately disruption of nerve impulses resulting in paralysis and death of the insect (USEPA, 2009). The primary route of toxicity for both insecticides is through ingestion. Since Chinese banyan depends only on its specific pollinator, *Eupristina verticillata*, possible negative impacts of imidacloprid and emamectin benzoate usage in this plant-pest system on common pollinators, such as honeybees, is extremely low. Phosphorous acid, although mainly used as fungicide, is considered to have some positive effect by stimulating the plants natural defense system and overall health (Smillie et al., 1989).

Trunk injection is a way to treat trees to combat problems related to insects, diseases and nutrient deficiencies. This method typically requires less active ingredients compared to conventional methods such as foliar spray, and soil drenching (Norris, 1965; Doccola and Wild, 2012). Trunk injection system is relatively simple, quick, and chemicals take a few hours to weeks to reach all parts of trees, depending on the specific insecticides and tree characteristics (Doccola et al., 2009). The difference in flow rate among chemicals could be due to the dilution of chemical formulation, tree canopy, size and health (McWain and Gregory, 1973; Doccola et al., 2009). Unlike conventional methods, trunk injection system directly injects chemicals into the vascular system of the tree, without exposing the environment to the chemicals.

The overall objective of this study was to find out the efficacy and longevity of efficacy of two systemic insecticides, imidacloprid and emamectin benzoate, with or without phosphorous acid amendment, delivered through trunk injection to control stem and leaf gall wasps. We hypothesized that 1) either or both imidacloprid and emamectin benzoate would be effective against stem and leaf gall wasps; 2) effectiveness could last for two years; and 3) phosphorous acid amendment would help suppressing gall wasps by enhancing plant's natural defense systems and overall health.

Materials and Methods

Experimental design

The research was conducted on the campus of University of Hawai‘i at Mānoa (21.2970° N, 157.8170° W) in Honolulu, Hawai‘i, USA. Forty-five Chinese banyan trees, *Ficus microcarpa*, of similar overall conditions (wasp infestation, canopy health, etc.) were included in this research. Trees included were considered to be at similar age on the basis of their size (diameter at breast height, DBH), although their exact ages were unclear. These trees were all infested with both stem and leaf gall wasps at a relatively uniform level of infestation. The average DBH of trees was 47.5 inches. Additional details are provided in Table 2.1.

Four treatments were applied (imidacloprid, emamectin benzoate, imidacloprid + phosphorous acid, emamectin benzoate + phosphorous acid) and a control. Details of treatments are provided in Table 1. There were nine trees per treatment and control. Arborjet QUIK-jet micro infusion system and pressurized Tree IV system (Arborjet, Inc. Woburn, MA, USA) were used for injections in July 2013. Treatments were allocated randomly to different trees under study.

Data collection

Sampling was initiated three months after injection, assuming the time required for chemical distribution throughout trees, and the approximate time required completing the life cycles by both stem and leaf gall wasp species, as treatments were intended to reduce gall formation on new leaves and shoots, rather than acting as a curative treatment for previously infested plant material.

Three new terminal shoots, each approximately 45 cm in length, were collected randomly on each month until one year and every other month thereafter, from the tree canopy using a tree pruner. Tree pruner could be extended up to 30 feet height. Shoots were collected from three different sub-trunks of the tree when several sub-trunks existed on one tree, to make the samples more representative for trees of varied size. Old exit holes of gall wasps were not considered as current infestation, as the wasp had already completed the life cycle and exited from those hole. Samples from each tree were collected monthly from three to 12 months post-treatment (October 2013 to July 2014), and then bi-monthly from 14 to 22 months post-treatment (December 2014 to May 2015). Seasonal variation in infestations of both leaf and stem gall wasps was minimum as the wasps were consistently active throughout the year (Fig. 2.2 and Fig. 2.4). One of the reasons could be due to the relatively consistent temperature in Honolulu, Hawai‘i.

Four parameters were measured from each samples: number of stem galls per 45 cm length, average stem infestation level (1-5, 1 being no infestation and 5 being severely infested (the shoot fully covered with stem galls), percentage of infested leaves and average leaf infestation level (1-5, 1 being no infestation and 5 being severely infested (multiple galls on each leaves and most of the leaves infested on shoot). In the 14th and 22nd months after treatment, visual ratings on new shoot emergence and overall tree health were evaluated. The ratings were defined as below. For tree condition, 1=excellent, 2=good, 3=fair, 4=poor, 5=dead. For new shoot emergence, 1=many, 2=moderate, 3=some, 4=little, 5=very little. Excellent tree health condition means the tree is in good shape with a lot of new shoot growth and no dead shoots/branches.

Statistical analysis

Statistical analysis was conducted using MINITAB (Version 15, Minitab, Inc. State College, PA, US), and differences were considered significant at $P < 0.05$. For number of stem galls and percentage of infested leaves, one-way analysis of variance (ANOVA) was performed, with treatment and time as the main factors. Tukey's tests were conducted for pairwise comparison. For all other variables measured, non-parametric Kruskal-Wallis tests were conducted for treatment effect at each sampling time and pairwise comparison was conducted using Dunn’s method.

Results

Phosphorous acid was expected to have some effect against gall wasps through enhanced tree health and immunity system in combination with systemic insecticides. However, the data did not show any benefit of phosphorous acid amendment to trees against wasps (Table 2.1). Therefore, we combined treatments with and without phosphorous acid and analyzed the data considering only two treatments (imidacloprid, and emamectin benzoate) and untreated control. The interaction of treatment and month after treatment was not significantly different in terms of number of stem galls (ANOVA, F = 1.47, df = 2, $P = 0.055$) and percentage of infested leaves

(ANOVA, F = 1.4, df = 2, $P = 0.08$). Therefore, for these two parameters, main treatment effect was presented (Figure 2.1 and Figure 2.3).

Emamectin benzoate was significantly more effective than imidacloprid and the control (Figure 2.1). Starting from the fourth month after treatment, we observed significantly lower new stem gall infestation levels in trees treated with emamectin benzoate compared to trees treated with imidacloprid and untreated control. The trend was consistent for up to 14 months after treatment (Figure 2.2). We observed up to 46% reduction in number of new stem gall infestation in trees treated with emamectin benzoate compared to untreated controls. Results did not show significant difference for stem infestation levels between treatments from 14 months post-treatment.

Overall, emamectin benzoate produced significantly greater reduction in percent of infested leaves than imidacloprid and untreated controls (Figure 2.3). Both insecticides were observed to be effective against leaf gall wasps with significant reduction in gall formation on leaves of new shoots. With the emamectin benzoate treatment, significant effects were observed starting from the fourth month after treatment and this pattern persisted for up to 18 months after treatment (Figures 2.4). The reduction in average percentage of infested leaves on trees treated with emamectin benzoate was up to 31%.

Evaluations of rating on overall tree health and new shoot emergence were conducted at 14th and 22nd months after treatments (October 2014 and May 2015). Based on the results from 14th month after treatment (Figure 2.5), trees treated with emamectin benzoate had significantly better tree health condition rating compared to trees treated with imidacloprid and untreated control (ANOVA, H = 8.18, df = 2, $P = 0.017$). Trees treated with insecticides produced significantly more new shoots compared to the trees under untreated control (ANOVA, H = 11.32, df = 2, *P* = 0.003).

On the 22nd month after treatment, a similar pattern was observed on the rating of tree health condition, with significant difference among treatments (ANOVA, H = 7.92, df = 2, *P* = 0.019), whereas the rating on new shoot emergence was not significant (H = 4.11, df = 2, *P* = 0.128) among trees under either treatment or untreated control (Figure 2.6).

Discussion

The key approach to protect Chinese banyans from infestation of stem and leaf gall wasps is to prevent and reduce new infestations. The systemic insecticides injected through the trunk injection system were expected to kill larvae inside the galls, disrupt wasp life cycle, and prevent female wasps from laying eggs.

Despite severe stem gall wasp pre-treatment infestations, trees treated with emamectin benzoate maintained canopy with reduced new gall formation on leaves and stems, and were protected from further canopy loss attributable to gall insects. Previous studies have shown that trunk injected emamectin benzoate provided excellent activity against some insect pests, such as eastern tent caterpillar, *Malocosoma americanum* Fabricius (Lepidoptera: Lasiocampidae) (Potter et al., 2005), southern pine engravers, *Ips* spp. (Coleoptera: Curculionidae) (Grosman and Upton, 2006). In addition, Tekai et al. (2003) found that trunk injected emamectin benzoate persisted in pine trees for three years at sufficient concentrations to inhibit nematode propagation and reduce pine wilt disease. For the gall wasps, *Callirhytis cornigera* Osten Sacken (Hymenoptera: Cynipidae), on pin oak, *Quercus palustris* Munchh (Fagales: Fagaceae), bidrin and abamectin (chemically similar to emamectin benzoate) had significant effects, but trunk injected imidacloprid did not reduce the number of new stem galls on trees (Eliason and Potter, 2000). Smitley et al. (2010) found nearly 100% control of emerald ash borer larvae, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), on green ash trees treated with trunk injected emamectin benzoate at the rate of 0.1- 0.4 gram active ingredient per inch DBH. The trunk injected emamectin benzoate was highly effective against adult and larvae of emerald ash borer for two seasons post-treatment, but the trunk-injected imidacloprid did not have effect against ash borer larvae (McCullough et al., 2011). Consistent with these studies, our study showed that emamectin benzoate effectively suppressed stem gall wasps on Chinese banyans for at least 14 months after tree injection application.

A study to investigate effectiveness of emamectin benzoate and imidacloprid against erythrina gall wasps, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae) on Wiliwili trees, *Erythrina sandwicensis* (Fabales: Fabaceae), (Doccola et al. 2009) indicated some effect of emamectin benzoate against erythrina gall wasp, but overall it was less effective than imidacloprid. In contrast, our findings suggest that emamectin benzoate is more effective than imidacloprid against banyan stem gall wasps, and that imidacloprid did not have significant effects against stem gall wasps on Chinese banyans. Lower effectiveness of imidacloprid against banyan stem gall wasps could be due to tolerance or lack of susceptibility of this wasp species to imidacloprid, or low residue of imidacloprid in shoots of this *Ficus* species.

Although imidacloprid was not effective against stem gall wasps, it showed some effect against leaf gall wasps. In fact both systemic insecticides tested showed activity against leaf gall wasps, with emamectin benzoate being more effective. The reduction in average percentage of infested leaves on trees treated with emamectin benzoate was up to 31%. Young (2002) studied the effectiveness of trunk injected imidacloprid to manage red gum lerp psyllid, *Glycaspis* *brimblecombei* Moore (Hemiptera: Psyllidae), on red gum eucalyptus trees, *Eucalyptus camaldulensis* Dehnhardt (Myrtales: Myrtaceae), and found it effective for approximately 8 months post-treatment. Trunk injection of imidacloprid was also conducted on Eastern hemlocks, *Tsuga canadensis* Carriere (Pinales: Pinaceae) to determine its effectiveness on hemlock woolly adelgid, *Adelges tsugae* Annand (Hemiptera: Adelgidae) (Eisenback et al., 2014). They found imidacloprid reduced *A. tsugae* populations after three and four years, resulting in new shoot growth and better visual ratings of tree health. We observed the effects of both imidacloprid and emamectin benzoate on leaf gall wasps for up to 18 months after treatment. It is interesting to observe that imidacloprid had effect against leaf gall wasp, but not against stem gall wasp. The reasons for the various efficacies in different plant-pest systems could be due to differences in toxicity tolerance among insect species, difference in chemical distribution pattern among tree species, difference in tree physiology, and/or different environmental conditions (Daccola et al., 2009).

Our findings did not show any benefit of phosphorous acid amendment. Phosphorous acid is primarily used as a fungicide for the control of oomycetes. When phosphorous acid comes in contact with bacteria associated with the plant root system or in the soil, the oxidation of phosphite to phosphate can take place, resulting in the slow release of nutrients (McDonald et al., 2001). It is also considered to have some positive effect by stimulating the plant's natural defense system and overall health (Smillie et al., 1989). Therefore we expected the phosphorous acid to have some effect against gall wasps through enhanced tree health and immunity system in combination with systemic insecticides, but the data showed no benefit of phosphorous acid in this particular tree-pest dynamic.

In conclusion, this study suggests that emamectin benzoate is effective for maintaining Chinese banyan tree canopy health for at least 14 months under severe infestation from stem gall wasps, and for at least 18 months under infestation from leaf gall wasps. Imidacloprid was only moderately effective against leaf gall wasps, but not effective against stem gall wasps. Phosphorous acid did not provide any benefit to Chinese banyans in terms of suppressing these two wasp species. Overall, trunk injection of emamectin benzoate could be a feasible management strategy to control stem and leaf gall wasps on Chinese banyans in Hawai‘i, and possibly in other tropical regions of the continental U.S. where stem and/or leaf gall wasp species has established, such as Florida and California.

References

Anonymous. (1998) Ficus leaf gall wasp, Josephiella sp., California Plant Pest and Disease Report, vol 16, 46.

Beardsley J. W. and Rasplus J-Y. (2001) A new species of *Josephiella* (Hymenoptera: Agaonidae) forming leaf galls on *Ficus microcarpa* L. (Moraceae). *Journal of Natural History,* 35, 33–40.

Caldwell D. (2008) Ficus Trees Under Severe Insect Attack. University of Florida IFIS Extension, Collier County, Naples Daily News. http://collier.ifas.ufl.edu/CommHort/CommHortPubs/FicusTreeAttack.PDF (Accessed on September 8, 2015).

Doccola J. J., Smith S. L., Strom B. L., Medeiros A.C., von Allmen E. (2009) Systemically applied insecticides for treatment of erythrina gall wasp, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae). *Arboriculture & Urban Forestry*, 35, 173-181.

Doccola J. J. and Wild P. M. (2012) Tree injection as an alternative method of insecticide application. Insecticides–Basic and Other Applications, ed. by Soloneski S and Larramendy M. InTech, Rijeka, Croatia, 61-78.

Eisenback B. M., Salom S. M., Kok L. T. and Lagalante A. F. (2014) Impacts of trunk and soil injections of low rates of imidacloprid on hemlock woolly adelgid (Hemiptera: Adelgidae) and eastern hemlock (Pinales: Pinaceae) health. *Journal of Economic Entomology*, 107, 250-258.

Eliason E. A. and Potter D. A. (2000) Impact of whole-canopy and systemic insecticidal treatments on *Callirhytis cornigera* (Hymenoptera: Cynipidae) and associated parasitoids on pin oak. *Journal of Economic Entomology,* 93, 165-171.

Emamectin benzoate- United States Environmental Protection Agency (EPA). (2009) http://www.epa.gov/opp00001/chem_search/cleared_reviews/csr_PC-122806_13-Jan-09_a.pdf (Accessed on July 28, 2015).

Fossen M. (2006) Environmental fate of imidacloprid. California Department of Pesticide Regulation, 1-16.

Grosman D. M. and Upton W. W. (2006) Efficacy of systemic insecticides for protection of loblolly pine against southern pine engraver beetles (Coleoptera: Curculionidae: Scolytinae) and wood borers (Coleoptera: Cerambycidae). *Journal of Economic Entomology*, 99, 94-101.

Hawaiʻi Department of Agriculture. (2012) Banyan Stem Galling Wasp, a New Insect In Hawaiʻi, Plant Pest Control Branch. http://alohaarborist.com/wp-content/uploads/2012/06/20120822-Banyan-stem-galling-wasp-HDOA-handout.pdf. (Accessed on July 28, 2015).

McCullough D. G., Poland T. M., Anulewicz A.C., Lewis P. and Cappaert D. (2011) Evaluation of *Agrilus planipennis* (Coleoptera: Buprestidae) control provided by emamectin benzoate and two neonicotinoid insecticides, one and two seasons after treatment. *Journal of Economic Entomology*, 104, 1599-1612.

McDonald A. E., Grant B. R. and Plaxton W.C. (2001) Phosphite (phosphorous acid): its relevance in the environment and agriculture and influence on plant phosphate starvation response. *Journal of Plant Nutrition*, 24, 1505-1519.

McWain P. and Gregory G. F. (1973) A benomyl-derived fungitioxicant for tree wilt disease control. USDA Forest Service Research Note NE-162. 3pp.

Norris D. M. (1965) Systemic pesticides in woody plants: Uptake. *Bulletin of Entomological Society of America*, 11, 187-190.

Pemberton C.E. (1939) Note on introduction and liberation of *Eupristina verticillata* Waterston in Honolulu. *Proceedings of Hawaiian Entomological Society*, 10, 182.

Potter D. A., Foss L., Baumler R. E. and Held D. W. (2005) Managing eastern tent caterpillars *Malacosoma americanum* (F) on horse farms to reduce risk of mare reproductive loss syndrome. *Pest Management Science*, 61, 3-15.

Ramirez B. W. and Montero S. J. (1988) *Ficus microcarpa* L., *F. benjamina* L. and other species introduced in the New World, their pollinators (Agaonidae) and other fig wasps. *International Journal of Tropical Biology and Conservation*, 36, 441-446.

Smillie R., Grant B. R. and Guest D. (1989) The mode of action of phosphite: evidence for both direct and indirect modes of action on three *Phytophthora spp.* in plants. *Phytopathology*, 79, 921-926.

Smitley D. R., Doccola J. J. and Cox D. L. (2010) Multiple-year protection of ash trees from emerald ash borer with a single trunk injection of emamectin benzoate, and single-year protection with an imidacloprid basal drench. *Journal of Arboriculture*, 36, 206.

Starr F., Starr K. and Loope L. (2003) *Ficus microcarpa*. Chinese Banyan, Moraceae. http://www.hear.org/starr/hiplants/reports/pdf/ficus_microcarpa.pdf. (Accessed on July 28, 2015).

Takai K., Suzuki T. and Kawazu K. (2003) Development and preventative effect against pine wilt disease of a novel liquid formulation of emamectin benzoate. *Pest Management Science*, 59, 365-370.

Wagner W. L., Herbst D. R. and Sohmer S. H. (1999) Manual of the Flowering Plants of Hawai'i, University of Hawai'i and Bishop Museum Press, Vols. 2.

Young L. C. (2002) The efficacy of micro-injected imidacloprid and oxydemeton-methyl on red gum eucalyptus trees (*Eucalyptus camaldulensis*) infested with red gum lerp psyllid (*Glycaspis brimblecombei*). *Journal of Arboriculture*, 28, 144-147.

Treatment	Mean DBH (meters)	Dose		
		Average imidacloprid (5%) at 8 ml per inch DBH	Average emamectin benzoate (4%) at 10 ml per inch DBH	Average phosphorous acid (45.8%, 7 ml per inch DBH)
Imidacloprid (A)	1.14	358		
Emamectin benzoate (B)	1.21		475	
Imidacloprid +Phosphorous acid (C)	1.21	381		334
Emamectin benzoate + Phosphorous acid (D)	1.20		474	332
Untreated/control (E)	1.29			

Table 2.1. Mean diameter at breast height (DBH) of *Ficus microcarpa* and average treatment dosages of trees assigned for different treatments.

Evaluation period (month after treatment)	Treatments comparision	No. of stem galls	% of infested leaves	Average stem infestation level	Average leaf infestation level
	A vs C	NS	NS	NS	NS
3	B vs D	NS	NS	NS	NS
	P- value	0.779	0.094	0.787	0.113
	A vs C	NS	NS	NS	NS
4	B vs D	NS	NS	NS	NS
	P- value	0.132	0.005	0.023	0.002
	A vs C	NS	NS	NS	NS
5	B vs D	NS	NS	NS	NS
	P- value	0.017	0.046	<0.001	0.005
	A vs C	S	NS	NS	NS
6	B vs D	NS	NS	NS	NS
	P- value	0.001	0.001	<0.001	<0.001
	A vs C	NS	NS	NS	NS
7	B vs D	NS	NS	NS	NS
	P- value	0.142	0.002	0.006	0.001
	A vs C	NS	NS	NS	NS
8	B vs D	NS	NS	NS	NS
	P- value	0.238	0.048	0.038	0.008
	A vs C	NS	NS	NS	NS
9	B vs D	NS	NS	NS	NS
	P- value	0.029	0.011	0.011	<0.001
	A vs C	NS	NS	NS	NS
10	B vs D	NS	NS	NS	NS
	P- value	<0.001	0.007	<0.001	0.001
	A vs C	NS	NS	NS	NS
11	B vs D	NS	NS	NS	NS
	P- value	0.148	<0.001	0.015	0.001
	A vs C	NS	NS	NS	NS
12	B vs D	NS	NS	NS	NS
	P- value	0.013	< 0.001	0.007	<0.001
	A vs C	NS	S	NS	NS
14	B vs D	NS	NS	NS	NS
	P- value	0.005	< 0.001	0.005	<0.001
	A vs C	NS	NS	NS	NS
16	B vs D	NS	NS	NS	NS
	P- value	0.66	0.11	0.572	0.022
18	A vs C	NS	NS	NS	NS
	B vs D	NS	NS	NS	NS

	P- value	0.24	0.0063	0.083	0.009
	A vs C	NS	NS	NS	NS
20	B vs D	NS	NS	NS	NS
	P- value	0.11	0.78	0.259	0.317
	A vs C	NS	NS	NS	NS
22	B vs D	NS	NS	NS	NS
	P- value	0.24	0.283	0.103	0.258

Table 2.2. One-way analysis using general linear model and Tukey's test for pairwise comparison for parameters- no. of stem galls and percentage of infested leaves; and Kruskal-Wallis test and pairwise comparison using Dunn's method for parameters- average stem infestation and average leaf infestation level to test treatments with or without Phosphorous acid. *P*-values on each month were calculated based on four treatments and untreated/control.

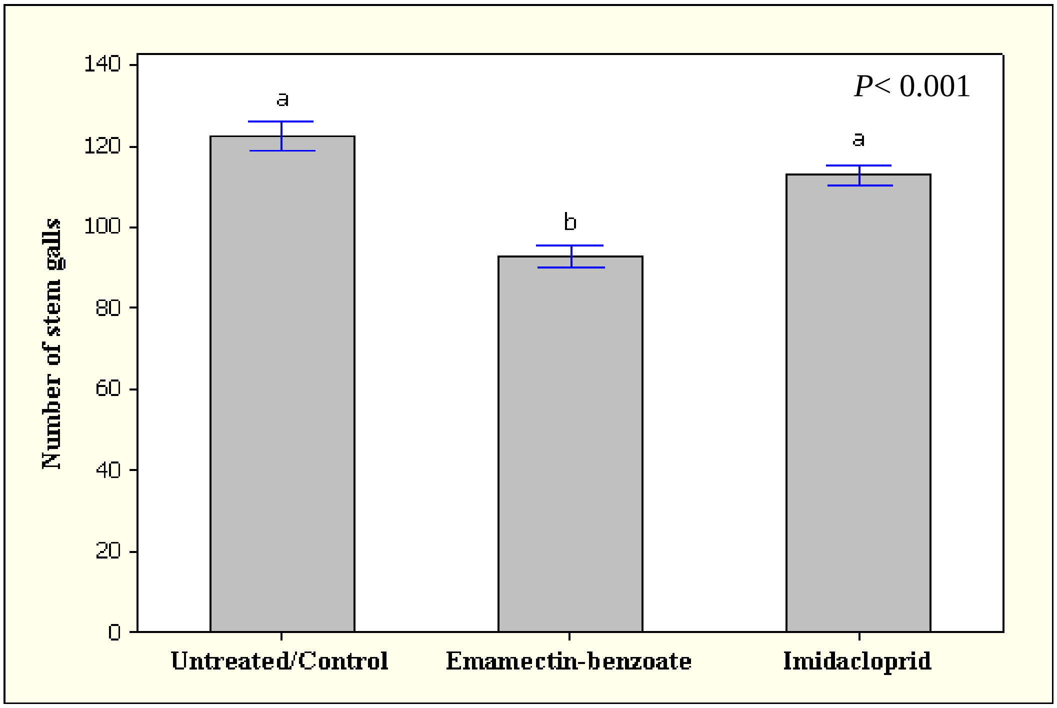


Fig. 2.1. Average number of stem galls for two treatments and control trees, *Error bars indicate standard error of the mean. Mean with same letter are not significantly different.

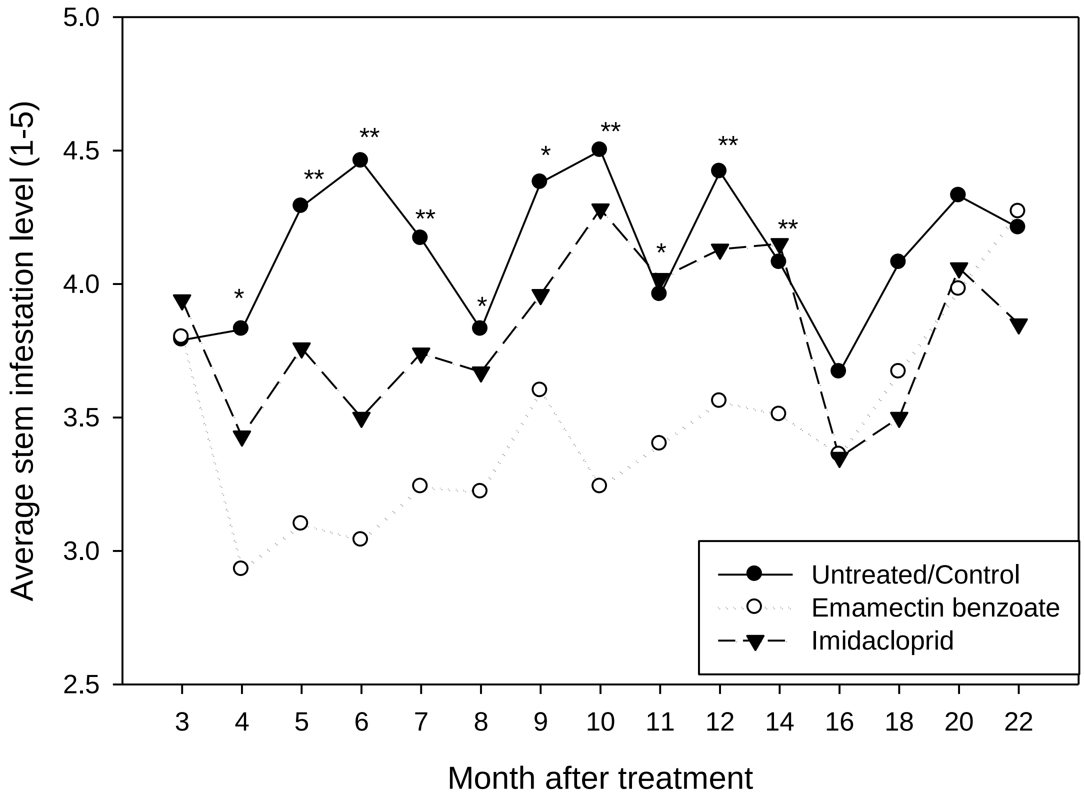


Fig. 2.2. Average stem infestation level on new shoots for two treatments and control trees (1-5, where 1=no infestation and 5=severe infestation), where * indicates *P*< 0.05 and ** indicates *P*< 0.01 within each sampling month (analyzed using Kruskal-Wallis test).

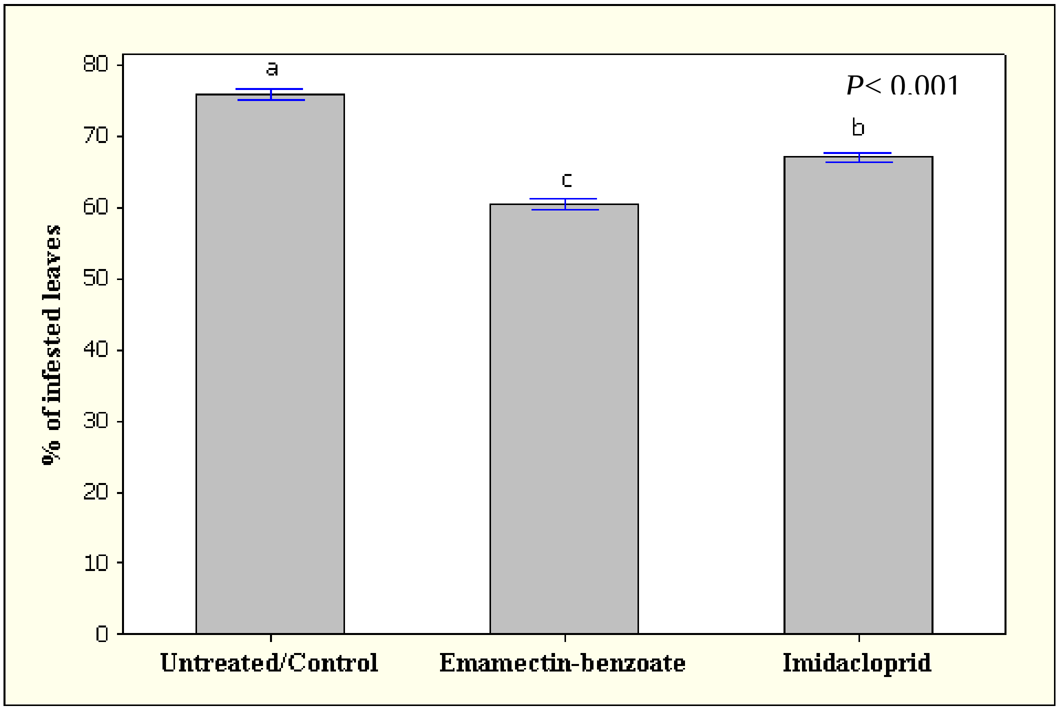


Fig. 2.3. Average percentage of infested leaves on new shoots for two treatments and control trees, *Error bars indicate standard error of the mean. Mean with same letter are not significantly different.

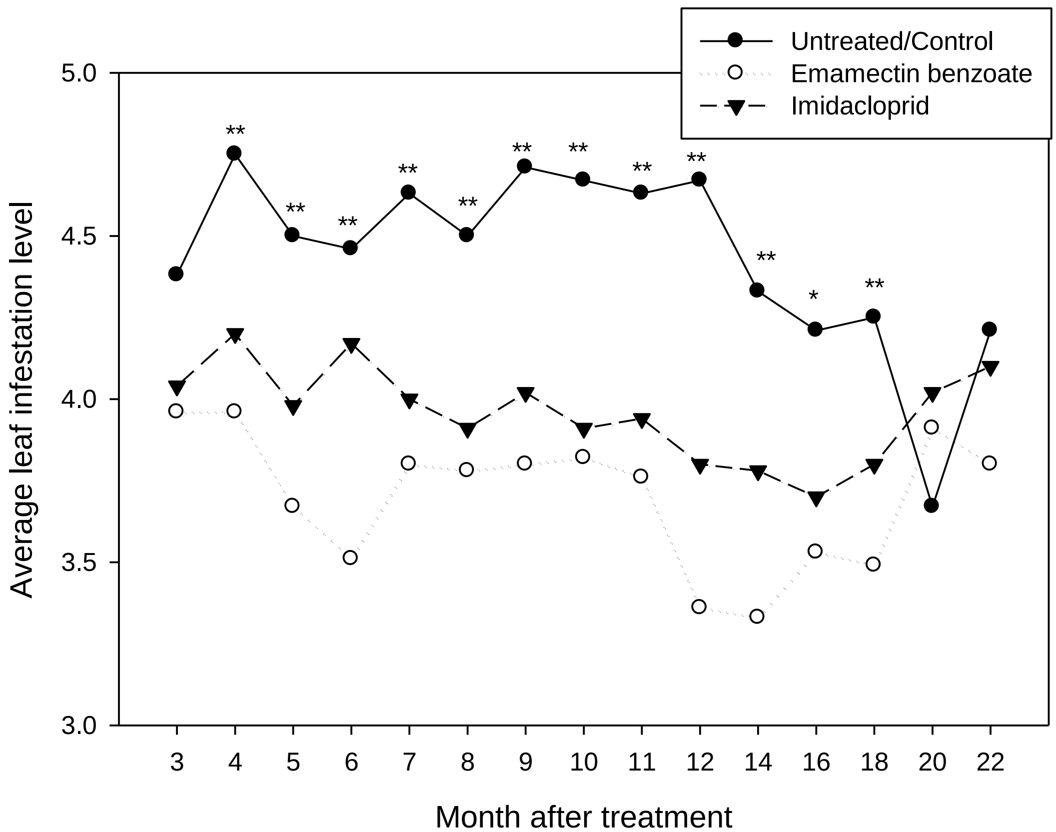


Fig. 2.4. Average leaf infestation level on new shoots for two treatments and control trees (1-5, where 1=no infestation and 5=severe infestation), where * indicates *P*< 0.05 and ** indicates *P*< 0.01 within each sampling month (analyzed using Kruskal-Wallis test).

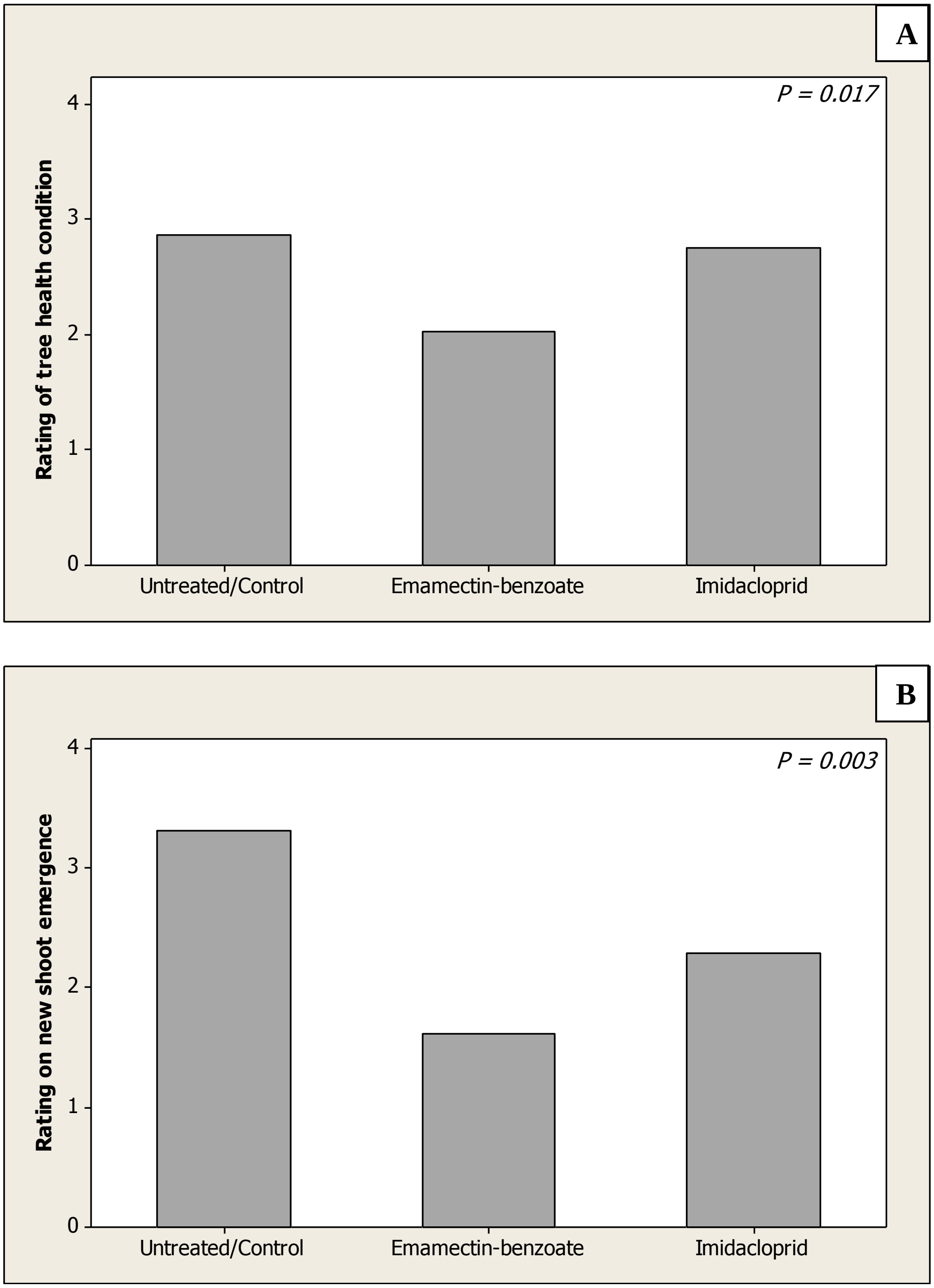
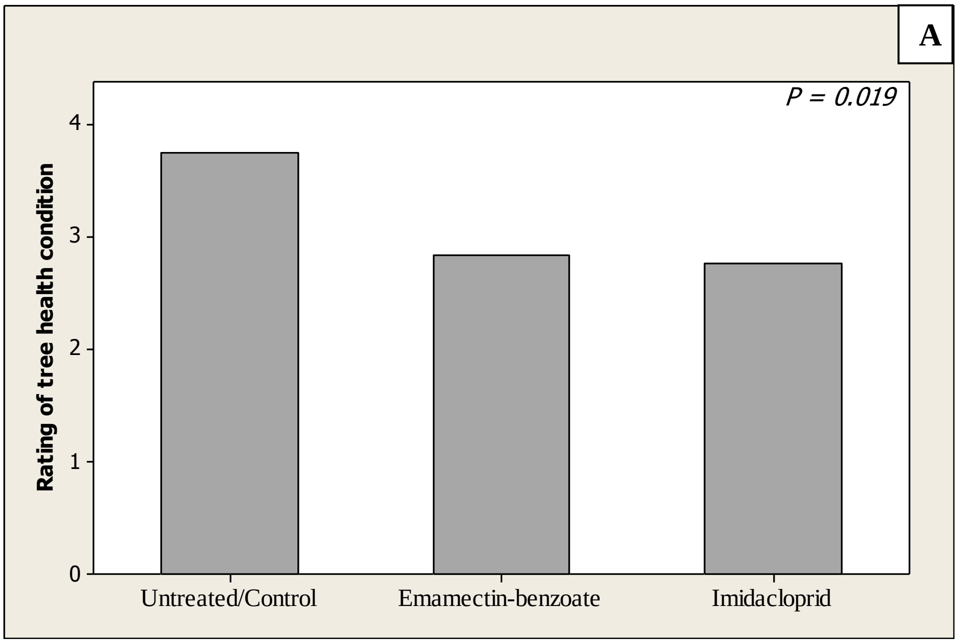


Fig. 2.5. Rating of tree health condition (A) and rating of new shoot emergence (B) in 14 months after treatment (Rating of tree health condition: 1=excellent, 2=good, 3=fair, 4=poor, 5=dead, Rating of new shoots emergence: 1=many, 2=moderate, 3=some, 4=little, 5=very little).



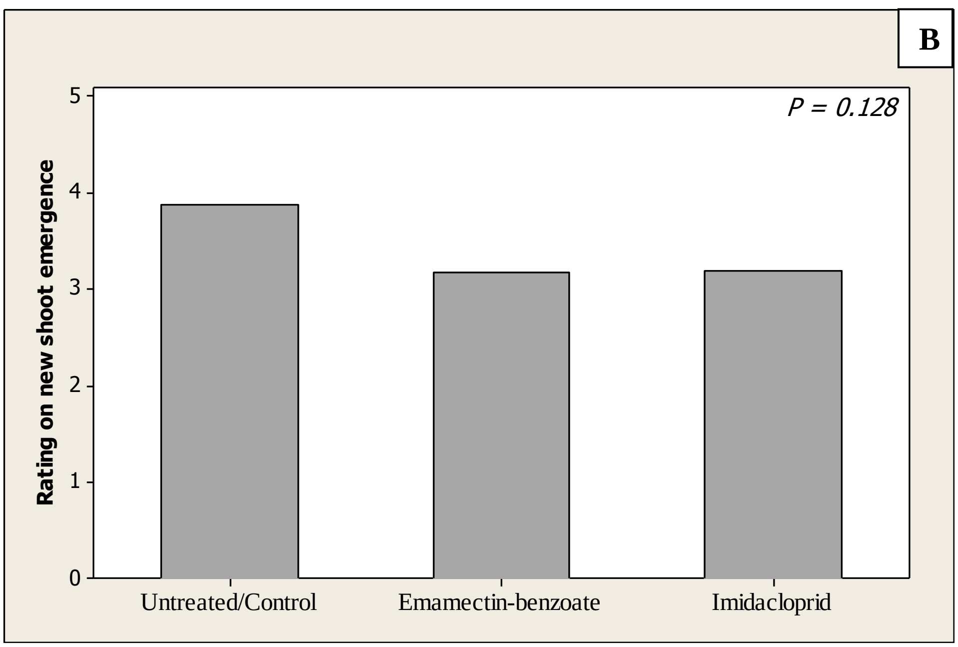


Fig. 2.6. Rating of tree health condition (A) and rating of new shoot emergence (B) on 22 months after treatment (Rating of tree health condition: 1=excellent, 2=good, 3=fair, 4=poor, 5=dead, Rating of new shoots emergence: 1=many, 2=moderate, 3=some, 4=little, 5=very little).

CHAPTER 3. Management of lobate lac scale, *Paratachardina pseudolobata,* on Chinese banyan, *Ficus microcarpa*, and weeping banyan *Ficus benjamina* in Hawai‘i

Abstract

The lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan, a recent insect invader in Hawai‘i (first found in October 2012), infests young branches of woody plants usually less than 2 cm in diameter, forming a mass that appears as a dark crust, resulting in unhealthy appearance, defoliation of leaves and eventually death of some plant species. This insect has infested many native and non-native plant species on Oahu, and the number of infested plant species is increasing. Efficacy and longevity of efficacy of preventive treatment using systemic insecticides imidacloprid and emamectin benzoate, delivered through trunk injection, against lobate lac scale on Chinese banyan, *Ficus microcarpa,* and curative treatment using imidacloprid on weeping banyan, *Ficus benjamina,* were evaluated. Forty-five Chinese banyans and ten weeping banyans were included in this study. Our findings suggested that the systemic insecticide imidacloprid delivered via trunk injection was very effective in preventing lobate lac scale infestation for at least 22 months post-treatment, and in reducing lobate lac scale infestation curatively for at least 20 months post treatment. This research provided a very effective management strategy, both preventively and curatively against this pest.

Key Words**:** trunk injection; Ficus trees; imidacloprid; emamectin benzoate

Introduction

The lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan (Kerriidae; Coccoidea; Hemiptera), is considered native in tropical Asia, although the exact native range is still unclear. Lobate lac scale was first discovered in the United States in 1999 in Southern Florida (Hamon, 2001). In Hawaiʻi, it was first found on weeping banyan, *Ficus benjamina*, on Oahu, in October, 2012 (HDOA, 2012). It has become a severe pest attacking many native and non-native plant species on Oahu, Hawaiʻi, especially in Oahu's urban landscapes where infestation first appeared and is the heaviest (personal observation). It has not been officially reported on any other Hawaiian islands to date.

Initially, lobate lac scale was identified mistakenly as *Paratachardina lobata* Chamberlin in earlier literature, and it was then corrected to *Paratachardina pseudolobata* after the taxonomic revision of the genus *Paratachardina* (Kondo and Gullan, 2007). The mature female lobate lac scales are about 2 mm long and 2 mm wide, with an x-shaped appearance and a deep maroon color. They have a hard, resinous protective armor covering their soft body underneath. The first instar measures approximately 0.4 mm in length and has a deep red color. The second instar molts to the adult. Development from instar to adult requires 15-19 weeks. The first instar stage lasts 8-11 weeks and the second instar lasts 7-8 weeks (Howard et al., 2010). The crawler exits the mother's shellac through the dorsal opening (Howard et al., 2010). The adults are wingless, immobile and attach tightly to twigs. This insect disperses at its crawler stage (either first or second instar) via air currents, birds, and other animals. Humans can unknowingly spread them by moving infested plants. Males have not been observed and thus lobate lac scale is considered parthenogenetic as are many other scale insects (Kundo and Gullan, 2007; Howard et al., 2010). The lobate lac scale infests the woody tissues of small, young twigs and branches of around pencil-size thickness, but less frequently the older branches. Major effects on hosts include the formation of sooty molds (with unhealthy appearance), the dieback of twigs and branches, the thinning of foliage, and eventually the death of entire plants of some species. No lobate lac scale has been found infesting leaves, petioles, flowers and roots of plants.

Lobate lac scale has a wide range of hosts, consisting of more than 300 mainly woody dicotyledonous plant species in Florida (Howard et al., 2010). In Hawaiʻi, our host survey conducted in 2014 indicated that lobate lac scale had over 80 native and non-native host plant species on Oahu (Cheng and Bhandari, 2015). Our continuing survey confirmed additional 28 host plant species of lobate lac scale in Hawaiʻi.

Among the wide range of plant hosts, ficus species are observed to be the primary hosts in urban landscape of Hawaiʻi, and infestation is high. Therefore, we conducted this research with intention to identify effective management strategies to control lobate lac scale on two ficus species, weeping banyan, *Ficus benjamina,* and Chinese banyan, *Ficus microcarpa*. Lobate lac scale may not be a major pest in its native range, so not much knowledge is known on its biological, chemical or other control methods. One study conducted at the University of Florida showed that imidacloprid was effective to some extent in controlling lobate lac scale when applied via soil drench (Howard and Steinberg, 2005). Therefore, we included imidacloprid and another low-risk systemic insecticide, emamectin benzoate, in our research reported here. However, we used a different approach, i.e. trunk injection, to deliver the insecticides rather than the soil drench method used in the Florida study. Trunk injection is a relatively new way to treat trees to combat problems related to insects, diseases and nutrient deficiencies. This method typically requires less active ingredients compared to conventional methods such as foliar spray, and soil drench. There was a greater accuracy in chemical uptake when applied through trunk injection compared to soil application (Johnson and Rediske, 1965; Doccola and Wild, 2012). Unlike conventional methods, trunk injection system directly injects chemicals into the vascular system of the tree, without exposing the chemicals to the environment. We hypothesized that imidacloprid and/or emamectin benzoate delivered through trunk injection would be effective in controlling lobate lac scale on weeping banyan and Chinese banyan, and the longevity of efficacy would be relatively long term.

Materials and Methods

Experimental design

This research was conducted on the campus of University of Hawaiʻi at Mānoa (21.2970° N, 157.8170° W), Honolulu, Hawaiʻi, USA. Two *Ficus* species, Chinese banyan, *Ficus microcarpa,* and weeping banyan, *Ficus benjamina*, primary hosts of lobate lac scale in Hawaiʻi, were included in this study.

For the preventive study, we included 45 Chinese banyan trees having similar overall conditions (size, canopy health, etc.). This study was conducted in conjunction with the gall wasp management study reported in Chapter 2 (same trees used). These trees had no lobate lac scale infestation at the time of preventive treatment application. The average diameter at breast height (DBH) of trees was 120.65 centimeters. Eighteen trees were injected in July 2013 with imidacloprid (5%) at 8 ml per 2.54 cm DBH and 18 with emamectin benzoate (4%) at 10 ml per 2.54 cm DBH. Nine trees were included as untreated control. Arborjet QUIK-jet micro infusion system and pressurized Tree IV system (Arborjet, Inc. Woburn, MA, USA) were used for trunk injection. The injection ports were created on each tree at breast height above the ground. The distances between two ports were maintained 10-15cm. The total number of ports per tree was determined based on the DBH of tree and imidacloprid dose. Each port was created by drilling about 2 inches deep and 9.53 mm in diameter, into the tree xylem with a cordless 1500 rpm drill. Ports were sealed immediately after drilling with Arborplug® no. 4 (Arborjet Inc., Woburn, MA, USA), using screwdriver-like plug tapper and a hammer, with plug positioned just below the bark level to let port closure with cambium. After that, each port was connected with Tree I. V. system. On average, each tree was treated within 30 minutes.

Data collection

Three new terminal shoots (approximately 45 cm long) from each tree were randomly collected from middle canopy monthly till one year after treatment and every other month afterwards. The lobate lac scale infestation level (1-5, 1= no infestation, 5= most severe infestation) was measured at each sampling time. Severe infestation means the shoot sampled were covered fully with juvenile and mature scale insect forming a contiguous mass that appears as a dark crust.

Ten weeping banyan trees of similar overall condition (lobate lac scale infestation, size, canopy health, etc.) were included to study the efficacy and longevity of efficacy of imidacloprid as curative treatment. In this study, five trees were treated with systemic insecticide imidacloprid with Tree IV system (Arborjet, Inc. Woburn, MA, USA) in December 2013. The dose of imidacloprid (5%) was at 8 ml per 2.54 cm DBH. Five trees were included as untreated controls. Five new terminal shoots (approximately 45 cm long) from each tree were randomly collected prior to treatment, and monthly up to one year after treatment, and every other month after one year. The lobate lac scale infestation level (1-5, 1= no infestation, 5= most severe infestation) was measured at each sampling time.

Statistical analysis

Statistical analysis was conducted using non-parametric Kruskal-Wallis tests to determine if there were statistically significant differences in each month's data. The differences were considered significant at $P < 0.05$. Minitab Version 14 (Minitab, Inc., State College, PA, USA) was used for analysis.

Results

We evaluated the efficacy and longevity of efficacy of preventive treatment using imidacloprid and emamectin benzoate against lobate lac scale on Chinese banyan trees, one of lobate lac scale's major hosts in Hawai‘i, up to 22 months post treatment. Starting from the seventh month after preventive injection, lobate lac scale infestation appeared on trees that were control and treated with emamectin benzoate (Fig. 3.1). Lobate lac scale infestation on imidacloprid-injected trees was very low or non-existent. Lobate lac scale infestation increased over time on emamectin benzoate treated trees and untreated/control trees (Fig. 3.1). Our results showed that imidacloprid was very effective in preventing lobate lac scale infestation up to 22 months after preventative treatment.

In the curative study including ten weeping banyan trees, the average lobate lac scale infestation level was measured each month till one year after treatment, and then every other month after one year following treatment. The effect of imidacloprid treatment became apparent starting from the second month after treatment, with a statistically significant decline in lobate lac scale infestation (Fig. 3.2). There was very low survival of juveniles (instars) and adults on imidacloprid treated trees. Figure 3.2 shows the results up to 20 months after treatment, where imidacloprid consistently was very effective against lobate lac scale on weeping banyans. Lobate lac scale was almost eliminated on imidacloprid injected trees and no new infestation was observed during the sampling period.

Discussion

In Florida, lobate lac scale populations were not consistent throughout the year, with some increase in population observed during the summer season (Howard et al., 2010). In contrast, our study showed no significant seasonal fluctuation in the infestation level of lobate lac scale after they established on weeping banyans in Hawai‘i. This could be due to relatively consistent temperature in Hawai‘i throughout the year. The lobate lac scale is more likely to invade and establish in areas where temperature does not drop below freezing point (Chong et al., 2008). This could be the main reason for the widespread distribution of lobate lac scale in Oahu, Hawai‘i, which seems to have occurred during a short period of time since it was first detected in October 2012. The wide host range of lobate lac scale including many native and endangered plant species underscores the severe threat of this pest to Hawai‘i’s urban ecosystems. Heavy infestation of scale insects leads the stems covered with sooty mold, defoliation and dieback. In another study, the first instar crawlers survived up to 14-18 days without host plant, which increases chances that this insect could disperse in tropical regions on national and international levels through human activities (Howard et al., 2010).

This preventive study of trunk injection with systemic insecticides imidacloprid and emamectin benzoate on Chinese banyan trees showed that imidacloprid was highly effective in preventing lobate lac scale infestation for at least 22 months after treatment. In previous studies, imidacloprid and emamectin benzoate varied in their effectiveness and longevity against different insect pests on different plants. Research on trunk injection of imidacloprid on eastern hemlocks, *Tsuga canadensis* Carriere (Pinales: Pinaceae), to determine its effectiveness on hemlock woolly adelgid, *Adelges tsugae* Annand (Hemiptera: Adelgidae), showed reduced *A. tsugae* populations following imidacloprid treatment, and the treatment prevented further damage up to four years post-treatment, resulting in new shoot growth and improved tree health (Eisenback et al., 2014). Trunk injected imidacloprid was effective against erythrina gall wasp, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae), on wiliwili trees, *Erythrina sandwicensis* (Fabales: Fabaceae), and should be able to prevent re-infestation of this pest beyond 13 months after treatment (Doccola et al., 2009). Some studies have shown that trunk injected emamectin benzoate provided good activity against some insect pests. A single trunk injection with emamectin benzoate resulted in significant control of emerald ash borer, *Agrilus planipennis* Fairmaire, for 2-3 years in ash trees, *Fraxinus pennsylvanica* Marshall (Lamiales: Oleaceae) (Smitley et al., 2010; McCullough et al., 2011). Similarly, this study showed emamectin benzoate was more effective than imidacloprid in managing leaf gall wasp, *Josephiella microcarpae,* and stem gall wasp, *Josephiella* sp., on Chinese banyan trees (Chapter 2). In contrast with these studies, our study did not show any effect of trunk injected emamectin benzoate in controlling lobate lac scale on Chinese banyan trees.

Our study on weeping banyan trees showed imidacloprid delivered via trunk injection was highly effective against lobate lac scale curatively. Similarly, a study on Chinese banyan, *F.*

microcarpa, in Florida to observe the effectiveness of root drenching of imidacloprid, organocide (containing fish and sesame seed oils and lecithin) and malathion combined with horticultural oil showed imidacloprid was very effective, almost eliminating lobate lac scales within 103 days after treatment (Howard and Steinberg, 2005). A study using trunk injection to manage red gum lerp psyllid (RGLP), *Glycaspis brimblecombei* Moore (Hemiptera: Psyllidae), on red gum eucalyptus trees, *Eucalyptus camaldulensis* Dehnhardt (Myrtales: Myrtaceae), found significantly reduced population of RGLP within a week following imidacloprid treatment with significantly reduced psyllid nymphs for 8 months in treated trees (Young, 2002). Our finding is consistent with these studies showing imidacloprid was effective to manage lobate lac scale for at least 20 months after treatment on weeping banyan trees when delivered through trunk injection. Only a small number of live juvenile scales were observed on the samples from trees treated with imidacloprid in certain months, but no adults were alive. Air currents, birds or other animals may have dispersed the live juveniles from untreated control trees in the surrounding areas.

Since the native range of lobate lac scale insect is still unclear, no potential biocontrol program has been developed yet. The imidacloprid treatment using trunk injection system appears to be an effective approach to preventively and curatively manage lobate lac scale on ficus trees in Hawai‘i’s urban landscape.

References

Cheng Z. and Bhandari B. P. (2015) Biology, Management, and Updated Host Range of the Lobate Lac Scale (*Paratachardina pseudolobata*) in Hawai‘i’s Urban Landscapes, CTAHR, University of Hawai‘i at Mānoa. http://www.ctahr.hawaii.edu/oc/freepubs/pdf/IP-34.pdf (Accessed on September 25, 2015)

Chong J. H., Roda A. L. and Mannion C. M. (2008) Mortality of the Lobate Lac Scale, *Paratachardina pseudolobata* (Hemiptera: Kerriidae), at near or Below Freezing Temperatures. *Florida Entomologist*, 91, 674-678.

Doccola J. J., Smith S. L., Strom B. L., Medeiros A. C. and von Allmen E. (2009) Systemically Applied Insecticides for Treatment of Erythrina Gall Wasp, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae). *Arboriculture & Urban Forestry*, 35, 173–181.

Doccola J. J. and Wild P. M. (2012) Tree injection as an alternative method of insecticide application. Insecticides–Basic and Other Applications, ed. by Soloneski S and Larramendy M. InTech, Rijeka, Croatia, 61-78.

Eisenback B. M., Salom S. M., Kok L. T. and Lagalante A. F. (2014) Impacts of trunk and soil injections of low rates of imidacloprid on hemlock woolly adelgid (Hemiptera: Adelgidae) and eastern hemlock (Pinales: Pinaceae) health. *Journal of Economic Entomology*, 107, 250-258.

Hamon A. (2001) Pest alert: Lobate lac scale, *Paratachardina pseudolobata* (Chamberlin) (Hemiptera: Kerriidae). Florida Department of Agriculture and Consumer Services, Division of Plant Industry. http://www.freshfromflorida.com/Divisions-Offices/Plant-Industry/Plant-Industry-Publications/Pest-Alerts/Pest-Alerts-Lobate-Lac-Scale-Paratachardina-Pseudolobata (Accessed on September 25, 2015).

Howard F. W., Pemberton R. W., Hodges G. S., Steinberg B., McLean D. and Liu H. (2006) Host plant range of lobate lac scale, *Paratachardina lobata*, in Florida. *Proceedings of Florida State Horticultural Society,* 119, 398-408.

Howard F. W., Pemberton R. W., Shroer S. and Hodges G. (2010) *Paratachardina pseudolobata* (Coccoidea: Kerriidae): Bionomics in Florida. *Florida entomologist*, 93, 1-7.

Howard F. W. and Steinberg B. (2005) Root drenches and topical insecticide treatments for control of the lobate lac scale, *Paratachardina lobata* (Chamberlin). *Proceedings of Florida State Horticultural Society,* 118, 314-318.

Johnson N. E. and Rediske J. H. (1965) Systemic pesticides in woody plants: translocation. *Bulletin of the Entomological Society of America*, *11*(3), 190-195.

Kondo T. and Gullan P. J. (2007) Taxonomic review of the lac insect genus *Paratachardina* Balachowsky (Hemiptera: Coccoidea: Kerriidae), with a revised key to genera of Kerriidae and description of two new species. *Zootaxa*, 1617, 1-41.

Lobate Lac Scale, *Paratachardina pseudolobata* Kundo and Gullan (Hemiptera: Kerriidae) New Pest Advisory, Nov 2012. http://reportapest.org/pdf/Paratachardina%20pseudolobataDOA_NewPestAdvisory.pdf (Accessed on August 2, 2015).

McCullough D. G., Poland T. M., Anulewicz A. C., Lewis P. and Cappaert D. (2011) Evaluation of *Agrilus planipennis* (Coleoptera: Buprestidae) control provided by emamectin benzoate and two neonicotinoid insecticides, one and two seasons after treatment. *Journal of Economic Entomology*, 104, 1599-1612.

Smitley D. R., Doccola J. J. and Cox D. L. (2010) Multiple-year protection of ash trees from emerald ash borer with a single trunk injection of emamectin benzoate, and single-year protection with an imidacloprid basal drench. *Journal of Arboriculture*, 36, 206.

Young L. C. (2002) The efficacy of micro-injected imidacloprid and oxydemeton-methyl on red gum eucalyptus trees (*Eucalyptus camaldulensis*) infested with red gum lerp psyllid (*Glycaspis brimblecombei*). *Journal of Arboriculture*, 28, 144-147.

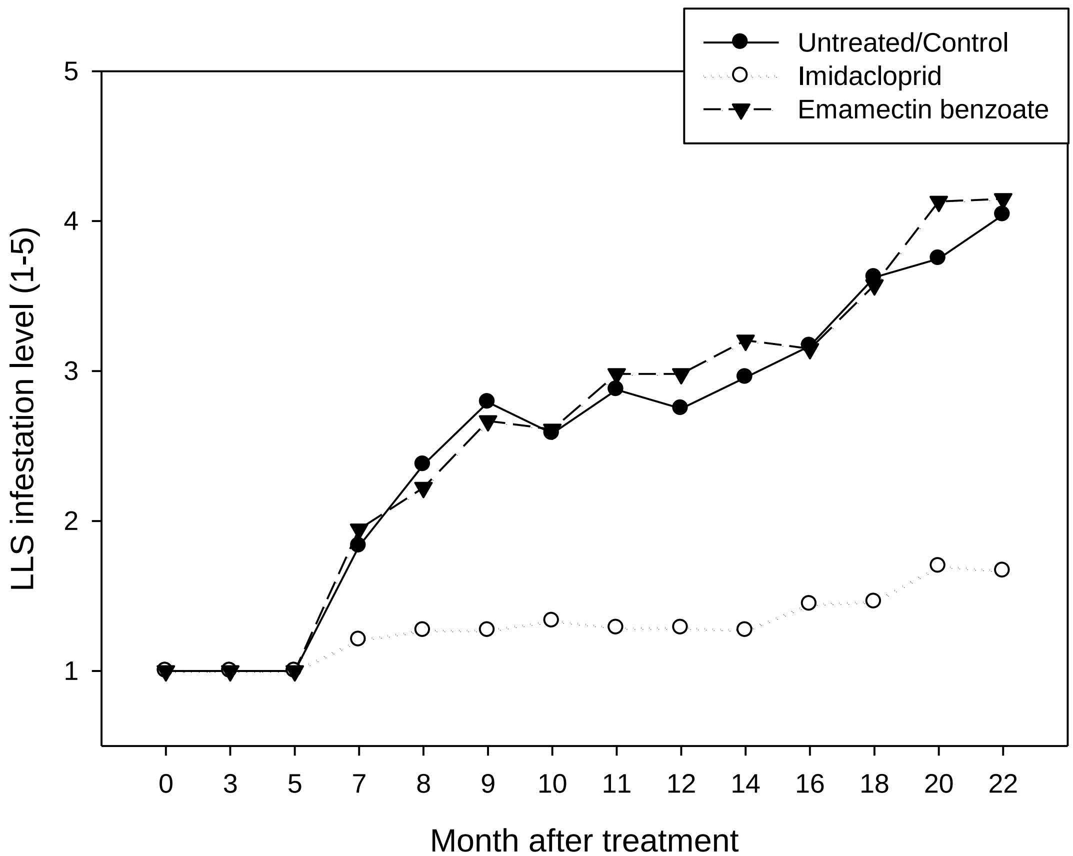


Fig. 3.1. Lobate lac scale infestation level on Chinese banyans up to 22 months after preventive treatment (infestation level: 1= no infestation and 5= most severe infestation). * indicates $P < 0.05$ and ** indicates $P < 0.01$ within each sampling month (analysis was conducted using Kruskal-Wallis tests).

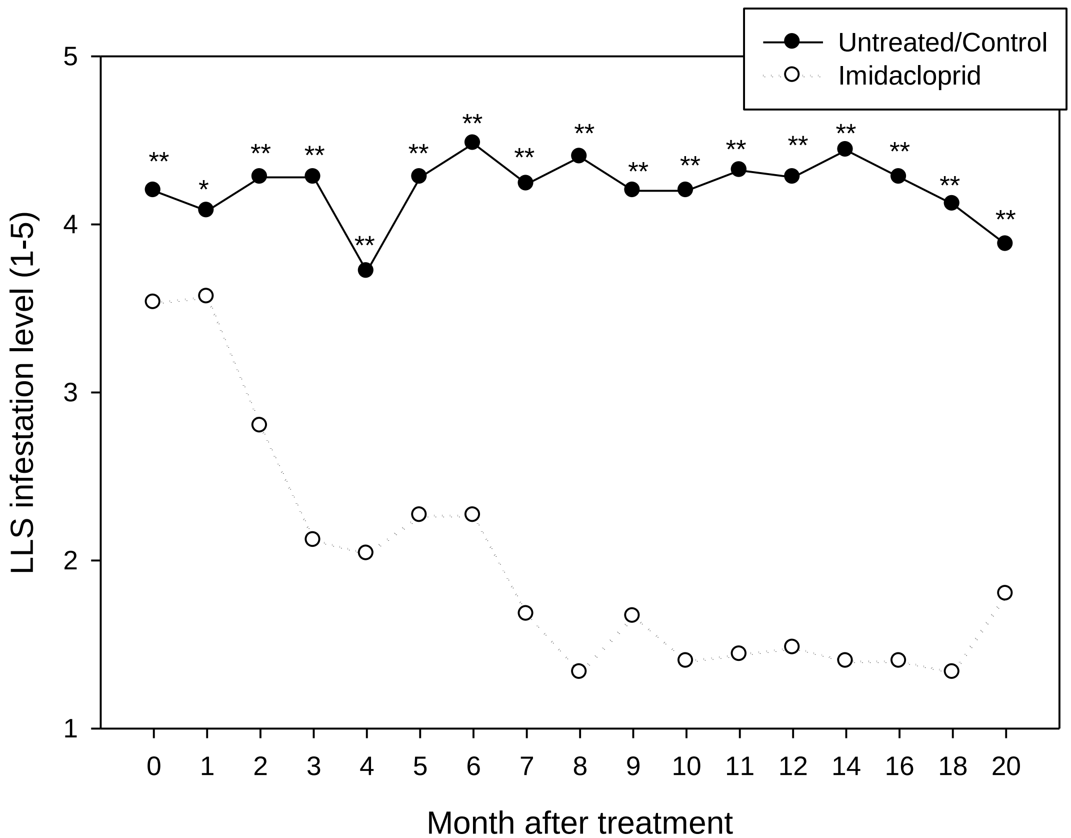


Fig. 3.2. Lobate lac scale infestation level on weeping banyans up to 20 months after curative treatment (Infestation level: 1= no infestation and 5= most severe infestation). * indicates *P* <0.05 and ** indicates *P* <0.01 within each sampling month (analysis was conducted using Kruskal-Wallis tests).

CHAPTER 4. Host range of lobate lac scale, *Paratachardina pseudolobata*, in urban landscape of Oahu, Hawai‘i

Abstract

The lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullen (Hemiptera: Coccoidea: Kerriidae), a recent insect invader in Hawai‘i, was first found in October 2012 on Oahu. The feeding and honeydew excretion activity of the scale insects result in a mass of sooty mold growing on plants, with the appearance of a dark crust, resulting in an unhealthy appearance, subsequent plant defoliation and eventually, death in some plant species. Infestations on Oahu have occurred and are continually spreading to many native and non-native plant species especially in urban areas. A survey of lobate lac scale’s host plants on Oahu’s urban landscape was conducted. Our survey has revealed 111 host plant species, including 29 plant species native to Hawai‘i, and seven endangered species. This research provided the critical update on lobate lac scale’s host species in Hawai‘i’s urban landscape.

Key words: Lobate lac scale; host range; urban landscape

Introduction

The lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan (Kerriidae: Coccoidea: Sternorrhyncha: Hemiptera) is likely to be native to Asia, although the exact native range is unknown. It was first discovered in United States in 1999 on a *Hibiscus rosa-sinensis* plant in Southern Florida (Hamon, 2001; Howard et al., 2010). In Hawai‘i, the lobate lac scale was first found on weeping banyan, *Ficus benjamina*, on Oahu by arborists participating in a tree climbing competition at Moanalua Gardens in October, 2012, and now it has built up alarming densities in the following three years infesting native and non-native plant species in urban landscape and natural forest areas of Oahu, Hawai‘i (HDOA, 2013). It has not been reported on any other Hawaiian islands to date, but eventually it might spread to Hawaiian Islands and other tropical and subtropical regions of the world.

Lobate lac scale has a wide range of hosts in Florida, where it has been recorded form more than 300 mainly woody dicotyledonous plant species (Howard et al., 2010). In Hawai‘i, our first host survey in 2014 indicated that lobate lac scale had over 80 native and non-native host plant species on Oahu (Cheng and Bhandari, 2015). The number of affected plant species in Hawai‘i is increasing as the lobate lac scale is gradually invading forest and natural areas. This survey identified 28 additional host plants, resulting 111 infested plant species. This chapter reports the most recently recorded host range of lobate lac scale in urban landscapes of Oahu, Hawai‘i.

Materials and Methods

This survey was started in April 2014 to document the host plants serving as hosts of the lobate. We covered University of Hawaiʻi at Mānoa campus and its nearby urban landscapes, Bishop Museum area, and some natural areas (Makiki valley loop trail, Kulanaahane trail, Diamond Head) in Honolulu Metropolitan area (Figure 4.1) until August 2015. In our survey, a plant species was considered as a host of lobate lac scale if at least one living mature female were found on the plant (Howard et al., 2006). In reality, we always observed multiple adults and crawlers on the host plants identified in our survey. Host plants were mostly identified to species level.

Results

The first phase of our survey recorded over 80 host plant species belonging to 34 families, including 15 plant species native to Hawaiʻi and four endangered plant species (Cheng and Bhandari, 2015). The second phase of our survey recorded 28 additional host plant species belonging to 20 families, including 14 plant species native to Hawaiʻi and three endangered plant species. Therefore, we now have documented a total of 111 plant species belonging to 44 plant families including 29 plant species native to Hawaiʻi and seven endangered plant species that are hosts of lobate lac scale in the urban landscape of Oahu, Hawaiʻi. Some of the plant families, such as Moraceae, Fabaceae, Malvaceae, Rubiaceae, and Myrtaceae were more susceptible, indicated by the high number of infested species in these families.

Table 4.1. List of the landscape and ornamental plant species infested by the lobate lac scale in the urban landscape of Oahu

Scientific Name	Common Name	Family	Remarks
Graptophyllum pictum	Caricature plant	Acanthaceae	
Sanchezia speciosa	Sanchezia	Acanthaceae	
Pseuderanthemum carruthersii	False eranthemum	Acanthaceae	
Mangifera indica	Mango	Anacardiaceae	
Schinus terebinthifolius	Christmasberry	Anacardiaceae	
Annona muricata	Soursop	Annonaceae	
Annona squamosa	Custard apple	Annonaceae	
Cananga odorata	Ylang Ylang	Annonaceae	
Polyscias guilfoylei	Panax	Araliaceae	
Ilex vomitoria	Weeping youpon holly	Aquifoliaceae	
Ilex dimorphophilla	Okinawa holly	Aquifoliaceae	
Podranea ricasoliana	Port John's creeper	Bignoniaceae	
Tabebuia impetiginosa	Amapa	Bignoniaceae	
Spathodea campanulata	African tulip tree	Bignoniaceae	
Cordia lutea	Yellow geiger	Boraginaceae	
Cordia dichotoma	Fragrant manjack	Boraginaceae	
Bursera simaruba	Copperwood	Burseraceae	
Mammea americana	Mamey apple	Calophyllaceae	
Casuarina equisetifolia	Ironwood	Casuarinaceae	
Elaeodendron orientale	False olive	Celastraceae	

Terminalia melanocarpa	Moo-jee, Brown damson	Combretaceae	
Terminalia spp.	Black terminalia	Combretaceae	
Terminalia catappa	Kamani haole	Combretaceae	
Diospyros sandwicensis	Lama	Ebenaceae	Native to Hawai‘i
Euphorbia celastroides, formerly *Chamaesyce celastroides*	‘Akoko	Euphorbiaceae	Native to Hawai‘i
Acacia koa	Koa tree	Fabaceae	Native to Hawai‘i
Acacia confuse	Formosa koa	Fabaceae	
Millettia pinnata	Pongamia India beech	Fabaceae	
Sesbania tomentosa	‘Ohai	Fabaceae	Endangered, native to Hawai‘i
Caesalpinia pulcherrima	Dwarf poinciana	Fabaceae	
Brownia coccinea	Scarlet flame bean	Fabaceae	
Acacia stenophylla	Shoe string acacia	Fabaceae	
Senna gaudichaudii	Kolomana	Fabaceae	Native to Hawai‘i
Caesalpinia kavaiensis	Uhiuhi	Fabaceae	Endangered, native to Hawai‘i
Tipuana tipu	Rosewood	Faboideae	
Scaevola gaudichaudii	Naupaka kuahiwi	Goodeniaceae	Native to Hawai‘i
Ocimum basilicum	Basil	Lamiaceae	

Persea Americana	Avocado	Lauraceae	
Cinnamomum burmannii	Korintji cassia	Lauraceae	
Laurus nobilis	Bay leaf tree	Lauraceae	
Lecythis minor	Monkeypot nut	Lecythidaceae	
Lagerstroemia speciosa	Banaba	Lythraceae	
Michelia champaca, syn, *Magnolia champaca*	Champak, Joy perfume tree	Magnoliaceae	
Hibiscus arnottianus	Hawaiian white hibiscus	Malvaceae	Native to Hawai‘i
Hibiscus clayi	Koki‘o ‘ula	Malvaceae	Endangered, native to Hawai‘i
Hibiscus rosa-sinensis	Chinese hibiscus	Malvaceae	
Hibiscus waimeae	Koki‘o ke‘oke‘o	Malvaceae	Native to Hawai‘i
Hibiscus kokio ssp. *kokio*	Hawaiian red hibiscus	Malvaceae	Native to Hawai‘i
Hibiscus spp.	Hibiscus	Malvaceae	
Hibiscus kokio ssp. *saintjohnianus*	Koki‘o	Malvaceae	Native to Hawai‘i
Hibiscus brackenridgei	Ma'o hau hale	Malvaceae	Native and Hawai‘i state flower
Thespesia grandiflora	Maga	Malvaceae	
Malvaviscus penduliflorus	Turk’s cap	Malvaceae	
Lebronnecia kokioides		Malvaceae	Endangered

Ficus benjamina	Weeping banyan	Moraceae	
Ficus microcarpa	Chinese banyan	Moraceae	
Ficus petiolaris	Mary's tree	Moraceae	
Ficus binnendykii	Narrow-leaf ficus	Moraceae	
Ficus rumphii	Rumpf's fig tree	Moraceae	
Ficus rubiginosa	Port Jackson fig	Moraceae	
Ficus spp.		Moraceae	
Ficus religiosa	Bo tree, Sacred fig	Moraceae	
Ficus celebensis	Willow fig	Moraceae	
Ficus elastic	Indian rubber tree	Moraceae	
Ficus calophylloides	Kamani-leaved fig	Moraceae	
Psidium guajava	Guava	Myrtaceae	
Pimenta dioica	Allspice	Myrtaceae	
Eugenia uniflora	Surinam cherry	Myrtaceae	
Syzygium cumini	Java plum	Myrtaceae	
Metrosideros polymorpha	‘Ōhi‘a lehua	Myrtaceae	Native to Hawai‘i
Lophostemon confertus	Vinegar tree	Myrtaceae	
Melaleuca quinquenervia	Broad-leaved paperbark	Myrtaceae	
Callistemon viminalis	Weeping bottlebrush	Myrtaceae	
Pimenta dioca	Allspice	Myrtaceae	

Myrsine juddii	Kokea	Myrsinaceae	Endangered, native to Hawai‘i
Myrsine lanaiesis	Kolea	Myrsinaceae	Native to Hawai‘i
Ardisia spp.		Myrsinaceae	
Brachychiton populneus	Bottle tree	Malvaceae	
Pisonia umbellifera	Pāpala kēpau	Nyctaginaceae	Native to Hawai‘i
Jasminum multiflorum	Pïkake hökü, Star jasmine	Oleaceae	
Averrhoa carambola	Starfruit	Oxalidaceae	
pittosporum spp.		Pittosporaceae	Native to Hawai‘i
Pittosporum confertiflorum	Hō‘awa	Pittosporaceae	Native to Hawai‘i
Plumbago auriculata	Plumbago	Plumbaginaceae	
Macadamia integrifolia	Macadamia nut	Proteaceae	
Rhizophora Spp	Mangroves	Rhizophoraceae	
Osteomeles anthyllidifolia	‘Ūlei	Rosaceae	Native to Hawai‘i
Morinda citrifolia	Noni, Indian mulberry	Rubiaceae	
Gardenia taitensis	Tiare, Tahitian gardenia	Rubiaceae	
Gardenia brighamii	Hawaiian gardenia	Rubiaceae	Endangered, native to Hawai‘i
Gardenia sootepensis	Golden gardenia	Rubiaceae	

Hamelia patens	Firebush	Rubiaceae	
Mussaenda erythrophylla	Red flag bush	Rubiaceae	
Gardenia taitensis	Tahitian gardenia	Rubiaceae	
Psydrax odorata	Alaheʻe	Rubiaceae	Native to Hawaiʻi
Santalum ellipticum	Coast sandalwood	Santalaceae	Native to Hawaiʻi
Santalum paniculatum	Iliahi sandalwood	Santalaceae	Native to Hawaiʻi
Dodonaea viscosa	'A'ali'i	Sapindaceae	Native to Hawaiʻi
Blighia sapida	Akee	Sapindaceae	
Litchi chinensis	Lychee	Sapindaceae	
Koelreuteria formosana	Golden-rain tree	Sapindaceae	
Dodonaea spp.	ʻAʻaliʻi	Sapindaceae	Native to Hawaiʻi
Sapindus oahuensis	Lonomea	Sapindaceae	Endangered, native to Hawaiʻi
Chrysophyllum oliviforme	Satin leaf	Sapotaceae	
Manilkara zapota	Chicle tree, Sapodilla	Sapotaceae	
Solanum melongena	Eggplant	Solanaceae	
Brunfelsia americana	Lady of the night	Solanaceae	
Wikstroemia spp.	Akia	Thymelaeaceae	Native to Hawaiʻi
Pipturus albidus	Waimea nettle, Māmaki	Urticaceae	Native to Hawaiʻi
Leea guineensis	Leea	Vitaceae	

Guaiacum officinale	Lignum vitae	Zygophyllaceae	

Discussion

The lobate lac scale is more likely to become established establish in areas where temperatures do not drop below freezing point (Chong et al., 2008). This could be one of the reasons for the wide distribution of lobate lac scale on Oahu that was achieved in a relatively short period since it was first discovered in October 2012. In addition, first instar lobate lac scale crawlers may survive for 14-18 days without host plants (Howard et al., 2010). Given the frequency of interisland, Hawai‘i-U.S. mainland, and international travel and movement of goods, and high scale populations near Honolulu International Airport, lobate lac scale is likely to spread, and eventually disperse to neighboring islands in Hawai‘i, tropical and subtropical regions in the United States and throughout the Pacific region. It is a polyphagous pest with more than 300 host plant species in Florida. It has more than 110 host species on Oahu and the number is increasing as it is gradually invading forest and natural areas. The wide host range of lobate lac scale including many native and endangered plant species underscores the severe threat of this pest to Hawai‘i's various ecosystems, despite the fact that the infestation is the heaviest in urban landscapes now. Appropriate actions must be taken to avoid the spread of this pest and to identify effective control strategies once this pest is established in new areas.

Results reported in Chapter 3 showed trunk injected systemic imidacloprid was very effective against lobate lac scale, both preventively and curatively on Chinese banyan and weeping banyan trees in Oahu's urban landscape. Chemical control would be difficult and costly in forest and natural areas with large number of host plants (Pemberton, 2003). Therefore, research efforts should be expanded to explore biological control strategies against lobate lac scale in different settings.

References

Cheng Z. and Bhandari B. P. (2015) Biology, Management, and Updated Host Range of the Lobate Lac Scale (*Paratachardina pseudolobata*) in Hawaiʻi's Urban Landscapes, CTAHR, University of Hawaiʻi at Mānoa. http://www.ctahr.hawaii.edu/oc/freepubs/pdf/IP-34.pdf (last accessed September 25, 2015).

Chong J. H., Roda A. L. and Mannion C. M. (2008) Mortality of the Lobate Lac Scale, *Paratachardina pseudolobata* (Hemiptera: Kerriidae), at near or Below Freezing Temperatures. *Florida Entomologist*, 91, 674-678.

Hamon A. (2001) Pest alert: Lobate lac scale, *Paratachardina pseudolobata* (Chamberlin) (Hemiptera: Kerriidae). Florida Department of Agriculture and Consumer Services, Division of Plant Industry. http://www.freshfromflorida.com/Divisions-Offices/Plant-Industry/Plant-Industry-Publications/Pest-Alerts/Pest-Alerts-Lobate-Lac-Scale-Paratachardina-Pseudolobata (Last accessed September 25, 2015).

Howard F. W., Pemberton R. W., Hodges G. S., Steinberg B., McLean D. and Liu H. (2006) Host plant range of lobate lac scale, *Paratachardina lobata*, in Florida. *Proceedings of Florida State Horticultural Society*, 119, 398-408.

Howard F. W., Pemberton R. W., Shroer S. and Hodges G. (2010) *Paratachardina pseudolobata* (Coccoidea: Kerriidae): Bionomics in Florida. *Florida entomologist*, 93, 1-7.

Pemberton R. W. (2003) Invasion of *Paratachardina lobata lobata* (Hemiptera: Kerriidae) in South Florida: A snapshot sample of an infestation in a residental yard. *Florida Entomologist*, *86*(3), 373-377.

State of Hawai‘i, Department of Agriculture. (2013) New Pest Advisory: Lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullen (Hemiptera: Kerriidae), No. 12-03. http://hdoa.hawaii.gov/pi/files/2013/01/3-27-2013-Lobate-lac-scale-NPA.pdf (Accessed on October 23, 2015).

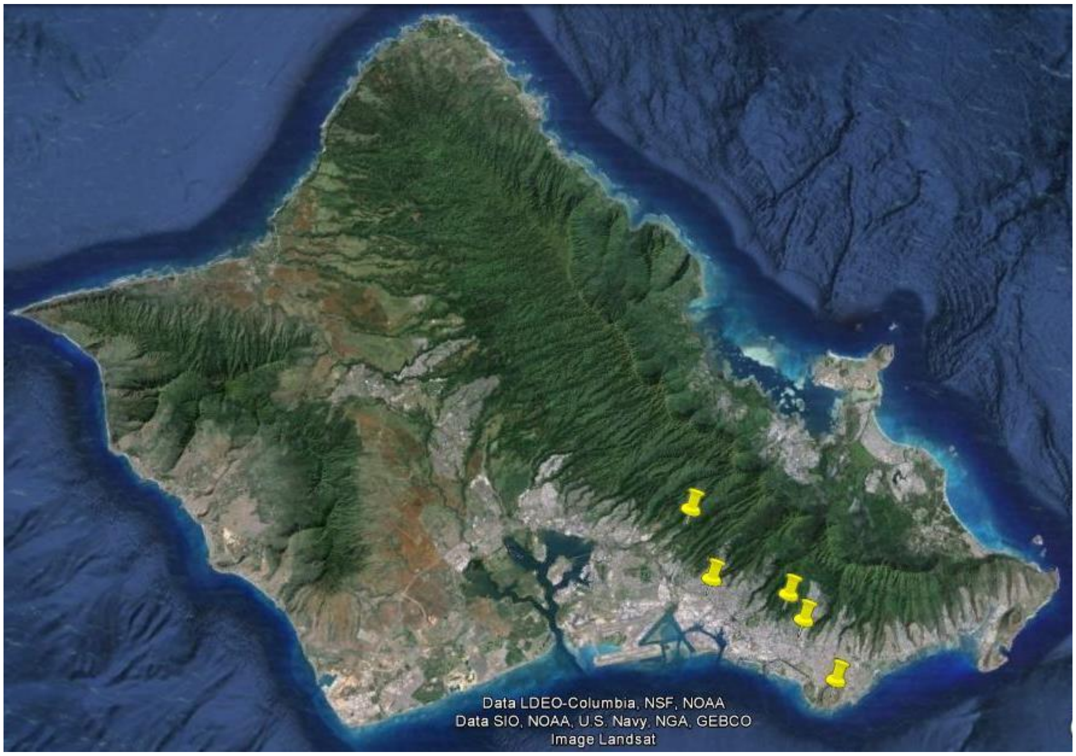


Fig. 4.1. Urban landscapes on Oahu, Hawai‘i where surveys of lobate lac scale were conducted.

CHAPTER 5. Overall Conclusions and Future Directions

The Hawaiian Islands are renowned for their aesthetically appeasing tropical landscapes, and trees are a major feature in many urban areas. There is a diversity of landscape trees established in Hawaiian urban areas, sourced from all over the world.

Ficus spp. are important landscape trees in tropical and sub-tropical regions of the world, and are widespread in the landscape and natural areas of Hawai‘i. These *Ficus* species are subject to attack from pest insects and diseases. The major insect pests of ficus trees in Hawai‘i are the Chinese banyan leaf gall wasp, *Josephiella microcarpae*, Chinese banyan stem gall wasp, *Josephiella spp*., (Hymenoptera: Chalcidoidea: Agaonidae), lobate lac scale, *Paratachardina pseudolobata* Kundo and Gullan (Hemiptera; Coccoidea: Kerriidae).

Insecticide application is one of the strategies to manage insect pests in landscape trees. Insecticides can be applied to trees in various ways such as spraying, soil drenching, and trunk injection. Among different methods of insecticide application, trunk injection is considered one of the safer and more efficient methods of applying insecticides (Doccola and Wild 2012). Trunk injection system can reduce pesticide losses caused by drifting. In addition, the trunk injection system typically uses less pesticide compared to conventional treatment methods, such as soil drenching and foliar sprays, which reduces costs associated with pesticides, health concerns and environmental impacts (Norris, 1965; Docolla and Wild, 2012).

Imidacloprid and emamectin benzoate are very commonly used systemic insecticides in the trunk injection system. Our study showed that, although both systemic insecticides had some effect against leaf gall wasp, *Josephiella microcarpae*, for up to 18 months post treatment, only emamectin benzoate had effect against stem gall wasp, *Josephiella spp.*, for up to 14 months post treatment. Phosphorous acid amendment did not provide any benefits for Chinese banyans to mitigate wasp infestations. Therefore, trunk injection of emamectin benzoate could be a feasible management strategy to control stem and leaf gall wasps on Chinese banyans in Hawai‘i, and possibly in other tropical regions of the continental U.S. where stem and/or leaf gall wasp species have established, such as Florida and California. In the other study, our finding suggested that the systemic insecticide imidacloprid delivered via trunk injection was very effective in preventing lobate lac scale infestation for at least 22 months post treatment, and also in reducing lobate lac scale infestation curatively for at least 20 months post treatment. The imidacloprid treatment using trunk injection system appears to be an effective approach to preventively and curatively manage lobate lac scale on ficus trees in Hawai‘i’s urban landscape.

Pesticide residue analysis would strengthen the findings by providing information about the residue concentration on the different plant parts, and will also help to identify the optimum pesticide residue concentration required to manage pests. Study of lifecycle and biology of these particular insect pests would support to develop new strategies for effective management. Biological control could be one of the approaches to manage the leaf and stem gall wasps. Searching for natural enemies in South-East Asia, where *Ficus microcarpa* is native, might be helpful in discovering new management strategy.

Since the native range of lobate lac scale insect is still unclear, no effective biological control agent of lobate lac scale has been identified yet. A quarantine trial of host acceptance was conducted in Florida, the parasitism by encyrtid wasps was observed but the parasitization level were very low (less than 3%) (Schroer et al., 2008). Identification of native ranges of lobate lac scale could facilitate to find potential biological control agents. Future research could include exploring biological control agents against lobate lac scape for long term management. Survey of lobate lac scale's host plant on Oahu's urban landscape has revealed 111 host plant species including 29 species native to Hawai'i and seven endangered species. To date, the lobate lac scale has not been discovered officially on Hawaiian Islands other than Oahu, but eventually they might spread to these neighbor islands. Therefore, a survey of lobate lac scale across Hawai'i islands is critically needed. Survey will be started in the near future covering the islands of Hawai'i- Maui, Kauai, Molokai, and Lanai.

References

Doccola J. J. and Wild P. M. (2012) Tree injection as an alternative method of insecticide application. Insecticides–Basic and Other Applications, ed. by Soloneski S and Larramendy M. InTech, Rijeka, Croatia, 61-78.

Norris D. M. (1965) Systemic pesticides in woody plants: Uptake. *Bulletin of the Entomological Society of America*, 11(3), 187-190.

Schroer S., Pemberton R. W., Cook L. G., Kondo T. and Gullan, P. J. (2008) The genetic diversity, relationships, and potential for biological control of the lobate lac scale, *Paratachardina pseudolobata* Kondo & Gullan (Hemiptera: Coccoidea: Kerriidae). *Biological Control*, 46(2), 256-266.