OCCURRENCE AND CONTROL OF COCONUT SCALE (ASPIDIOTUS DESTRUCTOR

SIGNORET) IN BANANAS

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ABSTRACTS

Field studies were conducted to determine the distribution of Coconut scale, *Aspidiotus destructor* Sign. in banana orchard. Populations with different densities were found year-round in the six surveyed orchards on the island of Oahu and Hawai`i. Significant reduction of infestation was found after two orchards adopted pruning culture practice. The spatial distribution within banana mat was investigated at sprayed and unsprayed orchard via Taylor's power law. Aggregative distribution (b=1.31) was found in the unsprayed field with highest infestation level among surveyed orchards. The sprayed orchard had a nearly uniform scale distribution (b=1.01) within banana cluster. Laboratory studies were conducted to evaluate insecticide compounds (diazinon, imidacloprid, pyriproxyfen and thiamethoxam) and hot water treatment as field control and quarantine control tactics. Complete control of nymphs was found in treatments of pyriproxyfen and thiamethoxam. Adults had various responses to the tested insecticides. Hot water treatments at 47 and 49°C were found successful for scale disinfestation. The minimum time requirement was 15 and 10 min for 47 and 49°C, respectively.

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INTRODUCTION

Armored scale insects (Homoptera: Diaspididae) constitute one of the most important groups of pest in agriculture, especially in tropical and subtropical regions (Rosen and DeBach 1978). These pests cause economic and cosmetic damages as well as quarantine concerns for various agricultural commodities in Hawai`i. The presence of any live or dead scale on fruit results in the fruit being downgraded or rejected from export. In addition, severe infestations cause yellow leaves, defoliation, branch dieback and tree death (Taylor and Paine 1935; Reyne 1948; Rafiq and Ghani 1972; Tabibullah and Gabriel 1973; Butani 1975; Gupta and Singh 1988; Koya et al. 1996).

Pest control for Hawai`i's banana orchards has been a combination of cultural and chemical tactics. Diazinon is the only insecticide labeled for use against homopteran pests. Coconut scale (CS, *Aspidiotus destructor* Signoret) has been considered partially or significantly controlled by biocontrol agents in most agroecosystems around the world and Hawai`i (Simmonds 1960; Cochereau 1969; Castel-branco 1972; Hagen and Chiang 1974; Gaprindashvili 1975; Wu and Tao 1976). The potential removal of diazinon has increased grower's concern with respect to CS control.

Hawai`i plantings of bananas, *Musa* spp., have increased in the past 4 years as has exported bananas, (HASS 2001). The export restrictions make CS an economic pest of bananas. The scale is a quarantine pest species for the state of California as well as for the international market in Japan. Coconut scale is the most common scale insect species that infest bananas. Latania scale (*Hemiberlesia lataniae*) and oleander scale (*A. nerii*) are also common on foliage but are rarely found on fruit. In the recent years, numerous

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phytosanitary rejections of fruit to export markets were due to the presence of CS. Fruit rejected by the state inspection officials are downgrade to local market. Destroyed of shipment occurred when the scale is found at the distant port of entry.

Because of the insect's small size and their secretive nature, the presence of an armored scale infestation often goes undetected during packing process. The adult female scales are from 0.6 to 1.1 mm in diameter whereas the 2nd-instar nymphs are usually smaller than 0.3 mm in diameter (Froggatt 1915; Williams and Watson 1988). Large numbers of first instar young, known as crawlers, usually settle on the natal leaf but also disperse on air currents. The presence of a few early instar scales is difficult to detect at the packinghouse. Other than a slight discoloration to fruit, their presence cannot be detected by the untrained employees.

Fortunately, natural enemies such as aphelinidae parasitoids and predatory coccinellids can effectively control the scale population (Beardsley 1970). Insecticides used to control scales usually includes diazinon, dimethoate, formothion, malathion, nicotine (Copland and Ibrahim. 1985; Jalaluddin and Mohanasundaram 1989; Kinawy 1991). Of these, diazinon is the only insecticide allowed for use on banana in Hawai`i. Application of oil spray to the abaxial leaf surfaces for disease control also limits the spread of CS (Pinese and Piper. 1994). However, effective CS control with insecticide is difficult and labor intensive in coconut and banana plantings (Kinawy 1991). Treatment costs for CS focused on spot treatment of fruit bunches in highly infested orchards. Diazinon treatments are usually applied upon bunch emergence.

During the 16 weeks of maturing period, the risk of infestation can be great. The use of polyethylene bunch covers reduces but not eliminates the risk. Any CS that settles on the fruit prior to placement of the bags poses potential risks for export rejections. The concern of CS infestation on fruits has elevated the importance of scale control in orchards intended for export.

The overall objectives of this project were to gain an understanding about the seasonal occurrence of CS and to evaluate potential control methods. The specific objectives were to analyze the factors affecting the CS infestation and to understand CS foliage and fruit infestations, to determine insecticide and non-chemical treatments. The dose-response analysis was conducted to establish baseline data for risk assessment.

LITERATURE REVIEW

Biology of *Aspidiotus destructor* Signoret

Coconut scale (CS, *Aspidiotus destructor* Signoret) is widely distributed in tropical and subtropical area (Froggatt 1915). A highly polyphagous species, it has been recorded on 75 genera in 45 families of plants worldwide (Borchsenius 1966). In Florida, this species was found to have over 100 hosts, including many economic important agricultural commodities and trees (Dekle 1976). Beside the primary host coconut palm, this armored scale also has been listed as a pest of banana, breadfruit, ginger, guava, mango, papaya and sugar cane (Ferris 1934; Beardsley and Gonzalez 1975; Chua and Wood 1990). CS occurs primarily on foliage, usually on the underside of leaves (Ferris 1934; Beardsley 1970). In addition to foliage, it can also occur on fruit, petiole, and peduncle.

The shape of adult CS female scales is oval to circular, fairly flat and thin. Their filaments are visible on the membranous scale (Williams and Watson 1988). Male scales are similar in color to that of females but are smaller and more oval shaped. The scales of the female diaspidid is composed of three basic materials: loose fibers secreted mainly by the pygideal glands, fluid discharged from the anus which is thought to bind the fibers together, and the larval exuviae which are incorporated into the scale at each molt (Disselkamp 1954).

Circular-shaped colonies are frequently confined to canopies of breadfruit and banana because of the large surface areas (Beardsley 1970). The circular pattern of leaf

chlorosis that results from scale feeding is distinctive and is indicative of CS infestations in banana plantations (Beardsley 1970). Also, presence of CS is fairly easily recognized by its closely packed colonies and by the semitransparent appearance of the scale armor.

The first instar nymphs, known as crawlers, are the only motile immature life stage of the life cycle. Upon hatching, the yellow crawlers disperse outward on the plant surface for 2 but usually not more than 48 h before settling to feed (Taylor and Paine 1935). Like other coccids, most crawlers settle within centimeters of where they hatch on the natal host (Koteja 1990).

With the assistance of the wind, crawlers can drift over 300 m from their initial location and still establish new colonies (Willard 1974). Air currents have been demonstrated to be an important environmental factor for armored scale dispersal. In coconut orchards, CS crawlers were trapped 50-500 m downwind and up to 1,000 m from the nearest infested palm (Reyne 1948). Based on the trapping rate, Reyne suggested that 35,000-60,000 crawlers could land on a mature coconut palm during a 24 h period. Dispersal from alternative host plants into orchards was demonstrated by Timlin (1964) and Blank et al. (1987; 1990) in the apple and kiwifruit model systems. The alternative host plants, some of which have been used as windbreaks, were found to be important sources for aerial invasion. Willard (1974) demonstrated that the numbers of crawlers in the air currents had a positive significant correlation with temperature and wind speed, and a negative correlation with relative humidity. With suitable environmental conditions, crawlers were able to establish colonies as far as 80 km away from their origin (Willard 1976).

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Transportation by animals or the commercial transport of infested plant materials

has been responsible for dispersal between distant areas(Dharmaraju and Laird 1984).

The spread of CS on Fiji islands was believed to have been on the movement of banana

vegetative propagules (suckers) (Taylor and Paine 1935). Live CS females with eggs

were once found in Louisiana on bananas imported from Honduras, suggesting that

commerce in tropical fruits could also spread this insect (Howard 1971).

The life history of CS has been well studied on coconut palm on Micronesian

islands (Taylor and Paine 1935). The species occurred year-round in tropical areas and

there were carried approximately 9 generations annually (Taylor and Paine 1935; Gupta

and Singh 1988; Tang and Qin 1991). In temperate areas of China, the CS only has 3

generations per year (Tang and Qin 1991; Zhou et al. 1993). The average life cycle for

one generation varied from 32 to 45 days depending on the environmental conditions

(Taylor and Paine 1935; Tabibullah and Gabriel 1973; Aisagbonhi and Agwu 1985).

After the crawler locates a suitable feeding site, it inserts piercing-sucking mouthparts

into the tissue and begin feeding. The legs and antennae of the crawler are lost during the

first molt. Females go through a second molt before reaching maturity, while males go

through a third molt and pupate underneath the scale. The external appearance of second

instar nymphs and adult females is similar. Male imago of CS emerges one to two days

prior to female maturation (Taylor and Paine 1935). The male lives only 1-3 d after

leaving puparium. The mouthparts are absent in the male imago but the antennae, wings,

and legs are well developed. The differentiation between sexes is distinguishable from

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the late second instar when male scales form elongated scale covers for pupation (Koteja 1990).

Successions of generations of mostly females are frequently followed by a generation of mostly of males. Taylor and Paine (1935) observed that a preponderance of males often preceded a CS outbreak. This suggested that mating plays an important role for CS. It influences the growth, reproduction and behavior of the adult female. Individuals that have not been inseminated in a given period of time stops growing, may leave their armor, and secrete abnormal wax products (Koteja 1990).

Under field conditions, females laid an average of 90-100 eggs during a 9-d oviposition period (Taylor and Paine 1935; Rafiq and Ghani 1972). Similar results were found in greenhouse studies demonstrated on coconut palms (Aisagbonhi and Agwu 1985). There was a positive correlation between the number of eggs laid per female and maximum temperature and hours of photoperiod and a negative correlation with evening relative humidity (Jalaluddin et al. 1992). The threshold temperature for egg and female development was 12.3 °C, and 10.5 °C, respectively (Tang and Qin 1991; Zhou et al. 1993).

Natural Enemies of *A. destructor*

Approximately 40 species of predators and parasites are known to attack CS worldwide (Beardsley 1970). They are mainly from two insect families: Coccinellidae (Coleoptera) and Aphelinidae (Hymenoptera). Predatory mites, predaceous thrips and

pathogens were also recorded attacking CS (Taylor and Paine 1935; Narendra and Rao 1974; Gaprindashvili 1975).

Aphytis lingnanensis and *Aphytis chrysomphali* are two common parasitoids associated with CS in Hawai'i (Beardsley 1970). These two species acted in a complementary manner to control CS. Chiu (1986) reported that the relative abundance of *A. lingnanensis* and *A. chrysomphali* fluctuated in a seasonal pattern. *Aphytis* had tremendous success in controlling armored scales in orchard agroecosystems (DeBach et al. 1971); however, parasitoids have not been as effective as predators in controlling CS outbreaks. *Aspidiotiphagus citrinus*, *Aphytis chrysomphali* in Malaysia and *Comperiella unifasciata* in Indonesia have often been found parasitizing CS during outbreaks, but their impacts were minimal (Lever 1964; Lever 1979).

Coconut scale, is under natural control in some areas, e.g. by the coccinellid *Chilocorus nigrita* in India and Sri Lanka (Simmonds 1960; Kinawy 1991), *Chilocorus politus* in Indonesia and *Pseudoscymnus anomalus* in Micronesia (Schreiner 1989). *Cryptogonus* sp., *Micraspis* sp. and *Scymnus* sp. are common predators of this insects in Philippine (Tabibullah and Gabriel 1973; Palacio 1986). *Cryptognatha nodiceps* Marshall was the most successful biological control agent against CS among all the predators and parasites introduced in Fiji (Taylor and Paine 1935). CS was rapidly controlled by the coccinellid shortly after the initial release. This oligophagous ladybird beetle attacks any instar of the host and feed upon other armored scales when the primary prey, coconut scale, is not available. The survey conducted in Hawai'i showed that *Rhyzobius lophanthae* was a predominate predator of the CS on Oahu, along with

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Telsimia nitida Chapin and *Lindorus lophanthae* (Blaisdell) (Beardsley 1970; Chiu 1986).

Efforts to control CS with introduced predators have not always been successful. In Malaysia and Mauritius, two predacious beetles, *Cybocephalus semiflavus* and *Cybocephalus* sp. (Nitidulidae), attacked CS aggressively but failed to suppress populations satisfactorily (Lever 1964; Lever 1979). Biological control of various armored scale insects has been attempted with many species of *Cybocephalus*, generally with disappointing results. Their slow feeding rate and low degree of adaptability to different scale insect hosts may be the factors (Drea 1990). In summary, different species of coccinellids have been used effectively to control CS in different localities. Their success in any given locality cannot be predicted.

Economic Importance of *A. destructor*

Coconut scale, believed to be native to the tropics of the eastern hemisphere, was described in 1869 from specimens on fronds of coconut palm (Signoret 1869). By 1902, it had reached several Caribbean islands but was not recognized as a pest until the 1950s (Goberdhan 1962). It continued to be reported in tropical regions of the eastern and western hemispheres throughout the 20th century, including Vanuatu in the Pacific in 1962 (Chazeau 1981), the Hawai'ian Islands in 1968 (Tenorio 1969) and San Andres in the Caribbean in 1974 (Mosquera 1977). In addition to the tropics, CS was found as a pest of economic importance in northern hemisphere of temperate regions such as Shanghai, China and Georgia, Russia (Dzhashi 1989; Tang and Qin 1991).

Records of complete defoliation have been observed when CS outbreak occurred in environments where natural enemies were absent (DeBach 1974). Reyne (1948) reported an unusually virulent outbreak of CS on the island of Sangi. The outbreak started in 1925 and spread over the island during the next 3 years. About 400,000 coconut palms were attacked, 300,000 of which died. In Philippines, it is the most common armored scale insect on coconut palm and is considered particularly damaging, because it attacks the fruits as well as the foliage, but it is much more damaging to palms in nurseries than to mature palms in plantations (Tabibullah and Gabriel 1973; Nafus and Schreiner 1989).

Evidence that severe infestations can reduce copra production was obtained on Principe Island (Simmonds 1960). Annual copra production had been about 1,350,0000 kg from 1946 to 1954, but fell to nearly one-third of this in 1955, three years after CS invaded the island. In Mauritius, coconut industry was almost destroyed by the CS during their first 10 years of invasion. The scale was first noticed on coconut in 1925, within 2 years, it had become a serious pest of coconut throughout the island. By 1937, the scale threatened the coconut palm with virtual extinction on the island (Rosen and DeBach 1978).

First presence of CS in the North America was documented during the 1930s. Coconut scale was a minor pest of ornamentals in Florida where the control was obtained through natural enemies introduced from Puerto Rico (Clausen 1956). CS is considered as a minor pest in environments where has abundant natural enemy complex (Butani

1975; Suresh and Mohanasundaram 1996). In addition of economic injuries, presence of CS makes agricultural commodities unacceptable for export (Pais 1973).

Control Strategies

Integrated pest management tactics against CS have been developed in several crops (Hagen and Chiang 1974; Mohyuddin and Mahmood 1993; Pinese and Piper. 1994). Control programs based on natural enemies have been applied successfully in many localities (Nafus and Schreiner 1989; Kinawy 1991; Tauili'ili and Vargo 1993). Although natural enemies provided effective control, conventional insecticides are widely used in some systems. The discovery of insecticide resistance in many important armored scale species makes it necessary to adopt integrated pest management (IPM) strategies that include biological and chemical controls. In addition, insecticide resistance management (IRM) strategies should be adopted to conserve useful pesticides.

Many different insecticides have been used for CS control. Dimethoate was effective in controlling CS on coconut palm in a large area of southern Oman. However, the practice was costly to employ because of the height of the crop. Fish-oil-rosin soap, considered to be a relatively safe treatment, was found to be highly effective in controlling CS in coconut palm nurseries in India (Jalaluddin and Mohanasundaram 1989).

Many armored scale species are commonly found sharing hosts with the CS. *C. aonidum* and *A. orientalis* often occur with the CS on coconut palms in Philippines and Florida. Usually, coconut scale is dominant in the Philippines, but outbreaks of *C.*

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aonidum have occurred (Gabriel 1976). On San Andres Island in the Caribbean,

Parlagena bennetti and *A. orientalis* occurred with CS on coconut palms and different

ones of these species were dominant in different blocks of palms (Mosquera 1977). As in

the case of *I. longirostris* and associated scale insects in the Seychelles, where multiple

species of armored scale insects share single palm host, control of one of the species

would be expected to result in an increase in others, because of reduced competition. In

such cases, armored scale insect species should be targeted simultaneously when

developing management programs.

Biological Control projects on *A. destructor* have been carried out successfully in

various areas of the world. They provide outstanding examples of the effectiveness of

biological control. Coccinellid beetles tend to be the most effective biological control

agents against *A. destructor*. *Cryptognatha nodiceps*, which introduced to Fiji, was one

of the most successful examples of classic CS biocontrol (DeBach 1974). After the

introduced parasitoids failed to suppress the CS outbreaks, the introduction of *C.

nodiceps* from Trinidad reduced the infestation to non-economic levels within few

months. The successful exportation of *C. nodiceps* rescued the copra industry in Fiji.

C. nodiceps was also used to control CS outbreaks in the island of Principe, West

Africa where CS destroyed 2/3 of the copra production prior to the predator was

introduced. It successfully brought the CS under control within the first year. Up to 285

of *C. nodiceps* was found on one tree at the population's peak high. *C. nodiceps* was also

found feeding on other species of scales on different host plants which maintained the

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population in the environment while the *A. destructor* population was very low (Simmonds 1960).

In Oman, *Chilocorus nigritus* was released to the CS heavily infested area. Rapid decline in *A. destructor* population at the investigation area was observed within the first 6 months of release. *C. migritus* established in Oman within two years and maintains *A. destructor* below damage level where pesticide treatments used to control *A. destructor* were no longer needed in the southern region of Oman (Kinawy 1991).

A. destructor was first reported on the windward side of Oahu in 1968 and probably was widespread on Oahu by the time it was discovered. Three species of coccinellid beetles, *Telsimia nitida* Chapin, *Pseudoscymnus anomalus* and *Lindorus lophanthae*, were the principle predators found attacking *A. destructor* on Oahu (Chiu 1986). These beetles were introduced into Hawai`i to combat other scale species. Two species of aphelinid parasitoids, *Aphytis lingnanensis* and *Aphytis chrysomphali*) were introduced from California in 1952 to control armored scales (Lai and Funasaki 1983). These two species were the only aphelinid parasitoids found attacking *A. destructor* in Hawai`i (Beardsley, 1970). Internal parasitoids *Aspidiotiphagus citrinus* and *Aspidiotiphagus agilior* were introduced to Hawai`i had been also recorded parasitized on *A. destructor* (Chiu 1986).

A. destructor is generally controlled by natural enemies present in Hawai`i. However, outbreaks may occur when climatic factors are favorable for the scale and unfavorable to its natural enemies (Chiu 1986). Detailed study of *A. destructor*

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population dynamics and its association with natural enemies in guava orchards was conducted by Chiu (1986).

Postharvest disinfestation. Methyl bromide was the most commonly used fumigant for controlling quarantine pests on perishable commodities; however, under the Clean Air Act, methyl bromide was declared as an ozone depleting compound in 1993, and its production and importation was expected to be phased out (Anonymous 2001). Unlike methyl bromide, heat treatments do not pose significant health and environmental risks (Couey et al. 1985).

Heat treatment is a non-chemical alternative to methyl bromide for quarantine security on some crops. It has been approved for some exported fruits and flower crop as a quarantine treatment by the U.S. Department of Agriculture's (USDA) Animal and Plant Health Inspection Service (APHIS).

Banana Morphology

Bananas are rhizomatous herbaceous plants ranging in height from 0.8 to 15 m (Turner 1994; Karamura et al. 1996). A *mat* (banana stool) consists of several plants (most commonly of different ages) growing from a shared underground *corm* (rhizome) (Stover and Simmmonds 1987) (Fig. 2.1). Each plant consists of a pseudostem (comprised of leaf petioles) and leaves. The true stem emerges through the center of the pseudostem and bears the flower and fruit. Leaf production ceases at flowering, while the plant dies back following harvest.

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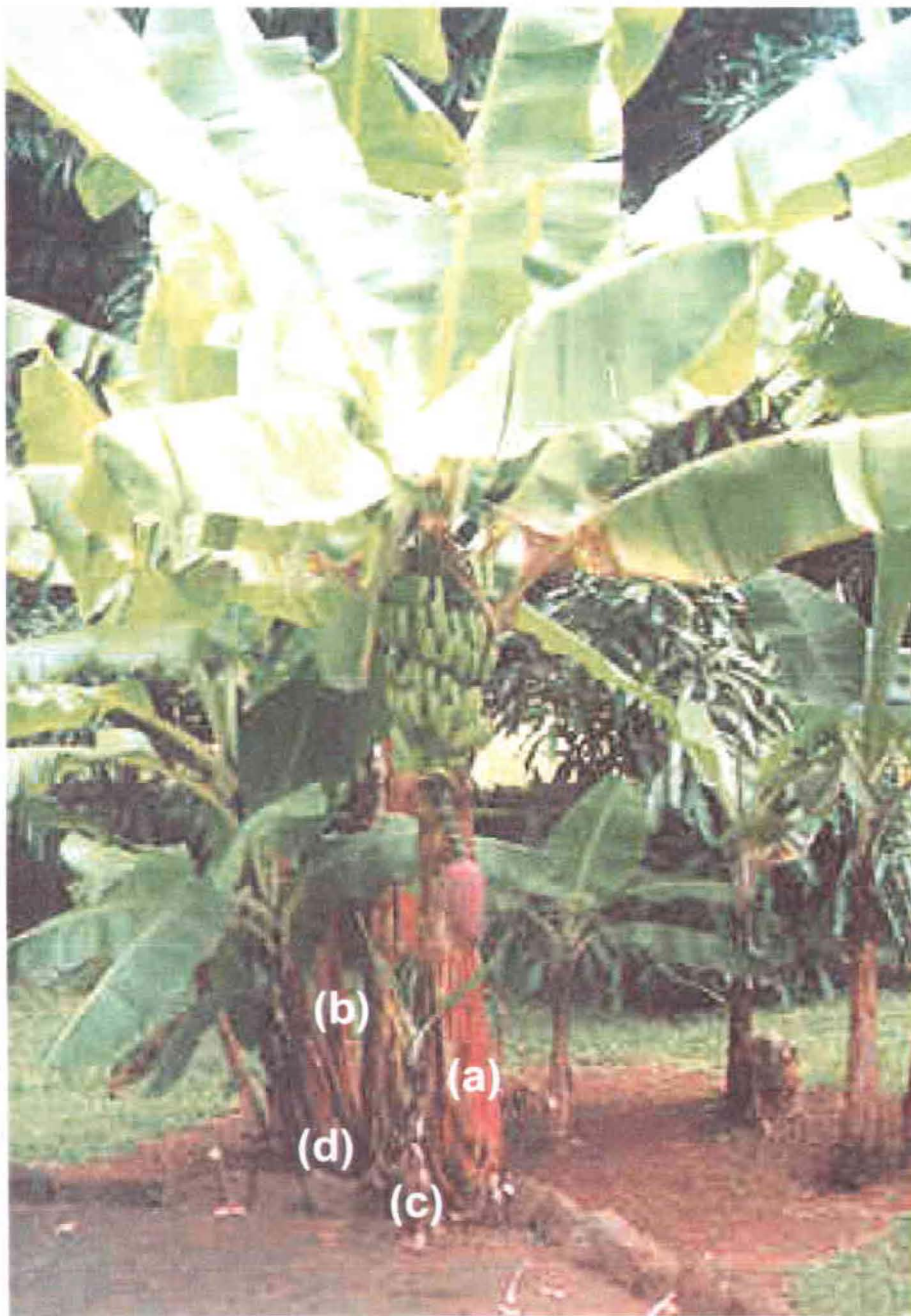
Fig. 2.1. The banana mat showing a basic structure of a flowered mother plant (a), a shooting daughter (b), a maiden sucker (c) and a sword (d).

Reproduction is vegetative through the formation of suckers emerging from the corm. These may be detached and used as planting material. Normally, a banana mat consists of three or more plant generations at any one time. The basic structure of a banana mat includes a flowered mother plant, a shooting daughter, and suckers known as maiden sucker or sword sucker. Usually, only one of these suckers is selected to grow out and regenerate the plant at commercial plantations (Robinson 1996). A single plant produces 25-50 leaves in its lifetime and normally supports 10-15 functional leaves at any one time (Nakasone and Paull 1998).

At a certain critical stage of plant development, the apical growing point at the base of the pseudostem ceases to produce young leaves and starts to develop an inflorescence (Robinson 1996). The fruits mature at 14 to 16 weeks after inflorescence emergence depending upon area and climate. In commercial terminology a "finger" is an individual fruit; each cluster of fruit is a "hand" and is attached to the stalk by a common "crown"; the "stalk" is the axis of the inflorescence and a "bunch" is the stalk with all the hand attached to the stalk; individual fruit (Fig. 2.2).
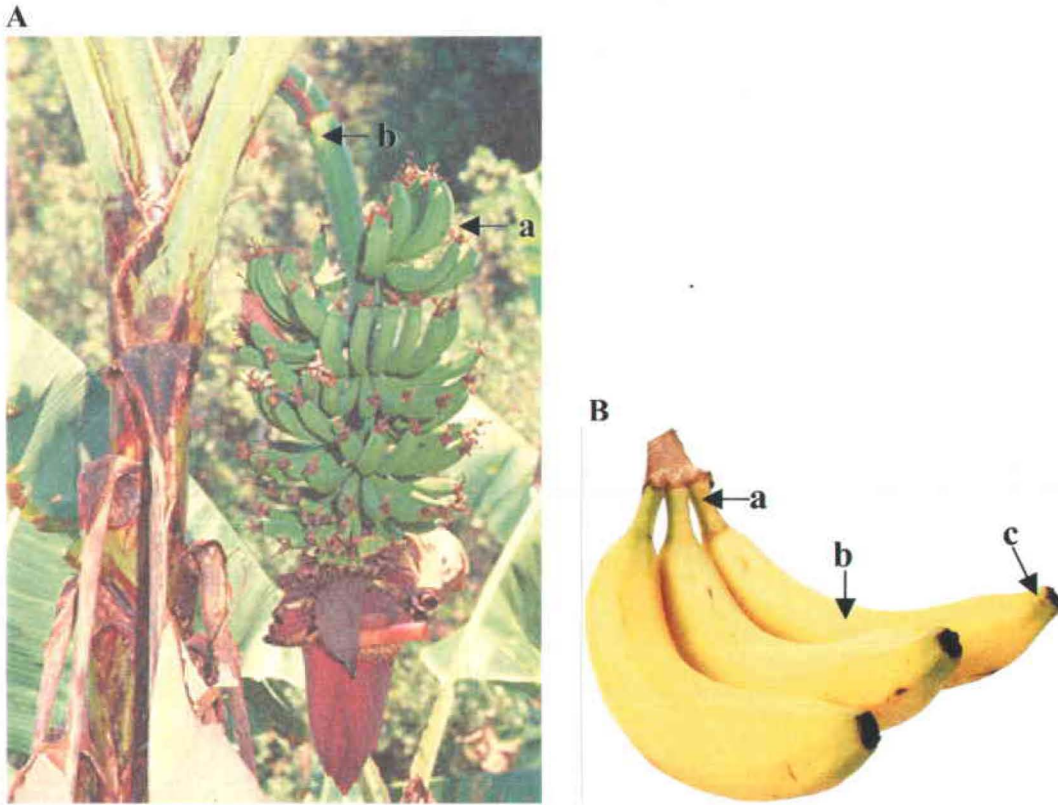
Fig. 2.2. (A) Banana bunch showing hands of bananas (a) and the stalk attached to the pseudostem (b). (B) Banana hand includes a crown connects fingers to the stalk (a), fruit (b) and tip (c).

ASPIDIOTUS DESTRUCTOR POPULATION DISTRIBUTION ON BANANAS

Introduction

Bananas, *Musa* spp. is a perennial herb grown year round in the most tropics and some sub tropical areas (Gowen 1995). Among many banana cultivars grown throughout Hawai`i, *Musa acuminata* (Cavendish subgroup) 'Williams', 'Valery', 'Chinese', and 'Grand Nain' accompany with *Musa* AAB 'Brazilian', and 'Dwarf Brazilian' are the dominant cultivars. The main production areas in Hawai`i are concentrated in the Hilo region of Hawai`i and North shore of Oahu. There is a total statewide acreage of 1550 acres, according to the survey conducted in 2000. Cavendish accounted nearly 60% of production. In 2000, banana production in Hawai`i totaled 23.5 million pounds with a wholesale value of 10.4 million dollars (HASS 2001).

Primary insect pests of Hawai`i's banana orchards are thrips (*Chaetanaphothrips signipennis, C. orchidii, Thrips hawaiiensis* and *Elixothrips brevisetis*), banana root borer (*Cosmopolites sordidus*), banana skipper (*Pelopidas thrax*) and banana aphids (*Pentalonia nigronervosa*). Fruit feeding pests include sugarcane bud moth (*Neodecadarachis flavistriata*), banana moth (Opogona sacchar) and thrips. Sugarcane bud moth and banana moth can be controlled through removing old flowers and thrips is effectively controlled with one to two applications of diazinon at bunch emergence followed by installation of bunch sleeves that remain until harvest. The CS has emerged as an economic pest of bananas destined for export markets. Although the primary importance of the CS in Hawai`i is quarantine security, economic losses caused by mass

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feeding were recorded in Fiji, Pureto Rico, Mauritius, Micronesia, Principe and New Hebrids (Rosen and DeBach 1978).

The CS is a polyphagous, cosmopolitan species, which produces 9 to 10 generations per year, depending on the host plant and location. DeBach (1971) considered CS to be under the biological control of the parasitic wasp and predatory coccinellid. Chemical and non-chemical tactics that are applied for thrips management may also be controlling coconut scale at present.

Scale infestation will result in phytosanitary rejection. Phytosanitary regulations require inspection of fruit destined for international export as well as to California. The discovery of a single CS results in the ban of the entire lot. This means that an entire 40 ft. shipping container could be downgraded at great economic loss to the shipper. Low levels of scale infestation will slow the packing process. Infested bananas are removed and held for local sales.

The CS has been studied extensively in guava to determine their field biology in Hawai'i (Chiu 1986) but no population forecasting system was developed. Management systems for predicting and preventing outbreaks require reliable methods for monitoring scale populations. Diaspidid damage threshold may be based on direct counts; for example, Shaw et al. (2000) demonstrated the efficacy and timing of insecticide by examined the scale number on apples. Alternatively, they may be based on scale incidence, expressed as the proportion of plants or plant parts infested (Nestel et al. 1995; Trumble et al. 1995; Berlinger et al. 1999). Yellow sticky traps and pheromone trapping

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is often used for estimating population densities (Gieselmann et al. 1979; Hoyt et al. 1983; Jactel et al. 1996).

An essential prerequisite to develop pest-sampling programs is an understanding of the distribution of the pest. Scale distribution within banana orchards is poorly known. The objectives for this study were to develop procedures for quantifying scale distribution on bananas. The specific goals are to gain an understanding about the seasonal occurrence of CS and to evaluate the effect of management practices on the CS infestation on banana plants.

Materials and Methods

A. destructor distribution in banana foliage

A field study was conducted on January 2000 to determine the distribution and abundance of CS in banana foliages. The study was initiated at Kahuku and Mokulēʻia on the island of Oahu where infestations were believed to be most severe. Leaf samples were collected from banana suckers, vegetative daughters, and mother plants to obtain CS colonies of varying sizes. On each sampling occasion about 40 CS colonies were collected from the canopies. Leaves were held individually in plastic bags and examined in the laboratory within 3 d.

The petiole and leaf blade were carefully examined on both the upper and lower leaf surfaces for scale using a binocular microscope to determine the number of live scales in each colony. Scales were assessed as live if they had a yellow body containing body fluids. The bodies of dead scale were dark brown or desiccated (Blank et al. 1995).

The colony diameter was measured by a circle template (2 mm-80 mm). Colonies larger than 80mm in diameter (20 samples) were measured by an area meter (Portable area meter; Li-Cor Inc., Lincoln, Nebraska) to estimate the diameter. At least nine 1-cm^2 areas in each sample were examined to determine the scale density. The total data set comprised 95 samples from two locations to ensured a wide range of scale infestation levels.

The mean density counts for each location were compared with a *two*-sample t-test. Data from three aerial shoot stages and two locations were pooled for linear regression (ANOVA) of colony diameter and relative scale density. The Waller-Duncan K-ratio *t*-test was used to separate means.

Seasonal population survey

Six commercial orchards with different management strategies and market focuses were used to compare the effects of management practices on the scale densities. Three orchards located at Kahuku, Punalu'u, and Waimānalo were local market oriented where no management program was implemented for scale control. Sites where export bananas were grown encompassed a wide spectrum of scale management practices. Plants at Kea'au and Pepe'eke'o were commercially managed and were routinely sprayed with diazinon to control scale. Each season, one to six diazinon applications were used to manage scale infestations. to control scale. Pruning practice was implemented to remove old or infested leaves at Mokulē'ia, Kea'au and Pepe'eke'o.

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Four population surveys were conducted at six commercial farms on the island of Oahu and Hawai`i during April 2000 to January 2001. Twenty mats of plants with three shoot stages (sucker, shooting daughter and mother) were marked with colored tape for repeat observation in each plot and the coordinate was recorded by GPS (e-Trex, Garmin, Olathe, KS). Three separated plots (at least 50 m apart) with total of 60 mats were designated at each farm to monitor the scale population.

A five-tier leaf infestation rating system was used to determine the CS relative abundance on banana leaves. The rating system was based on the number and size of the scale colonies per leaf. Data collected from the study conducted on January 2000 were used to define four categories of CS population density: colony diameter < 4cm; between 4 to 8cm; 8 to 12cm and >12cm in diameter. These four categories were statistically distinctive in represent the scale density in the examined samples. The rating scale was read as: 1= no infestation, 2= slight infestation, 3= medium infestation, 4= heavy infestation and 5= severe infestation (Table 3.1).

The height of banana shoots selected for sampling varied from 0.5 m to 3 m. Leaves from three growth stages were sampled to analyze the aerial distribution of the CS. Mother shoot is the stage bearing the inflorescence or fruit bunch which is usually over 3 m. Daughter shoot ranges from 1.5 m to 3 m. Sucker shoot is defined as those shoots shorter than 1.5 m bearing sword leaves. On each sampling occasion 5 leaves were picked from each of the three shoot canopies from each mat. Leaves were picked arbitrarily from the bottom of each canopy layers to determine the infestation grade.

Numbers and sizes of CS colonies on the infested leaf was measured and recorded. Infested leaves were kept on the plant for over time observation.

The model used was of a repeated measurements analysis of variance (ANOVA) on sixty mats, pooled from three replicated plots and each composed of three types of shoots from six locations. Variability between survey and location was analyzed through the error term within survey and location. Data were compared within mat to determine the differences between shoots (sucker, daughter and mother). Data were transformed to $\log_{10}$ to homogenize the variance. The Waller-Ducan K-ratio t-test was used to separate means.

To test whether the management practices were influencing scale abundance, samples of CS from Kahuku were compared with the samples from Kea'au. The means and variances of scale infestations were calculated for each mother shoot on each sampling date. Taylor's power law was used to describe the relationship between the logarithm of the variance (s^2) and the logarithm of the mean x (Taylor 1961):

$$\text{Log}_e \, s^2 = b \, \log_e \overline{x} + \log_e a,$$

where b is the slope of the regression line and a is the anti-logarithm of the intercept. The slope of Taylor's power law gives a measure of dispersion with; $b < 1$ uniform (regular); $b > 1$ aggregated (contagious); and $b = 1$ random. Regression lines were plotted together with a Poisson distribution line ($x = s^2$). The slope of the regression line was tested for significance from unity ($b = 1$) using Student t-test for the variance and mean.

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Table 3.1. *Aspidiotus destructor* infestation scale associate with colony
diameter and number of colonies.

Infestation scale	Colony diameter	Number of colonies
1=No infestation		No scale present
2=Slight infestation	< 4 cm	1 to 20
	4 to 8 cm	1 to 3 with no more than 10 colonies at < 4 cm
3=Medium infestation	4 to 8cm	4 to 10 with any number of colonies less than 4cm
	8 to 12cm	1 to 3 with no more than 3 colonies at 4 to 8cm
4=Heavy infestation	8 to 12cm	4 to 6 with no more than 8 colonies at 4 to 8cm
	> 12cm	1 to 2
5=Severe infestation	8 to 12cm	> 6 colonies
	> 12cm	> 2 colonies or one with at least 4 colonies at 8 to 12cm

Bunch infestation study

The surveys were conducted on harvested Cavendish bananas (*Musa acuminata* AAA, cultivar Williams) at an orchard in Hilo, Hawai`i over 3 months from 3 separate trails. The banana orchard was commercially managed and was under standard diazinon treatment program for scale control. A maximum of 6 foliar sprays per crop cycle and 1 to 3 bunch applications were applied upon the bunch emergence.

On each sampling occasion mature bunches from infested plants were inspected. Field surveys were conducted one week prior to the harvest in the plots where CS infestations were considered high from the field managers. A total of 60 bunches were examined on three consecutive days. Each bunch was searched thoroughly at the packing rack from the top of the bunch on the tip of fingers, fingers, crowns, and the stalk (Fig. 2.2) and the presence of CS were recorded according to their location on the fruits. A fruit had one or more scale present was defined as scale infested. Natural infestation rates were obtained by inspecting 100 bunches from all the harvest plots in each survey date. Bunch infestation rate from infested plants were compared with the natural infestation rate using the Chi-square test.

Results and discussions

CS distribution in banana foliage

Coconut scales were found on all three aerial shoots at both sample locations and colonies were only found on the lower leaf surface. These results are in agreement with others working with the CS (Beardsley 1970; Tabibullah and Gabriel 1973). The CS was highly aggregated on the banana leaves where they formed circular-shaped colonies based on the generations. In large colonies, distinctive layers of female and male bands were easily recognized with males on the inner side of the circle in each generation (Fig. 3.1).

The spatial distribution of the diaspidid can affect their responses to insecticide and natural enemies (McClure 1977; Shaw et al. 1997; Shaw et al. 2000). Among factors that determine the distribution within or between hosts, host phenology was one of the important factors that affect the within host distribution (McClure 1990; Trumble et al. 1995; Jactel et al. 1996). Infestations of *Quadraspidiotus perniciosus* (Comstock) varied significantly between the trunks, branches and fruits of host varieties (Kozar 1972; 1976). The confined CS distribution suggested that field sanitation should be considered as a central tactic for CS management. In addition to the cultural practice, spot treatment with foliar spray is expected to be an effective tactic for controlling the population.

The distinctive aggregation of males and females found in CS population was also documented in many diaspidid species, which males and females distribute themselves differently on the host plant. Females of *A. aurantii* on citrus settled most often on the

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Fig. 3.1. Circular-shaped *Aspidiotus destructor* colony with layers of aggregated females (f) and males (m).

upper surface of leaves while males usually settled on the lower surface

(Abul-Nasr et al. 1975). *Unaspis yanonensis* (Kuwana) present a fine segregation

between sexes on citrus, where females settled mainly on branches and along the

principle veins of both surfaces of leaves, while males occurred in groups on the lower

surfaces of leaves (Benassy and Pinet 1974).

No live scale was found on 12 (13%) of the Kahuku samples that were preyed by

coccinellid predators and these data were omitted from analysis. From random sampling,

50% of the samples collected were found from the mother shoots. Mother plants had a

greater chance of infestation because of their age and large canopies. Similar results

were reported on *Q. perniciosus* in the apple system where infestations were greatest on

oldest trees and least on youngest trees (Khamukov 1977). Heaviest infestation of

Lepidosaphes pallida (Green) on mango occurred in the mature leaves(Salama and

Hamdy 1973a, b).

The average numbers of scale per colony found were 1,012 (SE=238.8; n=46) and

2,379 (SE=518.2; n=49) from Kahuku and Mokulē'ia, respectively. Colony with less than

1,000 scales per colony was the majority among three aerial shoots (sucker, daughter,

mother) at Kahuku (Fig. 3.2). Most of the colonies in sucker and daughter plants from

Mokulé'ia were also in this category. The mean diameter of colonies in the category of

less than 1,000 scales per colony was 2.64cm (SE=0.19) with mean of 18 (SE=2.5) scales

per square centimeter. Meanwhile, large variation of the colony sizes was observed in

the mother shoots from Mokulē'ia. The largest colony found was 18cm in diameter with

approximately 15,000 CS.
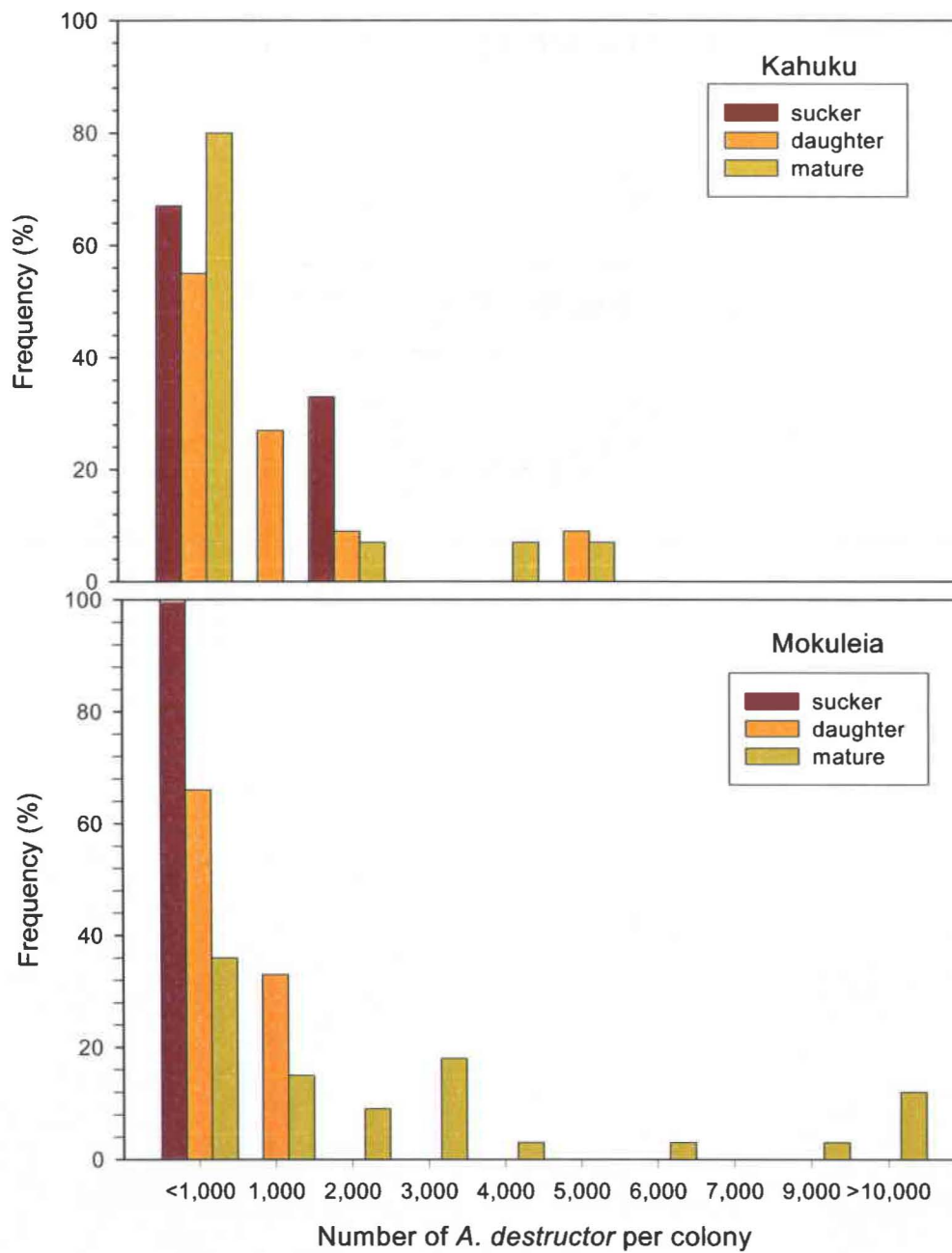
Fig. 3.2. *Aspidiotus destructor* colony in banana sucker, daughter and mother plants from Mokulē`ia and Kahuku.

Large colonies (diameter >12cm, more than 4 generations) were found in less than 10% (n=6) of the total samples indicated that there are natural factors that limited the population growth. One of the most significant factors is that of leaf maturation and senescence. During its life the plant may produce 30 or more leaves. The oldest leaves senesce at the rate of 1 every 10-12 d. No new leaves emergence once the flower stalk emerges from the pseudostem and the mature leaves produced prior to flower emergence live up to 150 d (Robinson 1996). This supports maximum of five CS generations based on a 30 d life cycle observed under field condition (Tabibullah and Gabriel 1973; Aisagbonhi and Agwu 1985). It explained few colony samples were found to have more than four generations.

Analysis of individual CS colonies using data from all three developmental shoots, multiple mats and two locations gave significant regressions for the relationship between the number of scales per colony and the colony diameter (Fig. 3.3). The highly correlated functions between these two factors suggested that colony diameter can be a visual indicator for population density.

According to the data using square root transformation , colonies were categorized according to the diameter of the colony. Four categories used here for field survey include: colony diameter < 4 cm, 72 scales per colony (SE=14.19) and 2.4cm in diameter (SE=0.11); colony diameter between 4 to 8 cm, which had an mean of 1,200 scales per colony (SE=153.9) with a colony diameter mean of 6cm (SE=0.22); colony diameter between 8 to 12 cm, an average of 9.3cm in diameter (SE=0.21) with 3,791 scales per
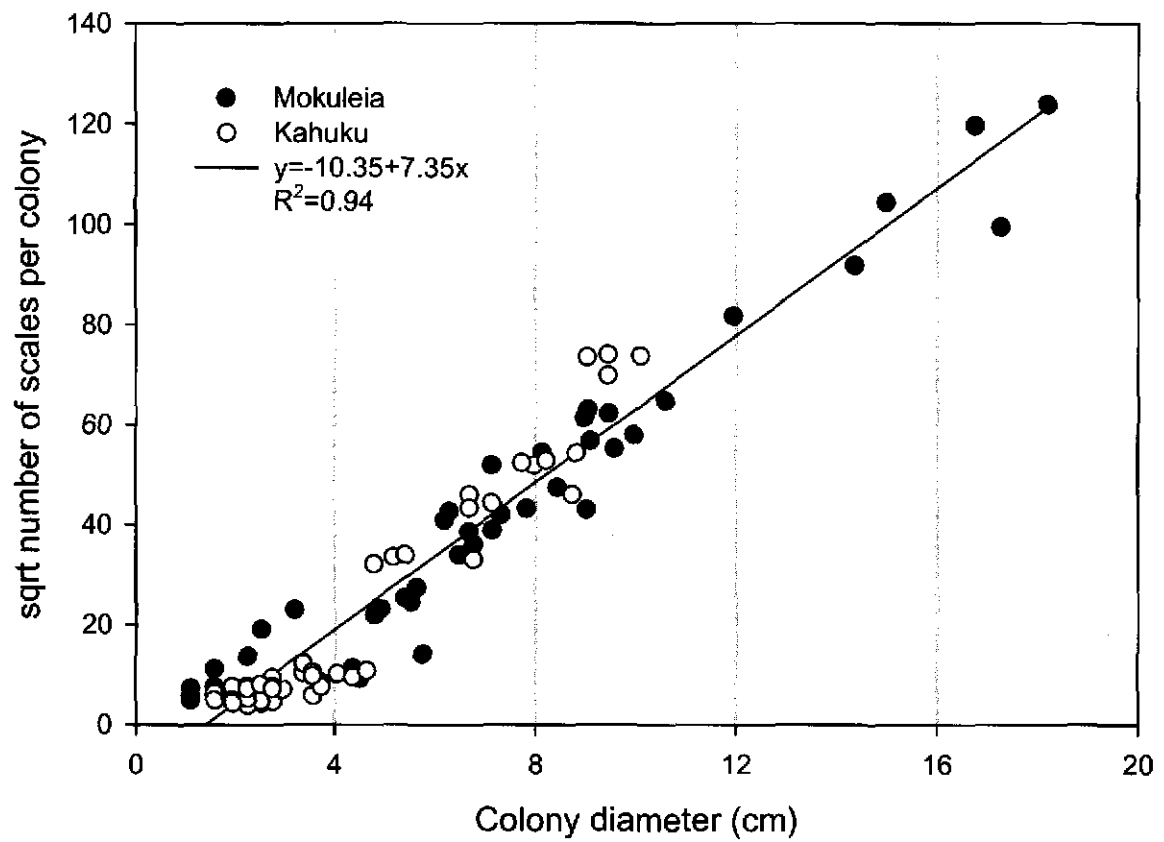
Fig. 3.3. Regression of the sqrt number of scales per colony on the colony

diameter for the *Aspidiotus destructor* comparing Mokulē'ia with Kahuku

assessment.

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colony (SE=314.39); and colony diameter over 12 cm of 11,767 scales per colony (SE=1,316.88) and mean diameter was 16.31cm (SE=0.72).

A circular-shaped chlorotic area was observed where the scales had settled. The discoloration increased with the scale density. On the mother plants, severe leaf damage exhibited by chlorotic and necrotic leaf tissue occurred CS colonies exceeded 10,000 scales per colony (Fig. 3.4A). Similar symptoms were observed on the sword suckers that had CS numbers greater than 2,000 (Fig. 3.4B). The CS density per cm^2 from the severely infested (dead tissue) sword suckers and mother plants (n=6) did not differ significantly (t=2.1, df=4, P=0.11) despite the differences of the scale numbers. This suggested that CS population density determined whether sever damage occurred and not *the total numbers.*

The mean scale density was 26 (SE=3.54) per cm^2 in Kahuku, where Brazilian banana was planted. Higher density was found on the Cavendish banana in Mokulē`ia with an average of 38.8 (SE=3.07) per cm^2. The scale densities from these two cultivars are significantly different (t=2.89, df=93, p=0.005). However, the significant difference cannot be ascribed to cultivar difference. Many factors in the environments may have contributed to the variation. The preference of CS between cultivars was documented in coconut and mango (Tabibullah and Gabriel 1973; Gupta and Singh 1988). Environmental factors also affect the population density. Mariau and Mallet (1999) found that CS was slightly less abundant on palms in the soil with higher levels of minerals.

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A

B

Fig. 3.4. (A) Leaf chlorosis on the mother plants and (B) dead tissue on

sucker leaf caused by *Aspidiotus destructor*.

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The colonization behavior and fitness of armored scale insects often varies a great deal among host species and varieties. Factors contribute to the variation also include weather, natural enemy density, irrigation and fertilization. Physiological responses of a host plant to changing edaphic conditions or to application of fertilizers often alters the plant's susceptibility to attack by diaspidids (McClure 1990). Mariau and Julia (1977) reported that deficiency in potassium and drier, less-shaded conditions favored the multiplication of the CS in palm. Argyriou (1976) observed that the severity of oleander scale (*Aspidiotus nerii* Bouché) infestations in olive and citrus groves in Greece may be correlated with the use of irrigation and fertilization, which create and especially favorable environment for insects. The density and structure of natural enemy complex in California coast and valley regions affected the control of *A. aurantii* (Maskell) in the citrus agro-ecosystem.

In conclusion, further research is needed to better understand factors that influence CS density on cultivars. Large colonies found on the mother plants directly increase the probability of fruit infestation. Better knowledge of the CS spatial distribution can lead to better control using pesticides and cultural methods.

Seasonal population survey

Coconut scale was the most common armored scale species found on banana leaves at all study sites on Oahu as well as Hawai'i. Latania scale (*Hemiberlesia lataniae*) and oleander scale (*A. nerii*) were occasionally found in very low density on the examined leaves. Coconut mealybug (*Nipaecoccus nipae*), a coccidae, which has a distinctive

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mussel shape and was thus readily distinguished from the CS, was common at Kahuku and present in low numbers at other locations.

Adult parasitoids that emerged from CS at survey locations were identified by Dr. J. Beardsley as *Aphytis chrysomphali*. *A. lingnanensis* is another aphelinid attacks CS in Hawai`i but was not collected during the survey. According to Beardsley (2000), *A. lingnanensis* is usually found at very low density in natural environment. Observations suggested that *A. chrysomphali* was the predominate species on bananas.

CS abundance was significantly different among plant stages. Higher infestation levels were found on the mother and daughter plants. This is consistent with generation duration and plant age. Differences of infestation level were not detected among three aerial shoots at Kahuku (p=0.09) where large variances of infestation level were found in the mother plants. The infestation rate was highest (p<0.0001) in the daughter plants which had an overall 25% (SE=0.02) of foliar infestation which also had highest infestation grade at 1.3 (SE=0.04). The infestations in mother and sucker plants were 14% (SE=0.02) and 11% (SE=0.02), respectively. No significant differences were probably caused by low numbers of infested leaves and great variance in infestation rating

Declines of infestations in the mother plants followed the armored scales spatial distribution model described in cotton and kiwifruit systems (Wilson and Room 1983; Blank et al. 2000). Initially as scale density increased, the proportion of infested leaves increased rapidly as the significant effects of aerial shoot on the infestation levels (Table

Table 3.2. Repeated-measures ANOVA table on CS infestation density in banana orchards from April 2000 to January 2001.

Source	Plot			Survey			Aerial shoot		
Locations	F	df	P>F	F	df	P>F	F	df	P>F
Punalu'u	0.34	2	0.71	0.3	2	0.74	5.18	2	0.01*
Waimānalo	0.35	2	0.71	2.11	2	0.17	4.5	2	0.04*
Kahuku	0.93	2	0.41	1.01	3	0.41	2.62	2	0.09
Kea'au	0.34	2	0.71	1.45	2	0.26	3.86	2	0.04*
Pepe'eke'o	0.61	2	0.56	12.75	2	0.001*	10.23	2	0.001*
Mokulē'ia	0.69	2	0.51	57.01	3	<0.0001*	16.86	2	<0.0001*

*Significant difference were observed within locations (P=0.05)

3.2). *Once the proportion of leaves infested becomes saturated, further increases in* scale density, there was only a small corresponding increase in leaf infestation..

Once scales become established on the leaves and survive through to the mature stage the scene is set for the release of the second generation of crawlers. Many of these crawlers settled in close proximity to the mother scale on the same leaf increased the scale density. Others dispersed to other leaves and increased the proportion of leaves infested. Scales that settle on sucker or daughter plants reproduce rapidly as the plants age and the pattern of dispersion at any shoot stage will therefore be comprised of the various scale densities. However, further aggregation of scales in the mother plants appeared to be limited by the natural regulation of scale populations from the plant itself. Banana plants are deciduous and the leaves live from 50 to 150 d (Robinson 1996) then fall at the rate of 1 every 10-12 d once the petiole collapses. Scale density reaches the severe infestation grade in the daughter leaves are most likely on the older leaves which falls once the plant mature. Hence, mother plants have a variable infestation levels that consist of highly infested leaves from the early infestation and less dense colonies that resulted from aerial invasion. Large variation of infestation on the mother plants suggested that removing infested leaves prevents CS increase within a banana mat. If CS density can be regulated before flowering, the probability of infestations to the fruit is greatly reduced.

Table 3.3. Average infestation rank (1-5) of *Aspidiotus destructor* in the six locations of the sample sites

and during the different sampling dates

Sampling date	Location mean (SE)					
	Punalu'u	Waimānalo	Kahuku	Kea'au	Pepe'eke'o	Mokulē'ia
April 00	1.01 (0.01) a	1.14 (0.04) a	1.29 (0.04) a	1.12 (0.03) a	1.28 (0.03) a	1.11 (0.01a
June 00	1.01 (0.01) a	1.18 (0.03) a	1.23 (0.05) a	1.11 (0.02) a	1.11 (0.03) b	1.37 (0.03) b
September 00	1.01 (0.01) a	1.06 (0.02) ab	1.23 (0.04) a	1.05 (0.02) a	1.11 (0.03) b	1.04 (0.01) c
January 01	NA	NA	1.07 (0.02) a	NA	NA	1.01 (0.01) c
Mean	1.01 (0.01)	1.14 (0.03)	1.19 (0.02)	1.09 (0.01)	1.15 (0.02)	1.12 (0.01)

Means followed by the same letter are not significantly different ($p > 0.05$; Waller-Ducan K-ratio t-test)

There was a significant date x infestation interaction at Mokule'ia and Pepe'eke'o. This was contributed to the implementation of pruning practice during the survey. The average infestation levels in six surveyed locations ranged from 1.01(SE=0.01) to 1.19 (SE=0.02) based on the 5 points scale (Table 3.3). The effect of sampling date was not significant at Punalu'u, Waimānalo and Kahuku where growers did not consider CS as an economic pest. No control practices were applied at these orchards and the highest mean infestation was found at Kahuku. Infestation levels from these three orchards ranged up to 30% the lowest point of 1.01 per leaf from Punalu'u. Implementation of pruning practice was deployed at Mokule'ia and Pepe'eke'o after infestations was found close or higher than Kahuku site. Significant reductions in infestation occurred after pruning practice was adopted.

Scale distribution within the unsprayed site at Kahuku had a slope of 1.3 and was significantly more clumped ($t = 2.37$, df $= 222$, $p = 0.02$) than the sprayed site at Kea'au. The slope was significantly different from unity ($p < 0.001$) indicated an aggregated distribution (Fig. 3.5). The distribution of scales from the sprayed Kea'au had a distribution close to unity (b=1.01). The degrees of infestation at the sprayed and unsprayed sites were 2.6 and 3.4 per leaf respectively. Diazinon spray treatments reduced the aggregation of scales within a mat. Pruning practice further reduced the infestation at Mokule'ia and Pepe'eke'o.
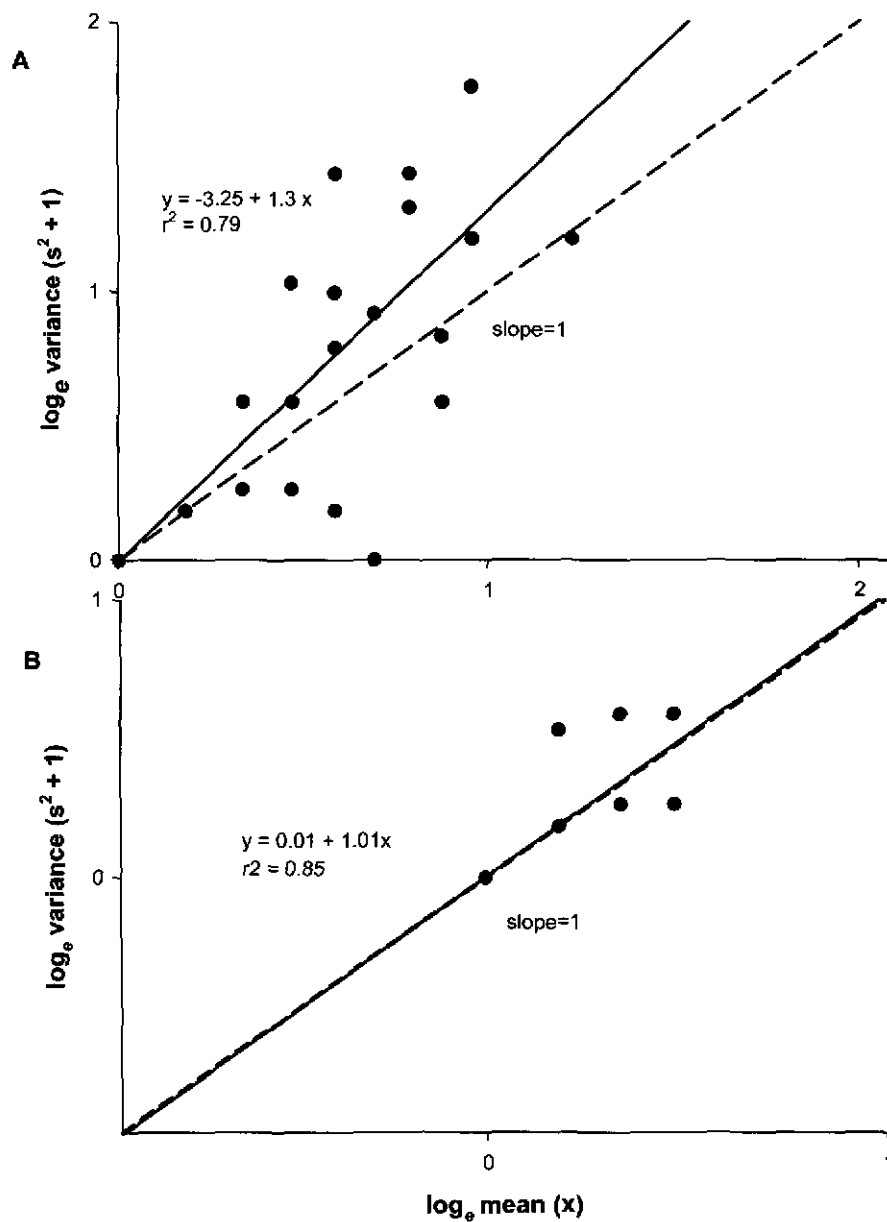
Fig. 3.5. Spatial distribution of *Aspidiotus destructor* populations on banana mother shoots at calculated using the regression of variance on mean density per leaf for the (A) Kahuku and (B) Kea'au blocks.

Bunch infestation survey

In the random bunch surveys, 20% of the bunches were found infested with CS. Most of infested bunches had no visible cosmetic damage. Only a slight blemish was associated with the adult scale. Scale numbers on infested fruits were generally low. Most of the scales were found on the tip of the fruit and near the fruit base at the crown. Some scales were found between the fingers. These scales were usually missed during inspection by workers who processed the fruit.

Bunches from infested plants showed significantly higher percentage of infested rate (x^2= 12.72, p<0.001). A total of 39% of bunches from infested plants were also infested. This supported actions to control CS using insecticidal sprays or by removing infested leaves prior to appearance of the flower. However, the difficulty for field sanitation, especially on the tall plants, and the low number of scale found on bunches suggested that a control strategy that focuses on the fruit protection would be the most economically feasible especially on those targeted for export.

PESTICIDE DOSE-RESPONSE BIOASSAYS FOR ASPIDIOTUS DESTRUCTOR CONTROL

Introduction

The adoption of integrated pest management in Hawai'i and the potential withdraw of available organophosphate using for scale insect control have resulted increasing grower concerns about these previously minor pests. Many armored scales are pests of economic importance and the damages usually include rejection of fruits destined for export market and downgrade due to cosmetic damage. These armored scale cause not only quarantine risk, but also physical damages include leaf chlorosis, defoliation, and possible plant death when the pest density is high (Beardsley 1970). To prevent the possible physical damages caused by CS to the banana, Hawai'i's banana growers have depended on broad-spectrum insecticide to control armored scale.

Cultural practices combined with natural enemy conservation and selective pesticides are important strategies in developing an IPM program for banana system. In Hawai'i, a group of natural enemies including the parasitoid *Aphytis lingnanensis* and *Aphytis chrysomphali*, as well as predatory coccinellids provide effective CS control (Beardsley 1970). Reliance on beneficial insects and natural enemies for control of coconut scale has been historically applied in many localities (Taylor and Paine 1935; Simmonds 1960; Lai and Funasaki 1983; Kinawy 1991). Diazinon has been the only pesticide registered in Hawai'i for banana pest control. However, the application of the broad-spectrum insecticide can disrupt the actions of these biological control agents

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whose susceptibility to insecticides is often greater than that of the associated pest species (Croft and Brown 1975; Morse and Brawner 1986).

Diazinon was labeled for us in banana in 1995 as Diazinon 500AG, under a section 24 (c) registration (SLN, special local needs) for use against banana aphid, *Pentalonia nigronervosa* Coquerel. Diazinon is an organophosphate insecticide which is being widely used on a variety of agricultural corps against various insect pests. However, the toxicity of diazinon is not restricted to the insect class. High toxicity has been noted with fishes and birds (Tomlin 1994). Because of the concerns about the environmental impacts from its long-term stability and effects on the wildlife, diazinon use has been withdrawn from some crops by the U.S. Environmental Protection Agency. It may not be available for agricultural purpose in the near future.

Several newly developed low human and environmental risk products are suitable for armored scale control in bananas. Insecticides have systemic mode action and reduced toxicity to beneficial insects such as growth regulators (IGR) are practical for scale control. The potential for selection of resistant populations of scale insects suggests that a careful resistance management strategy is also needed. One of the strategies of resistance management is to reduce selection pressure by rotating insecticides with different modes of action. The purpose of this study was to investigate the effects of neonicotinoids and IGR against the coconut scale, to determine relative efficacy and to establish toxicity baseline information that might be helpful in monitoring the onset of resistance.

Imidacloprid is a recently developed chloronicotinyl insecticide that exhibits both systemic and contact activity primarily against sucking insects (Mullins 1993). It has relatively low mammalian toxicity and is some beneficial insects. Because of its systemic movement, it is especially active against a range of homopteran pest species, including those already resistant to conventional insecticides (Elbert et al. 1990; Nauen et al. 1996). It is used in seed treatments, soil applications or foliar applications and its systemic properties allow it to become evenly distributed in the plant (Elbert et al. 1990). Other recently introduced neonicotinoids for insecticidal use are acetamiprid and thiamethoxam (Horowitz et al. 1998) (Maienfisch et al. 1999).

Thiamethoxam is a second-generation neonicotinoid insecticide in the subclass thianicotinyl. It has a different mode of action as imidacloprid. It has strong activity against sucking insects (Lawson et al. 1999). Thiamethoxam acts by contact and ingestion and causes insect death within short time after exposure. Although the compound does not immediately kill the sucking insects, it causes a rapid feeding cessation (Koenig et al. 1999).

Pyriproxyfen is a juvenile hormone (JH) mimic that affects the hormonal balance and chitin deposition in juvenile insect stages and causes deformation and death during molting and pupation. In some cases, this insecticide causes a strong suppression of embryogensis, metamorphosis, and adult formation (Ishaaya and Horowitz 1992). Pyriproxyfen affects larvae by preventing adult emergence and exposed adults may lay sterile eggs.

Pyriproxyfen is known to be very effective on scale insects such as California red scale, *Aonidiella aurantii* (Maskell) and coccid scales such as Florida wax scale, *Ceroplastes floridensis* Comstock (Peleg 1988). It is used commercially to control California red scale on citrus in South Africa (Hattingh and Tate 1995). It is also effective against homoptera pests such as sweet potato whitefly, *Bemisia tabaci* (Gennadius) and aphids (Devine et al. 1999).

Materials and methods

Insect Culture and Rearing. Coconut scales used in the study were reared on meristem cultured banana plantlets (Cavendish), which were held in environmental chambers at $26 \pm 2°C$ and photoperiod 16:8 (L: D) h. The original CS source was from the banana orchard at Kahuku, Oahu in 1999 where no scale management program had been implemented. Laboratory culture was obtained by transferring fertile females to laboratory cultured banana plantlets. The method was modified from Chiu and Kouskolekas (Chiu and Kouskolekas 1980). Leaf discs with mature eggs were pasted on the banana plantlet with multi-purpose glue (Glue-All, Elmer's Products, Inc., Colubbus, OH). The leaf discs were removed from the new host 48 h after scale nymphs reached the white cap stage.

Insecticides. All insecticides used were commercial formulations. Serial dilutions of the insecticides were suspended in distilled water. Diazinon (Diazinon 500AG; Prentiss Inc.), pyriproxyfen (Esteem; Valent Corporation), imidacloprid (Provado 1.6 F;

Bayer Corporation), thiamethoxam (Actara 25 WG; Norvatis Crop Protection, Inc.) were evaluated.

Toxicity Studies. Insecticide efficacy in the control of CS was compared with an application of an organophosphate insecticide and a water treatment check. Banana plantlets infested with CS were dipped in various concentrations of pesticide solutions for a complete coverage of testing compounds. Untreated checks were dipped into distilled water only. Each treatment was conducted with four replications. The plants were allowed to air dry for 10 min under room temperature. Treated plants were held at controlled conditions of $26 \pm 2^{\circ}C$, and a photoperiod of 16:8 (L:D) h.

The treatment rate for each insecticide was determined by the labeled recommendation for managing scale insects or other homopteran pests. The insecticide dilutions with water were made at a rate of 378.5 liter of spray per acre. The dose of each treatment was: diazinon 500 AG, 600ppm (16 fl. oz./acre); thiamethoxam, 100ppm (3 oz./acre); imidacloprid, 17ppm (1 fl. oz./acre); and pyriproxyfen, 67ppm (8 fl. oz./acre). Assays were carried out as described by Vehrs and Grafton-Cardwell (1994). Newly settled nymphs at white cap stage and newly emerged adult females were used for the bioassay. Samples on each plant were observed under binocular dissecting microscope and marked with a permanent black marker. The mortality of nymphs and adults were assessed 7 and 14 days after treatment, respectively. Mortality was determined by the external appearance. Dead scales appeared desiccated or discolored.

To estimate concentration-mortality regressions, at least four insecticide concentrations plus a control were used in the test for each compound. Nymphal stage

CS was targeted for the experiment. Each treatment was replicated 4 times. After preliminary toxicity tests, doses that might cause about 15 to 85% mortality were selected. Mortalities were determined 7 days after dipping treatment. The scale was regarded as dead if the external appearance matched the criteria mentioned above.

Statistical Analysis. All data were presented as mean ± SE of at least four replicates or as stated. Treatments were subjected to one-way analysis of variance (ANOVA) and means were separated by Waller-Ducan K-ratio t-tests (P=0.05). Data were corrected for natural mortality using Abbott's correction (Abbott 1925) before statistical analysis. Probit regressions were estimated with PROC PROBIT procedure using the statistics package SAS (SAS Institute 1985)

Results and discussions

Bioassay for CS insecticide susceptibility treated with recommended field rate caused high mortalities of CS nymphs and adults (Table 4.1). CS nymphs were significantly sensitive to all products. Pyriproxyfen, thiamethoxam and diazinon were the most effective treatments against CS nymphs while imidacloprid provided 80% nymphs mortality. Adult mortality obtained from four treatments varied. Pyriproxyfen showing significantly lower effectiveness on CS adult was a result of the larvacidal activity which did not effect the adult mortality.

Out of the two chloronicotinyl insecticides tested, thiamethoxam had significantly higher CS mortalities than imidacloprid on both nymphs and adults. Neither chloronicotinyl insecticide caused immediate knockdown, and oviposition was observed in both

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treatments. However, fewer eggs were observed from the imidacloprid-treated and thiamethoxam-treated females compared to untreated checks. It was known that imidacloprid has strong ovicidal activity on sweet potato whiteflies (Horowitz et al. 1998) while the effect of thiamethoxam on homopteran fecundity needs further investigation. The adult mortality obtained from imidacloprid was significantly lower than other products (Table 4.1). This was due in part to the protection from the scale armor, adult feeding rate, and concentration used in the experiment. The protective property of the scale armor limits the contact action of the toxicant. Studies on the Florida red scale, *Chrysomphalus aonidum* (L.), showed six time lesser malathion toxicity with the scale cover removed (Cohen et al. 1987). LC_{50} value obtained from thiamethoxam was slightly higher than imidacloprid on the CS nymphs (Table 4.2). In most efficacy bioassays conducted previously, thiamethoxam was usually equally or only slightly less active than imidacloprid (Maienfisch et al. 2001).

As an insect growth regulator, pyriproxyfen was highly effective against CS nymphs. Pyriproxyfen showed mild lethal effect on CS adults and eggs were absent in the treated females. Strong suppression of embryogenesis and adult emergence from pyriproxyfen were observed in homopteran such as sweet potato whitefly and pear psylla, *Cacopsylla pyricola* Foerster (Ishaaya and Horowitz 1992; Higbee et al. 1995). Treatment on adult *B. germanica* with pyriproxyfen resulted in suppression of ovary growth, immature oothecae, and nonviable eggs (Kawada et al. 1988). Treatments on nymphal stage showed molting failure. Pupation was difficult to be found from the samples treated with pyriproxyfen at various rates.

Table 4.1. Susceptibility of *A. destructor* nymphs and adults to labeled

rates treatment of diazinon, imidacloprid, pyriproxyfen and thiamethoxam.

Insecticide	Application Rate	Percent mortality (SE)	
	mmg AI / liter	Nymph	Adult
diazinon	600	99 (0.48) a	88 (2.28) a
thiamethoxam	100	100 (0) a	96 (1.51) a
pyriproxyfen	67.2	100 (0) a	39 (11.41) b
imidacloprid	17.4	83 (4.32) b	57 (16.65) b

Column means followed by the same letter did not differ significantly at

P=0.05 by Waller-Ducan K-ratio *t*-test

Series bioassay of concentration-mortality regressions showed that CS had the least susceptibility to diazinon among the four testing chemicals (Table 4.2). Although results from commercial rates provided satisfied control of CS, the high application rate may stimulate the developing of resistance in the CS.

Table 4.2. Susceptibility of *A. destructor* to diazinon, imidacloprid,

pyriproxyfen and thiamethoxam.

Insecticide	Slope (SE)	N	LC_{50}	95%C. L.	Chi-square
			mg AI/liter		
diazinon	3.55 (0.43)	1,679	23.02	17.68-27.65	1.74*
imidacloprid	5.08 (0.78)	1,552	6.48	5.64-7.34	1.26*
pyriproxyfen	2.26 (0.46)	1,828	1.32	0.36-2.39	1.65*
thiamethoxam	1.9 (0.33)	1,987	7.47	5.25-9.5	52.44

*Predicated slope not significantly different from actual at P<0.05.

HOT WATER IMMERSION FOR SCALE DISINFESTATION

Introduction

The CS occurs occasionally on bananas over the growing season, primarily appearing in clusters on the foliage. The infestation is not usually a serious constraint to production (Gowen 1995). However, CS infested fruit bunches can result in economic losses for growers who depend on the export market. The loss results from the rejection of the entire shipment by foreign, federal and state quarantine inspectors. Losses are less if the shipment has not left from the farm as the fruit can be sold to the local vendors. Losses of entire shipment occur when CS is found at the distant port of entry. The shipment would need to be destroyed or trans-shipped elsewhere.

To obtain scale-free produce for export, Hawai'i banana growers rely on conventional chemical control to prevent the scale from infesting the fruit bunch. Currently, a maximum of 6 applications of diazinon (Diazinon AG 500, Prentiss Inc.) is allowed per crop cycle to banana. Some growers make 1-3 diazinon applications to bunches during the period from anthesis to blossom senescence when the petals are removed and a polyethylene shroud is installed. The applications can be applied only prior to the installation of polyethylene shrouds. Fruits under the shrouds remain vulnerable to scale invasion during the fruit maturation if crawlers can gain entry.

CS feeding results in fruit discoloration, a relatively minor direct injury (Fig. 5.1). Presence of CS is one of the main causes of rejection of shipment destined for export markets (Anonymous 1997; Anonymous 1999). Banana exporters rely on scrubbing the fruits with soapy water and a scouring pad to remove the scales. This practice does not

Fig. 5.1. *A. destructor* settled near apical tip of banana fruit.

guarantee pest-free produces and is both time-consuming and labor-intensive. Studies

on various commodities showed that chemical treatment such as pesticide dip provided

pest mortality of only 65% to 95% of the tested diaspidid pests (Reinert 1974; Hansen et

al. 1992). Chemical treatment does not provide acceptable quarantine security.

Current quarantine treatments approved by the U.S.D.A. Animal and Plant Health

Inspection Service (APHIS) against surface pests such as mealybug and scale insect on

perishable fruit commodities include methyl bromide fumigation and hot water

immersion (HWI) treatment (Anonymous 2002). For many insects the lethal temperature

for short-term exposure is between 40 and 50 °C (Chapman 1969). The efficacy of HWI

is determined upon the commodity and target pest species. Hara et al. (1993)

demonstrated complete disinfection of *Pseudaulacaspis cockerelli* at 49°C water

exposure for 5 to 6 min on bird of paradise, *Strelitzia reginae* Ait., without significant

impact on the vase life. Additionally, 99.9% reduction of green scale, *Coccus virdis*

(Green) crawlers and adults on cape jasmine, *Gardenia jasminoides* Ellis, was obtained

through HWI for 10 min at 49°C water (Hara et al. 1994). Mealybugs require longer

treatment times which is probably due to the increased wax secretion (Hara et al. 1997).

In Persian limes, *Citrus latifolia* Tanaka, a 20-min 49°C HWI treatment is effective in

disinfesting *Planococcus citri* Risso and *Pseudococcus odermatti* Miller & Williams

(Gould and McGuire 2000). A HWI treatment in 49°C water for 12 to 15 min eliminated

>95% of mealybugs infesting red ginger flowers, *Alpinia purpurata* (Vieill.) K. Schum

(Hara et al. 1996). Lester et al. (1995) reported that longtail mealybug, *Pseudococcus*

longispinus (Targioni-Tozetti), required an estimated 19 min to reach 99% mortality on persimmons, *Diospyros kaki* L., dipped in 49°C hot water.

For bananas, hot water immersion has been used for quarantine purposes and to extend the commercial life of the fruit. Armstrong (1982) tested hot water treatments to control fruit fly eggs and larvae in bananas. A 15-min, 50°C HWI was sufficient to disinfect Brazilian bananas, *Musa acuminata* (Colla) AAB, at the probit-9 level against the fruit flies without detriment to either fruit quality or shelf life. Treatment with HWI was found effective against banana crown rot fungus (López Cabrera and Domínguez 1998; Reyes et al. 1998). In this study, HWI treatment temperature and time were evaluated as potential quarantine treatment for scale disinfestation.

Materials and methods

Banana bunches of the Brazilian cultivars, *Musa acuminata* (Colla) AAB, were acquired from banana plantation located in Kea'au, Hawai'i and studies were conducted at Waiakea Agricultural Research Station, Hilo, HI. Infested fruits were collected at the packinghouse during the de-handing process. Sample hands were cut into clusters of 3 to 4 fingers in each cluster.

Only scales without apparent signs of parasitism were selected for the tests. Samples were examined under binocular microscope prior to treatment to remove any dead and to assure that none of the scales were parasitized. Test water temperatures included 45, 47 and 49°C with test times between 0 and 20 min. Three replicates of each

treatment were done. Each treatment consisted of at least 100 scales and associated eggs on infested fingers.

The heat treatment tank was a stainless steel tank (106-liter) described by Hara et al. (1993). Constant temperature was maintained and monitored with two isotemp immersion circulators (model 730; Fisher, Pittsburgh, PA). A grid constructed of polyvinyl chloride pipe was used to hold the samples below the water surface. Water temperature was maintained within $\pm 0.1\,^{\circ}C$ of the designated temperature throughout the treatment.

Immediately after treatment, the cuttings were cooled in a water bath at ambient temperatures (25-27°C) for 5min. Controls were immersed in a water bath at ambient temperatures. After the treatments, the fruits were allowed to ripen naturally at room temperature (about 24°C). The mortality of crawlers, nymphs, and adults was assessed 1 wk after treatment to allow live scales to recover from possible heat stupor and to allow identification of dead scales. The criterion for adult scale mortality was body color. Live scales were yellow, and dead scales were brown. Numbers of live and dead adults, nymphs, and crawlers were recorded and the percentage of mortality calculated.

Data Analysis. Because numbers of eggs, crawlers, and nymphs per adult were variable, the data were pooled to ensure adequate numbers of immature stages per exposure time. Percentage of mortality was subjected to analysis of variance (ANOVA), and means were separated by Wall-Duncan k-ratio t-test (SAS Institute 1985).

Results and discussions

The 100% mortality points were reached between 47 to 49°C. At 49°C, total

mortality of CS occurring after 15, 10, and 7 min exposure, respectively (Table 5.1).

Exposure to 49°C for 7 to 15 min resulted in 100% nymph mortality. The 7-min

immersion at 49°C resulted in 3.32% (SE=1.81) adult survival rate from a total of 110

treated scales in three replicates. No CS progeny were found from all three treatments at

49°C. A 15-min immersion at 47°C caused 100% disinfestation. The results indicated

that a minimum treatment time of 7 min at 49°C or 15 min at 47°C is required for

complete CS disinfestation.

Complete mortality did not occur with 12 and 8 min exposure at 47°C (Table 5.1).

Nymphs from 47°C treatment developed into adults and oviposition was observed in

some surviving adults. At 45°C, no significant difference was found between treatments

(Table 5.1). All treatments failed to obtain probit-9 mortality. This was attributed to

large variation influenced by egg hatch after treatments. However, progeny emerged

after treatment should not be taken into account of the quarantine risk because the

unlikelihood of new colonization at the designated site. According to Beardsley &

Gonzalez (1975), the probability of crawlers establishing a new infestation by

nonpropagative plant material is unlikely because crawlers must be in close proximity to

suitable growing hosts.

The 49°C immersions caused slight fruit injury in the form of scalded tissue (Fig.

5.2). Fruit immersed at 47°C did not differ significantly in fruit appearance compared to

untreated control fruits. Large variation in fruit injury was reported and this was

Table 5.1. Mean ± SE percent mortality of *A. destructor* after HWI at 45-49°C.

Time (min)	Mean ± SE					
	49°C	n	47°C	N	45°C	N
0	0 (0) a	346	8.92 (6.78) a	64	--	--
7	96.68 (1.81) b	124	--	--	25.09 (15.42) a	313
8	--	--	49.93 (13.88) b	141	--	--
10	100 (0) c	152	--	--	43.94 (29.5) b	236
12	--	--	71.75 (6.14) b	30	--	--
15	100 (0) c	89	100 (0) c	185	42.33 (9.00) b	455
20	--	--	--	--	41.06 (14.71) b	510

Total numbers of scales treated are given in parentheses. Means in the same column followed by the same letter do not different significantly at p=0.05 by Waller-Ducan k-ratio *t*-test.

probably due to plant conditions and target cultivars. Domínguez et al. (1997) reported

delay in ripening when the cultivar, Santa Catarina Prata (AAB) was treated at 52°C for

15 min. The 52.5°C immersions caused significant fruit damage to the 'Brazilian'

banana even with short period of exposure (Armstrong 1982). Hot water temperature of

50°C in excess of 30 min gave the suitable results against oriental fruit fly (*Bactrocera*

dorsalis Hendel) in Brazilian banana without any apparent injury to the fruit (Armstrong

1982). In the trial tested against crown rot fungi, slight damage was found on the

Brazilian banana with more than 1 min of exposure and significant damage was seen after

30 min of exposure at 50°C (Reyes et al. 1998).

Based on the field survey conducted at a commercial farm, an average of 10-20% of

harvest banana bunches were infested with CS. The limited CS distribution will be

difficult to confirm probit 9 with no more than 3 survivors out of 100,000 samples. Chew

& Ouye (1985) and Jang (1991) suggested that quarantine treatments based on load or

degree of infestations would relate more realistically to a given treatment for quarantine

security than strict adherence to probit 9 security. Low degree of infestation from the

commercially grown fruit suggested that a system approach to quarantine security could

be implemented by use of field pest management and hot-water immersion (Hara et al.

1994).

Thus, with the similar equipment set up in commercial packinghouse the proposed

hot water immersion provided promising results for CS disinfestation. The similar setup

would allow fast adoption by the industry and simplify the training protocols for workers.

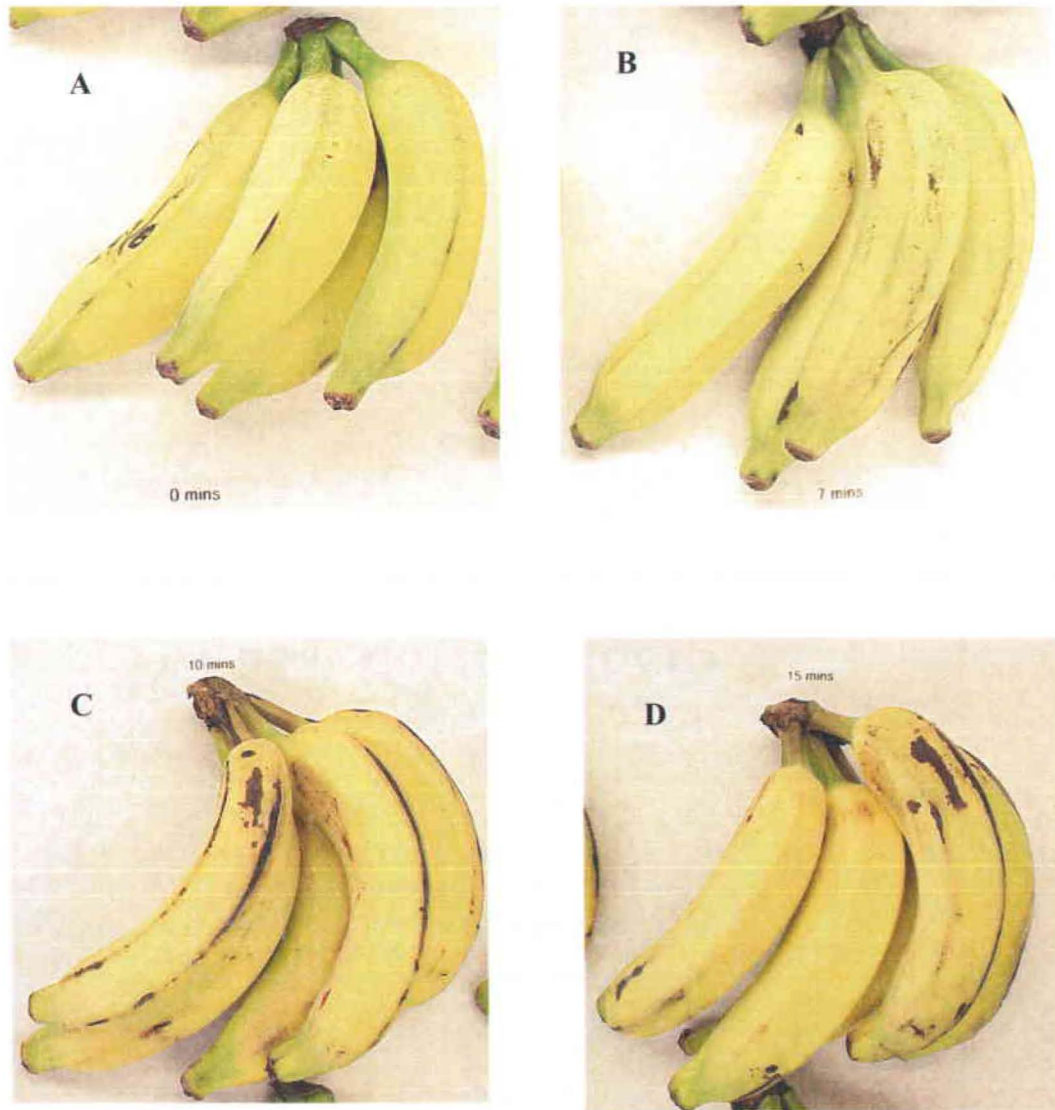Further advantages of the hot water immersion treatment over other quarantine treatments

Fig. 5.2. Brazilian banana treated at 49°C, (A) untreated control, (B) 7 min treatment, (C) 10 min treatment and (D) 15 min treatment.

include less pesticide residue, worker exposure, and waste disposal as compared with insecticidal dips after harvest; no development of pesticide resistance; and no requirement for expensive equipment as opposed to vapor-heat or irradiation treatment (Hara et al. 1993).

Additional work is needed to establish the comprehensive database for temperature x time regression in order to obtain the linear relationship between time and mortality. Data from this primary test suggested that 7-10 min at 49°C and 12-15 min at 47°C are the suitable time frame to target the probit-9 mortality.

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