JOSH GREEN, M.D.
Governor

SYLVIA LUKE
Lt. Governor

SHARON HURD
Chairperson, Board of Agriculture

DEXTER KISHIDA
Deputy to the Chairperson

State of Hawaiʻi
DEPARTMENT OF AGRICULTURE
KA ʻOIHANA MAHIʻAI
1428 South King Street
Honolulu, Hawaiʻi 96814-2512
Phone: (808) 973-9600 FAX: (808) 973-9613

December 29, 2023

Ms. Mary Alice Evans, Director
State of Hawaiʻi
Office of Planning and Sustainable Development
Environmental Review Program
235 S. Beretania Street, Room 702
Honolulu, Hawaiʻi 96813

SUBJECT: DRAFT ENVIRONMENTAL ASSESSMENT AND ANTICIPATED FINDING OF NO SIGNIFICANT IMPACT (FONSI) FOR THE PROPOSED FIELD RELEASE OF *METAPHYCUS MACADAMIAE* POLASZEK & NOYES (HYMENOPTERA: ENCYRTIDAE) FOR BIOLOGICAL CONTROL OF THE MACADAMIA FELTED COCCID, *ACANTHOCOCCUS IRONSIDEI* (WILLIAMS) (HEMIPTERA: ERIOCOCCIDAE), IN HAWAIʻI

Dear Ms. Evans:

With this letter, the Hawaiʻi Department of Agriculture (HDOA) hereby transmits the Draft Environmental Assessment and Anticipated Finding of No Significant Impact (DEA-AFNSI) for the Proposed Field Release of *Metaphycus macadamiae* Polaszek & Noyes, 2020 (Hymenoptera: Encyrtidae) for Biological Control of the macadamia felted coccid, *Acanthococcus ironsidei* (Hemiptera: Eriococcidae) for publication in the next available edition of *The Environmental Notice*.

If there are any questions, please contact Darcy Oishi, Acting Plant Pest Control Branch Manager at: (808) 973-9530 or Darcy.E.Oishi@hawaii.gov.

Sincerely,

Sharon Hurd
Digitally signed by Sharon Hurd
Date: 2023.12.27 19:09:20 -10'00'

Sharon Hurd
Chairperson, Board of Agriculture

From:	webmaster@hawaii.gov
To:	DBEDT OPSD Environmental Review Program
Subject:	New online submission for The Environmental Notice
Date:	Friday, December 29, 2023 1:11:41 PM

Action Name

Proposed Statewide Field Release of Metaphycus macadamiae Polaszek & Noyes (Hymenoptera: Encyrtidae) for Biological Control of Macadamia Felted Coccid, Acanthococcus ironsidei (Williams) (Hemiptera: Eriococcidae), in Hawaiʻi

Type of Document/Determination

Draft environmental assessment and anticipated finding of no significant impact (DEA-AFNSI)

HRS §343-5(a) Trigger(s)

- (1) Propose the use of state or county lands or the use of state or county funds
- (2) Propose any use within any land classified as a conservation district

Judicial district

Statewide

Tax Map Key(s) (TMK(s))

(9)9-9-999:999

Action type

Agency

Other required permits and approvals

USDA-APHIS-PPQ; Board of Agriculture (HDOA Plant Quarantine Branch)

Proposing/determining agency

State of Hawai'i Department of Agriculture

Agency contact name

Janis Matsunaga

Agency contact email (for info about the action)

janis.n.matsunaga@hawaii.gov

Email address or URL for receiving comments

hdoa.ppc@hawaii.gov

Agency contact phone

(808) 973-9536

Agency address

1428 S. King St.
Honolulu, HI 96814
United States
Map It

Was this submittal prepared by a consultant?

No

Action summary

The Hawaiʻi Department of Agriculture proposes the Statewide field release of Metaphycus macadamiae, a host-specific minute parasitoid wasp, in the State of Hawaiʻi for biological control of Acanthococcus ironsidei, the macadamia felted coccid (MFC). MFC, a serious pest of macadamia trees, is native to Australia and continues to threaten the macadamia nut industry in Hawaiʻi. MFC feeding causes leaves to be distorted, early flower drop, and branch die-back, leading to the death of trees and a substantial reduction in nut production. If MFC is not controlled sustainably and at the landscape level soon, it may spread throughout the State and will continue to devastate Hawaiʻi's macadamia nut industry. M. macadamiae is a monophagous parasitoid of MFC and does not pose any risk to native and beneficial species, thus making this natural enemy of MFC safe to release in the environment to control MFC in Hawaiʻi.

Reasons supporting determination

Based on the results of host specificity tests, Metaphycus macadamiae is host specific to A. ironsidei (MFC), does not pose any risk to native and beneficial species in Hawaiʻi, and is safe to release in the environment to control MFC in Hawaiʻi.
Please refer to Sections 5 (Affected Environment and Impact Assessment), 6 (Impacts on Cultural Values), & 8 (Determination) in the DEA.

Attached documents (signed agency letter & EA/EIS)

- Action-Location-Map-disclaimer.pdf
- M.-macadamiae-DEA-w-appendicies-12-27-2023.pdf
- AFNSI-M.-macadamiae-12-29-2023-signed.pdf

Action location map

- FEA-Shapefile.zip

Authorized individual

Janis Matsunaga

Authorization

- The above named authorized individual hereby certifies that he/she has the authority to make this submission.

Draft Environmental Assessment and Anticipated Finding of No Significant Impact (AFNSI) for the Proposed Statewide Field Release of *Metaphycus macadamiae* Polaszek & Noyes (Hymenoptera: Encyrtidae) for Biological Control of Macadamia Felted Coccid, *Acanthococcus ironsidei* (Williams) (Hemiptera: Eriococcidae), in Hawaiʻi

The proposed action involves the statewide release of an insect that will be able to move independently throughout the state. Therefore, no shapefile or spatial data is relevant to the action location boundary.

Field Release of *Metaphycus macadamiae* Polaszek & Noyes (Hymenoptera: Encyrtidae) for Biological Control of Macadamia Felted Coccid, *Acanthococcus ironsidei* (Williams) (Hemiptera: Eriococcidae), in Hawai‘i

Prepared by

Hawai‘i Department of Agriculture
Plant Pest Control Branch
1428 South King Street
Honolulu, HI 96814

December 2023

FIELD RELEASE OF *METAPHYCUS MACADAMIAE* POLASZEK & NOYES (HYMENOPTERA: ENCYRTIDAE) FOR BIOLOGICAL CONTROL OF MACADAMIA FELTED COCCID, *ACANTHOCOCCUS IRONSIDEI* (WILLIAMS) (HEMIPTERA: ERIOCOCCIDAE), IN HAWAI‘I

DRAFT ENVIRONMENTAL ASSESSMENT
DECEMBER 2023

PREPARED BY

HAWAI‘I DEPARTMENT OF AGRICULTURE
PLANT PEST CONTROL BRANCH
1428 SOUTH KING STREET
HONOLULU, HI 96814

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1. Background

The macadamia felted coccid (MFC), *Acanthococcus* (=*Eriococcus*) *ironsidei* (Williams, 1973) (Hemiptera: Eriococcidae), is an invasive plant-feeding pest that has devastating impacts on macadamia nut tree, *Macadamia integrifolia* Maiden & Betche (Proteaceae) health and nut yield and threatens the existence of the macadamia nut industry in Hawaiʻi. MFC is a scale insect that feeds by inserting its piercing mouth parts into macadamia nut plants and sucking phloem from the plant tissue. MFC is exceptionally pestiferous in that it can infest and feed on all above-ground parts of macadamia nut trees, including tree trunks, branches, leaves, flowers, and fruit. Their feeding causes leaves to be distorted, early flower drop, and branch die-back, leading to the death of trees and a substantial reduction in nut production. Yield losses are found to be severe even with relatively low infestations of MFC, particularly in hot dry growing areas like South Kona.

The Hawaiʻi Department of Agriculture (HDOA) initiated a Classical Biological Control project to search for potential natural enemies of MFC in its native range. In 2013, a tiny parasitoid wasp was collected in New South Wales, Australia and shipped to Hawaiʻi for research and evaluation. Host specificity studies on the effects of this parasitoid wasp on non-target organisms have been completed in the Hawaiʻi Department of Agriculture Plant Pest Control Branchʻs (HDOA-PPC) Insect Containment Facility (ICF). Results show that this parasitoid is specific to MFC.

This promising natural enemy was described as the new species *Metaphycus macadamiae* (Hymenoptera: Encyrtidae) by Polaszek and Noyes (Polaszek et al. 2020) upon HDOA's biocontrol efforts and potential release into the environment. The approved release of *M. macadamiae* on MFC-infested farms and orchards is expected to result in an effective long-term, sustainable solution for controlling MFC on macadamia nut trees in Hawaiʻi.

2. Project Summary Description

Project Name:	Field Release of *Metaphycus macadamiae* Polaszek & Noyes (Hymenoptera: Encyrtidae), for Biological Control of Macadamia Felted Coccid, *Acanthococcus ironsidei* (Williams) (Hemiptera: Eriococcidae), in Hawaiʻi
Proposing Agency:	State of Hawaiʻi Department of Agriculture
Project Location:	Statewide
Property Owner:	State of Hawaiʻi
Agency Determination:	Anticipated Finding of No Significant Impact

2.1. Executive Summary

This Draft Environmental Assessment (DEA) supports a proposed field release of a minute parasitoid wasp, *Metaphycus macadamiae* (Hymenoptera: Encyrtidae), in the State of Hawaiʻi for biological control of *Acanthococcus ironsidei*, the macadamia felted coccid, (Hemiptera: Eriococcidae). The proposing agency for this program is the State of Hawaiʻi Department of Agriculture (HDOA).

The proposed action of releasing the biological control agent involves the use of state funds and approval of permits. Therefore, in accordance with the Hawaiʻi Revised Statutes (HRS) Chapter 343, Hawaiʻi Environmental Policy Act, and the National Environmental Policy Act, the proposing agency is conducting an Environmental Assessment (EA) of the proposed project.

This Draft Environmental Assessment identifies proposed and alternative actions of the project; describes the affected physical, biological, cultural, and socioeconomic environments; and analyzes potential environmental impacts on the existing environment resulting from the proposed action.

Host specificity studies conducted in the HDOA-PPC ICF with thirteen species of non-target insects and butterfly eggs show that *M. macadamiae* is host specific to *A. ironsidei* in Hawaiʻi. Because *M. macadamiae* has been shown to be highly specific to MFC based on physiological host range testing, its release is expected to be beneficial to Hawaiʻi's agricultural economy. Therefore, the anticipated determination from this Draft Environmental Assessment is an Anticipated Finding of No Significant Impact (AFNSI).

2.2. Propose and Need for Proposed Action

The HDOA Plant Pest Control Branch (HDOA-PPC) is responsible for limiting plant pest populations that have the potential to cause significant economic damage in Hawaiʻi. HDOA's purpose for releasing *M. macadamiae* is to control MFC and suppress its damaging effects to macadamia plants thus relieving macadamia farms from the mounting cost of chemical control and losses in nut production attributable to MFC. The macadamia felted coccid is widespread on the Hawaiʻi Island (Fig. 1) where over 90% of the State's macadamia farms are located and has not yet been detected on other islands.

Commercial production of macadamia in Hawaiʻi began in the 1930s (Bennell 1984) and has grown exponentially to be the second-ranked commodity in Hawaiʻi (NASS 2017). In recent years however, local macadamia nut farmers have been struggling to compete with countries like Australia, South Africa, Kenya, and China, which are able to sell unprocessed nuts at a much lower price point. The utilized production in Hawaiʻi macadamia in 2022 totaled 37.7 million pounds, down 29% from 2021 while bearing acreage was estimated at 16,200, down 5% from 2021 (NASS 2023). Hawaiʻi macadamia farmers reported facing challenges such as MFC affecting their production (NASS 2023).

With the increase of producers all over the globe, the price per pound for Hawaiʻi grown unprocessed macadamia nuts has decreased from \$1.24/lb back in 2020 to around \$.88/lb one year later, the lowest price since 2015. Meanwhile, the costs associated with producing macadamia nuts (fuel, fertilizer, etc.) in Hawaiʻi have skyrocketed (Yerton 2022; NASS 2023).

If MFC is not controlled at the landscape level soon, it will spread throughout the State and will continue to devastate Hawaiʻi's macadamia nut industry. Current estimates of yield losses to MFC range from 40-60% in different macadamia nut varieties under various environmental conditions (Gutierrez-Coarite et al. 2021).

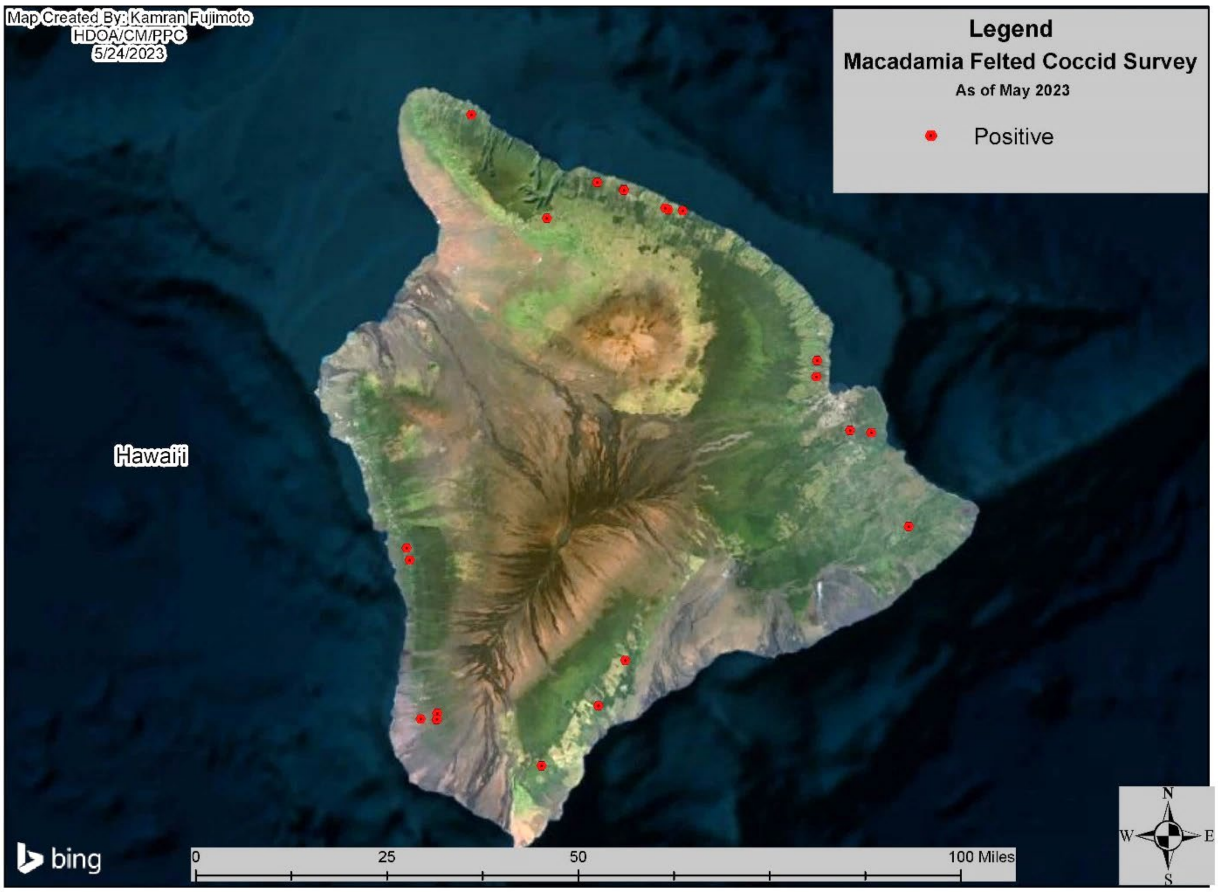


Figure 1. MFC distribution on Hawaiʻi Island (As of May 2023).

2.3. Proposed Action

HDOA proposes to release a natural enemy of MFC, the parasitoid *Metaphycus macadamiae* Polaszek & Noyes, 2020 (Hymenoptera: Encyrtidae), from quarantine containment in HDOA-PPC's ICF. This beneficial insect would be used by the applicant to control and suppress the invasive pest macadamia felted coccid, *Acanthococcus ironsidei* (Williams, 1973) (Hemiptera: Eriococcidae) in the State of Hawaiʻi.

An application will be submitted by the HDOA Plant Pest Control Branch (HDOA-PPC) to the HDOA Plant Quarantine Branch (HDOA-PQB), 1849 Auiki Street, Honolulu, HI 96819, to (1) Place *Metaphycus macadamiae* on the List of Restricted Animals (Part A) as a biocontrol agent of *A. ironsidei* by HDOA-PPC; (2) Provided *M. macadamiae* is placed on the List of Restricted Animals (Part A), allow the import and field release of *M. macadamiae* from the HDOA-PPC Insect Containment Facility into the State of Hawaiʻi, by permit, for biocontrol of *A. ironsidei* by HDOA-PPC; and (3) Provided *M. macadamiae* is placed on the List of Restricted Animals (Part A), establish permit conditions for the import and field release of *M. macadamiae* as a biocontrol agent of *A. ironsidei* by HDOA-PPC under the provisions of Hawaiʻi Revised Statutes, Chapter 141, Department of Agriculture, and Chapter 150A, Plant and Non-Domestic Animal Quarantine.

This Draft Environmental Assessment (DEA) was prepared by the applicant for the Environmental Review Program (ERP), State of Hawaiʻi Office of Planning and Sustainable Development, to comply with the provisions of Hawaiʻi Revised Statutes, Chapter 343, Environmental Impact Statements.

2.3.1. Location of Rearing Facility

Live specimens of *M. macadamiae* are reared and studied at the Insect Containment Facility (ICF) which is located at the HDOA-PPC Main Office Complex in the city of Honolulu, on the Island of Oʻahu in the State of Hawaiʻi. The address of the property is 1428 South King Street, Honolulu, Hawaiʻi 96814-2512. If *M. macadamiae* is approved for release from the ICF as a biocontrol agent, it will be removed from the ICF and brought into the HDOA-PPC Insect Rearing Facility at the same location where mass rearing will occur before official field releases can be made.

2.3.2. Release Sites and Methods of Release

While MFC is only known to be established on Hawaiʻi Island to date (December 2023), HDOA-PPC is applying for a state-wide field release should MFC be detected on other islands. Release sites on the Big Island (Hawaiʻi Island) have been selected according to the presence and abundance of MFC-infested macadamia trees. Should release permits be granted by HDOA-PQB and the United States Department of Agriculture Animal and Plant Health Inspection Station (USDA-APHIS), HDOA-PPC staff will hand carry adult *M. macadamiae* wasps in contained vials on inter-island flights from Oʻahu to Hawaiʻi Island for release at pre-selected sites. Contained adults may also be shipped from Oʻahu HDOA-PPC to HDOA-PPC Hilo staff on Hawaiʻi Island via Hawaiian Air Cargo for field release once initial releases have been made. Adult *M. macadamiae* will be released from vials directly onto MFC infested macadamia trees. Releases of *M. macadamiae* mature adults will continue to be made on infested farms until the wasp becomes well-established and widespread. The numbers of individuals to be released at each site cannot be predicted at this time, but HDOA staff will be able to mass rear individuals for field releases. Currently, there is no set timeline of release due to the length of time release permit approvals take. Once HDOA-PQB and USDA-APHIS approve releases, HDOA-PPC will prioritize initial releases on macadamia-growing farms with high infestations of MFC. Once initial releases are complete, HDOA-PPC will work with our partner agencies such as USDA-ARS and the University of Hawaiʻi to continue mass rearing and field releases on Hawaiʻi Island, and post-release monitoring studies on establishment and effectiveness of *A. macadamiae*.

2.4. Alternatives Considered

This section explains the alternative actions being considered in this EA. These actions are: (1) the No Action Alternative (No release of *M. macadamiae*) and (2) the Proposed Action (Preferred Alternative: permit issued for release of *M. macadamiae*).

2.4.1. No Action Alternative

Under the No Action Alternative, *M. macadamiae* will not be released for the control of MFC in Hawaiʻi. In the absence of releases of *M. macadamiae*, MFC populations will continually multiply to high densities unabated and remain a major pest of macadamia nut trees in Hawaiʻi. MFC will continue to be a major pest on macadamia farms on Hawaiʻi Island and will eventually spread to other macadamia farms throughout the Hawaiian Islands and potentially impact around 620 macadamia nut farms Statewide. Macadamia nut farmers will continue to rely on pesticide applications to suppress MFC populations in attempting to avoid massive economic impacts.

The continued use of chemical control, cultural control and largely ineffectual predation and parasitism at current levels would result if the "no action" alternative is chosen. Despite these management options which are variable in terms of efficacy and sustainability, MFC continues to be a major pest for macadamia farms and orchards in Hawaiʻi and continued dependence on pesticides to manage the pest would create sustainability issues for Hawaiʻi macadamia nut growers.

2.4.1.1. Chemical Control

Insect growth regulators (IGRs) and horticultural oils are insecticides used to help control MFC in Hawaiʻi. Some of these insecticides are effective against MFC but have negative impacts on natural enemies that are currently present in orchards, such as Coccinellidae. Based on studies done by Gutierrez-Coarite et al. (2017), insecticide treatments with IGR compounds are appropriate when MFC populations are high, whereas horticultural oils combined with natural enemies are most effective when populations are low. Macadamia trees are large, often attaining heights of more than 20m and canopy diameters of 16m (Bennell 1984). Insecticide applications are not only challenging in terms of achieving effective coverage but are costly in terms of product and equipment needs as well. Hawaiʻi's macadamia nut farmers are already struggling to compete with countries that can grow and sell their unprocessed nuts at a much lower price point without the added costs of pricey insecticides.

If no action is taken, use of chemicals to control MFC would continue at current levels or may even increase. This action would negatively impact not only the current resident natural enemies in macadamia orchards, but other non-targets as well (such as honeybees used for pollination, natural enemies of other macadamia nut pests). If MFC remains a major pest of macadamia nut trees in Hawaiʻi, insecticide use, the non-target effects associated with the use of those chemicals, and the costs associated with buying large quantities of insecticides and the labor to apply them, will continue to be a burden for our local growers.

2.4.1.2. Cultural Control

Cultural control is an essential component of the Integrated Pest Management system utilized by macadamia orchards in Hawaiʻi. Keeping macadamia nut trees healthy by maintaining the right soil moisture, fertilizing, cleaning, and pruning helps defend them against MFC infestation. Stressed plants are often the first to be colonized heavily by scale insects (Wright & Conant 2009). In addition, MFC infestation is heaviest in shaded positions within the orchards (Ironside, 1970) and on trees with sucker shoots (Gutierrez-Coarite et al. 2019) hence trees need to be pruned and cleaned regularly to prevent build-up of pest populations. Cultural management alone is insufficient to reduce MFC impacts. However, effective pruning encourages resident predators of MFC within orchards to utilize trees as a habitat more frequently and to prey upon MFC (Gutierrez-Coarite et al. 2019). Despite resident generalist predators providing insufficient MFC control to prevent yield losses, the practice of pruning will likely benefit *M. macadamiae* extensively once it is introduced.

Cultural control integrated with other control methods helps lower MFC populations but used alone, in the absence of specialized natural enemies, is not effective in reducing MFC impacts to below economically sustainable levels.

2.4.1.3. Existing Natural Enemies

Field surveys of natural enemies in macadamia nut orchards on Hawaiʻi Island revealed several predatory coccinellid lady beetles, *Halmus chalybeus* (Boisduval), *Rhyzobius forestieri* (Mulsant), *Sticholotis ruficeps* Weise, and *Telsimia nitida* Chapin, associated with MFC. DNA gut content analysis of the lady beetles confirmed that a number of these species feed on MFC (Gutierrez-Coarite et al. 2017). A parasitoid wasp, *Encarsia lounsburyi* (Berlese & Paoli, 1916), was first found associated with MFC infestations on Hawaiʻi Island during HDOA surveys in 2005 (Conant & Hirayama 2005). *E. lounsburyi* is recorded to parasitize a range of armored scale insects and is not host specific to MFC.

These natural enemies may play a small role in reducing low numbers of MFC, but do not prevent populations from reaching damagingly high densities. These resident species are considered generalists and the impacts they have on high MFC infestations are inadequate to reduce the pest populations below economically injurious levels (EIL). With the high MFC populations that are typical in Hawaiʻi macadamia nut orchards without an effective specialized biological control agent, the EIL will frequently be surpassed (Gutierrez-Coarite et al. 2021).

2.4.2. Proposed Action (Preferred Alternative)

Under this alternative, a permit would be issued for field release of *M. macadamiae* for the biological control of MFC in Hawaiʻi.

Research conducted by HDOA-PPC found that *M. macadamiae* is host specific to *Acanthococcus ironsidei* during laboratory host specificity tests using closely related scale insect species and other species of importance in Hawaiʻi. Releasing this parasitoid with high host specificity will result in long-term, sustainable control of MFC, one of the most destructive pests of macadamia in Hawaiʻi.

3. Target Pest Species: *Acanthococcus ironsidei* – Macadamia Felted Coccid

3.1. Taxonomy

Order:	Hemiptera
Suborder:	Sternorrhyncha
Infraorder:	Coccomorpha
Superfamily:	Coccoidea
Family:	Eriococcidae
Genus:	*Acanthococcus* (previously *Eriococcus*)
Species:	*ironsidei* (Williams, 1973)
Suggested Common Name:	Macadamia felted coccid (MFC)

3.2. Distribution

3.2.1. Native and Worldwide Distribution

Macadamia felted coccid and its host plants, *Macadamia integrifolia* and *M. tetraphylla*, are native to Queensland, Australia. Specimens reviewed by Williams (1973) in the U.S. National Museum reveal that MFC was intercepted in Hawai‘i on a shipment of *Macadamia* sp. from Australia as far back as August 1954, however, was not recorded as established in Hawai‘i until it's field discovery in 2005. In 2017, MFC was found severely infesting macadamia nut trees in South Africa (Schoeman & Millar 2018) where it is also a devastating pest to the country's macadamia nut producing industry. In Australia, MFC is only a problem in newly infested localities until natural enemies catch up to exert adequate control (Ironside 1978).

3.2.2. Present Distribution in Hawai‘i

MFC is established and has spread throughout all macadamia growing areas on Hawai‘i Island. MFC has not been detected on other Hawaiian Islands as of surveys conducted in May 2023 (Fig. 2). It has economically damaging impacts on macadamia farms with persistent, high-density infestations of bearing trees, resulting in substantial decline in nut production, with up to 60% yield losses in some macadamia nut varieties (Wright, pers comm., Gutierrez-Coarite et al. 2021). With the current control methods and the recurring population outbreaks, it is anticipated that MFC will eventually spread to other islands in the Hawaiian archipelago.

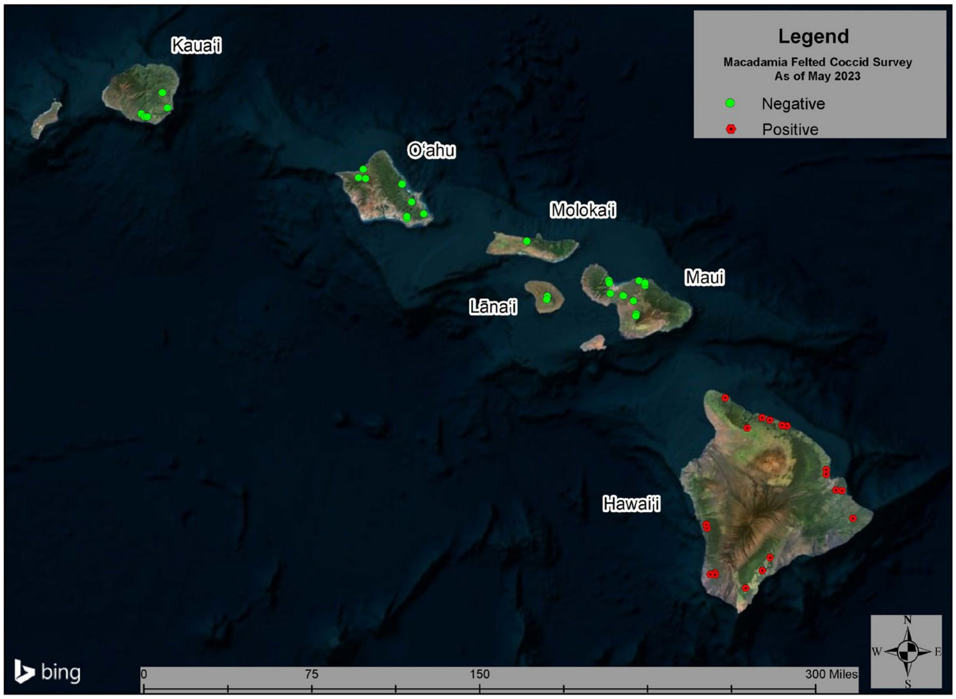


Figure 2. Statewide survey map showing MFC distribution in Hawai'i (As of May 2023).

3.3. Biology

MFC belongs to the scale insect Family Eriococcidae, the felt scales. Females (Fig. 3) pass through three juvenile stages, over an average of 32 days, before becoming a sessile adult at around 1.25 mm in length. Eggs are laid within the pale-yellow felted sacs that enclose the female bodies. Adult females can lay up to 97 eggs and are capable of producing eggs for over 50 days under laboratory conditions (Zarders & Wright 2016). The life cycle takes six weeks in the summer and many overlapping generations are produced (Swaine et. al. 1985). Adult males have wings and can fly, but they do not feed. Their sole purpose is to mate with the females. After the eggs hatch, the early instar crawlers move about on plant surfaces and are spread among trees by wind or by phoresis (hitchhiking on other insects or birds). Long distance dispersal is mainly by passive transport of infested propagative material such as budwood, scion wood cuttings and potted nursery trees (Ironside 1978).

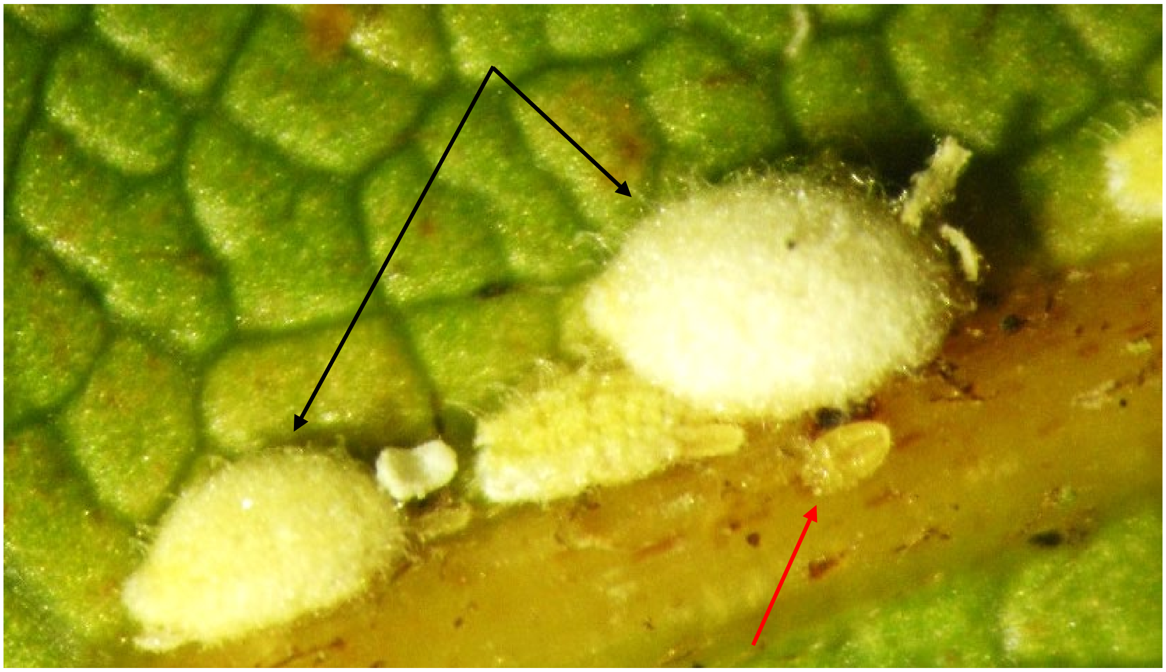


Figure 3. Image of macadamia felted coccids (*Acanthococcus ironsidei*) under magnification. Black arrows pointing to mature adult MFC females enclosed in felted sacs; red arrow pointing to immature crawler.

3.4. Host Range

Two host plant species are recorded for MFC: *Macadamia integrifolia* Maiden & Betche and *Macadamia tetraphylla* L.A.S. Johnson (Proteaceae) (Williams 1973, Zarders & Wright 2016). There are no other host records in scientific literature.

3.5. Impact in Hawai'i

MFC, a serious pest of macadamia nut trees in Hawai'i, was initially discovered infesting macadamia trees in South Kona, Hawai'i Island, in February 2005 (Conant et al. 2005). MFC is a scale insect native to Australia where it has been recorded from smooth and rough-shelled macadamia variants (Jones 2002). It is suspected to have arrived in Hawai'i on scion wood and macadamia seedlings imported from Australia.

MFC infests all above-ground parts (Figs. 4-7) of macadamia trees (Ironside 1978). MFC feeds by inserting its stylet (mouthparts) into the plant tissue and extracting plant fluids that transport nutrients within the trees. Feeding causes discoloration and distortion of plant foliage and new shoots, premature flower and nut drop, branch die back, death of seedlings, and substantial reduction in nut production. Heavy infestations cause severe damage and death to large portions of trees (Fig. 7). The adult females can be observed anywhere above ground on the macadamia tree, but they generally prefer to populate the lower branches and trunk of the tree (Gutierrez-Coarite et. al. 2017). Stressed plants are often the first to be colonized heavily by scale insects (Wright & Conant 2009). Weakened trees heavily infested by MFC are also subject to attack by stem-boring bark beetles (Scolytinae) *Xyleborus ferrugineus* and *Xylosandrus crassiusculus*, which places additional severe stress upon the trees, often resulting in branch breakages (Angel Acebes-Doria, pers comm.).

Figure 4. Infested husks of macadamia nuts.

Figure 5. MFC infested macadamia nut tree leaves and branches.

Figure 6. MFC infested macadamia nut tree trunks.

Figure 7. Dying macadamia nut tree branches due to heavy MFC infestations.

4. Biocontrol Agent to be Released: *Metaphycus macadamiae*

4.1. Taxonomy and Vouchering

Order: Hymenoptera
Superfamily: Chalcidoidea
Family: Encyrtidae
Subfamily: Encyrtinae
Genus: *Metaphycus*
Species: *macadamiae* Polaszek & Noyes, 2020
Common Name: None

Metaphycus macadamiae Polaszek & Noyes (Hymenoptera: Encyrtidae) was described by Dr. Andrew Polaszek, Dr. John S. Noyes (Natural History Museum, London, England, United Kingdom) and others (Polaszek et al. 2020) on April 8, 2020 (Appendix A). Voucher specimens were deposited in the Australian National Insect Collection, CSIRO, Canberra, Australia; Natural History Museum, London, UK; United States National Museum, Washington D.C., USA; Bernice P. Bishop Museum, Honolulu, Hawaiʻi, USA; and Hawaiʻi Department of Agriculture, Plant Pest Control Branch, Honolulu, Hawaiʻi, USA

4.2. Biology and Description

The genus *Metaphycus* comprises 466 described species (Polaszek et al. 2020) of which many play important roles as biocontrol agents of scale insects in a range of cropping systems worldwide. Species of this genus are typically primary endoparasitoids of the scale insect families Coccidae and Diaspididae (Hemiptera: Coccoidea) (Lotfalizadeh 2010, Noyes 2019).

About 30 *Metaphycus* species have been purposefully released around the world as biocontrol agents to control soft (Coccidae) and armored (Diaspididae) scale pests, including three species released in Hawaiʻi. One of the three species is known to have established in the islands, *M. stanleyi*. Six other species recorded in Hawaiʻi have arrived accidentally, most likely with their host insect.

Metaphycus macadamiae is a solitary endoparasitoid whose females oviposit a single egg into a newly molted MFC adult female (Fig. 8). The immature larval stages of the *M. macadamiae* parasitoid develop within the host MFC, killing it in the process (Fig. 9). Adult female wasps host-feed on MFC nymphs, thereby adding to the mortality of MFC attributable to the wasp. The total life cycle of *M. macadamiae* ranges from 12 to 21 days depending on ambient temperature. During warmer summer days, male *M. macadamiae* progeny begin emerging from parasitized MFC as early as 12 days after initial exposure of the agent to mature MFC. Females emerged shortly after male emergence. Results of longevity studies revealed that females lived significantly longer at an average of 33 days compared to males (8 days).

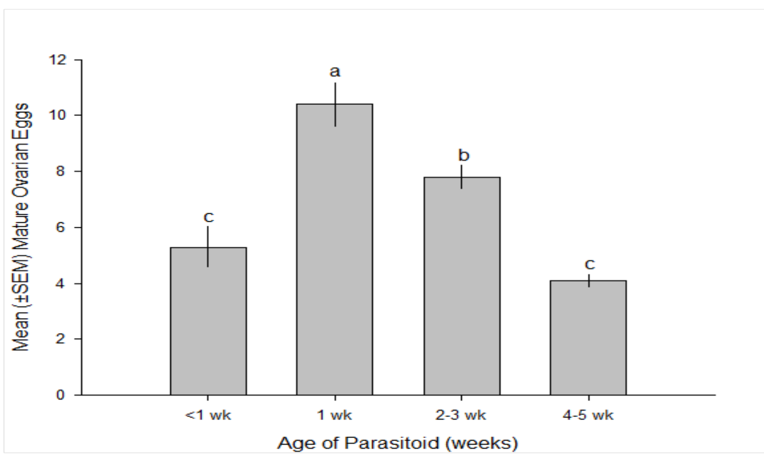
Figure 8. Female *Metaphycus macadamiae* attempting to oviposit on a teneral adult MFC female.

Figure 9. A single *M. macadamiae* larva developing inside of a dead MFC female.

The adult females range from 0.63-0.78mm in length (Polaszek et al. 2020) and are yellow-organgish in color (Fig. 10). Dissections of adult female wasps at various ages showed that egg production ranges from 1 to 3 eggs in females younger than one-week, and peaks at 14 eggs per female in mature females that are 1 week old (Fig. 12). Adult males are darker in color (Fig. 11) and smaller in size 0.46-0.66 mm (Polaszek et.al. 2020).

Figure 10. Female *Metaphycus macadamiae*.

Figure 11. Male *M. macadamiae*.



Age of parasitoid (weeks)	N	Mature Ovarian Eggs	
		Mean ± SEM	Range
<1 wk	10	5.3 ± 0.7 c	3-10
1 wk	10	10.4 ± 0.8 a	7-14
2-3 wk	10	7.8 ± 0.4 b	6-10
4-5 wk	10	4.1 ± 0.2 c	3-5

Comparison for all pairs using Tukey-Kramer HSD. (ANOVA: $F = 21.8233$; $df = 3,36$; $P < 0.0001$)

Figure 12. Average number (±SEM) of eggs per ovary at various ages of *M. macadamiae* females.

4.3. Natural Geographic Range of *Metaphycus macadamiae*

Metaphycus macadamiae was first collected in November 2013 by HDOA Exploratory Entomologist Mohsen M. Ramadan in Alstonville, New South Wales, Australia (-28.85558N, 153.44206E), then an undescribed species of *Metaphycus*, new to science. There are no records known in literature of this parasitoid from elsewhere in the world.

4.4. Field Collection Information of Founding Colony

Metaphycus macadamiae emerged from and was dissected from macadamia felted coccids on infested leaves of *Macadamia integrifolia* collected in Alstonville, NSW, Australia. Two batches of infested macadamia leaves were collected from different trees that were not known to be sprayed with insecticides and subsequently shipped to HDOA-PPC's ICF in Hawaiʻi under the United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection & Quarantine Permit to Move Live Plant Pests, Noxious Weeds, and Soil #P526P-13-03537. MFC individuals collected on the infested macadamia leaves yielded adult unidentified *Metaphycus* wasps. A colony was initiated from 55 founder *Metaphycus* sp. adults reared on macadamia nut seedlings infested with MFC at the HDOA-PPC ICF (Honolulu). Preserved specimens were sent to Dr. Andrew Polaszek and Dr. John S. Noyes of the Natural History of Museum, London, England, United Kingdom for identification and description of this new species.

4.5. Known Host Range in Country of Origin

No information was available on the host range of *M. macadamiae* in the scientific literature because it was a species not known to science. Host information of *M. macadamiae* from Australia is provided only by collections from *A. ironsidei* on *Macadamia integrifolia* during the 2013 HDOA exploration for MFC natural enemies. No host specificity testing of *M. macadamiae* was done in the country of origin (Australia).

4.6. Host Specificity Testing in Hawaiʻi

4.6.1. Non-Target Hosts Tested

Non-target species tested in host specificity assays (Table 1) were chosen by evaluating the insect taxa established in Hawaiʻi that are most closely related to the target pest (MFC, Hemiptera: Sternorrhyncha: Coccoidea: Eriococcidae: *Acanthococcus ironsidei*). This includes other members of the scale insect family Eriococcidae, all of which are adventive to Hawaiʻi, and one purposefully introduced as an invasive weed biological control agent.

Metaphycus species are mainly parasitoids of Coccidae and Diaspididae (Noyes 2019), therefore, representatives from each family were chosen as non-target test species during no-choice assays.

Because there are endemic species of scale insects in the families Halimococcidae and Pseudococcidae (Hemiptera: Sternorrhyncha: Coccoidea) Hawaiʻi, endemic species representatives were chosen from each family for non-target assays. There are no other representatives of endemic scale insect families Hawaiʻi. While other scale insect families and whiteflies are recorded as hosts of *Metaphycus* species (Noyes 2019), in Hawaiʻi, these insect families are mostly pestiferous to horticulture, agriculture, and native plant species.

Noyes (2019) lists reports of a few *Metaphycus* species parasitizing triozid psyllids (Sternorrhyncha: Psylloidea: Triozidae). There are at least 76 species of endemic psyllids in the family Triozidae described, the largest genus being *Pariaconus*. One species representative was tested during these non-target host assays. Many of the endemic psyllid species are as rare as their endemic host plant which they are dependent on in the wild, making collection and non-target testing problematic.

In total, thirteen insect species were exposed to *Metaphycus macadamiae* for non-target screening assays (Table 1), of which eight were economically important or endemic members of the Superfamily Coccoidea. The species tested included one endemic Halimococcidae, one endemic Pseudococcidae, two weed biocontrol agents (one Eriococcidae and one Dactylopiidae), and four alien pests (one Eriococcidae, one Halimococcidae, one Coccidae, and one Diaspididae). One species of invasive Aleyrodidae (Sternorrhyncha: Aleyrodoidea) and one species of endemic psyllid (Triozidae) were also tested.

It has been recorded (Noyes 2019) that some other members of family Encyrtidae (not in the genus *Metaphycus*) parasitize Lepidoptera (moths and butterflies) eggs, therefore we included three representatives of this order in our tests: one endemic and one naturalized Nymphalidae, and one beneficial Erebidae released for biological control of the invasive weeds *Senecio madagascariensis* and *Delairea odorata*.

Table 1. Non-target insect species used in host screening.

Order	Superfamily	Family	Non-target host	Status in HI	Life Stage Tested	Non-target Species' Host Plant
Hemiptera	Coccoidea	Eriococcidae	*Tectococcus ovatus* (Hempel)	Biocontrol agent	Adults & Immatures	*Psidium cattleianum*
Hemiptera	Coccoidea	Eriococcidae	*Uhleria araucariae* (Maskell)	Pest	Adults & Immatures	*Araucaria* sp.
Hemiptera	Coccoidea	Coccidae	*Saissetia oleae* (Olivier)	Pest	Adults & Immatures	*Erythrina variegata*
Hemiptera	Coccoidea	Diaspididae	*Hemiberlesia lataniae* (Signoret)	Pest	Adults & Immatures	*Macadamia integrifolia*
Hemiptera	Coccoidea	Halimococcidae	*Thysanococcus pandani* (Stickney)	Pest	Adults & Immatures	*Pandanus tectorius*
Hemiptera	Coccoidea	Halimococcidae	*Colobopyga pritchardiae* (Stickney)	Endemic	Adults & Immatures	*Pritchardia* sp.
Hemiptera	Coccoidea	Pseudococcidae	*Pseudococcus montanus* (Erhorn)	Endemic	Adults & Immatures	*Freycinetia arborea*
Hemiptera	Coccoidea	Dactylopiidae	*Dactylopius opuntiae* (Cockerell)	Biocontrol agent	Adults & Immatures	*Opuntia ficus-indica*
Hemiptera	Aleyrodoidea	Aleyrodidae	*Tetraleurodes acaciae* (Quaintance)	Pest	Adults & Immatures	*Erythrina variegata*
Hemiptera	Psylloidea	Triozidae	*Pariaconus ohiacola* (Crawford)	Endemic	Immatures	*Metrosideros polymorpha*
Lepidoptera	Papilionoidea	Nymphalidae	*Vanessa tameamea* (Eschscholtz)	Endemic	Egg	*Pipturus albidus*
Lepidoptera	Papilionoidea	Nymphalidae	*Danaus plexippus* (Linnaeus)	Adventive	Egg	*Calotropis gigantea*
Lepidoptera	Noctuioidea	Erebidae	*Secusio extensa* (Butler)	Biocontrol agent	Egg	*Senecio madgascariensis*

4.6.2. Methods

Host specificity evaluations were based on no-choice tests to maximize the probability that adult female *Metaphycus macadamiae* will accept the the non-target test species for oviposition, proving a strictly conservative non-target bioassay. The objective of no-choice tests is to determine whether *M. macadamiae* would have any negative impact on non-target species, either by feeding and/or by parasitizing non-target species, in the absence of the target pest (MFC). In other words, *M. macadamiae* is forced to either feed on and/or parasitize (via oviposition of eggs and devlopment of offspring) a non-target host if physiologically suitable, or perish.

If non-target host species tested in no-choice trials were ignored or rejected as potential hosts by *M. macadamiae* (no feeding, no oviposition, no female probing), then no further choice trials were conducted with the rejected non-target species, and no additional non-target species in the same insect family were tested. In some cases, we tested two species from a family to test.

Colonies of non-target insects on their host plants (potted seedlings) were placed in a 12” x 12” x 24” collapsible aluminum framed rearing cage (Fig. 13). These non-target species were then exposed to ten female and five male *M. macadamiae* adults placed in each cage and held until all *M. macadamiae* parasitoids died. Concurrently in another cage, a control trial was set up with one MFC infested macadamia seedling exposed to the same number of mature adult *M. macadamiae*. All macadamia control cage plants were infested with the various stages of MFC at exposure. Each test was replicated three times.

Figure 13. Example of a host specificity test replicate: Control cage (MFC infested macadamia seedling with ten female and give male *M. macadamiae* adults) (L) and non-target cage (*Tectococcus ovatus* infested strawberry guava seedling with ten female and give male *M. macadamiae adults*) (R).

If no adult *M. macadamiae* progeny emerged from the control or non-target species assays after four weeks of exposure, 100 individuals of the non-target insects and 100 MFC from the control were dissected and examined using a dissecting microscope for evidence of parasitism. Three MFC infested macadamia leaves were randomly picked from each control plant and the number of insects on each leaf was quantified. Parasitism was determined by the presence of adult wasp exit holes on individual scale insect bodies (fully developed adult *M. macadamiae* emerged from pupation within each MFC body by chewing circular exit holes), or unemerged parasitoids detected by dissection of each scale.

Three Lepidoptera non-target species were also included in host specificity tests. Parts of associated non-target species' host plant with their eggs attached were collected and placed in 15 cm x 2.5 cm Petri dishes. Five female and five male *M. macadamiae* were released inside each Petri dish. Control replicates using each non-target species eggs not exposed to *M. macadamiae* were also held. Each of the unhatched lepidopteran eggs were examined under a dissecting microscope for evidence of female *M. macadamiae* probing or oviposition scars. All tests were replicated three times.

For more details on Materials and Methods for biological studies and host specificity testing of *Metaphycus macadamiae* in the HDOA-ICF, see Yalemar et al. (2023) (Appendix B).

4.6.3. Summary of Host Specificity Results and Impact on MFC

Results of host specificity tests showed clearly that *M. macadamiae* is monophagous on *Acanthococcus ironsidei*. Zero parasitoids emerged from each of the non-target host species exposed *to M. macadamiae*. Moreover, dissections of non-target hosts after exposure to *M. macadamiae* showed no evidence of parasitism nor host-feeding. Although parasitism rates varied among MFC controls, all had some degree of parasitism and host-feeding (Fig.14). Based on the results of these tests, *M. macadamiae* is host specific on *A. ironsidei* (MFC), does not pose any risk to endemic and beneficial species in Hawaiʻi, and is safe to release in the environment to control MFC in Hawaiʻi.

These laboratory studies show that MFC parasitism rate by *M. macadamiae* can exceed 60% (Fig. 14). In addition, female wasps host-feed on MFC nymphs, thereby adding to the mortality rate of MFC attributable to the wasp. Although the number of MFC nymphs affected by each female host-feeding during its lifetime was not measured, it was observed that females consistently fed on more than one nymph.

During November 2013 exploratory sampling in Alstonville, NSW, the mean infestation rate of *Acanthococcus ironsidei* per infested *Macadamia* leaf ranged 16.7-19.9. The rate of *A. ironsidei* parasitism by *Metaphycus macadamiae* in the field ranged 21.2–32.7% in the presence of at least two observed coccinellid predators. Coccinellid predation of *A. ironsidei* reached a mean of ≥5%. *M. macadamiae* exhibited a higher parasitism rate of *A. ironsidei* on leaves than petioles of *Macadamia* (Yalemar et al. 2023).

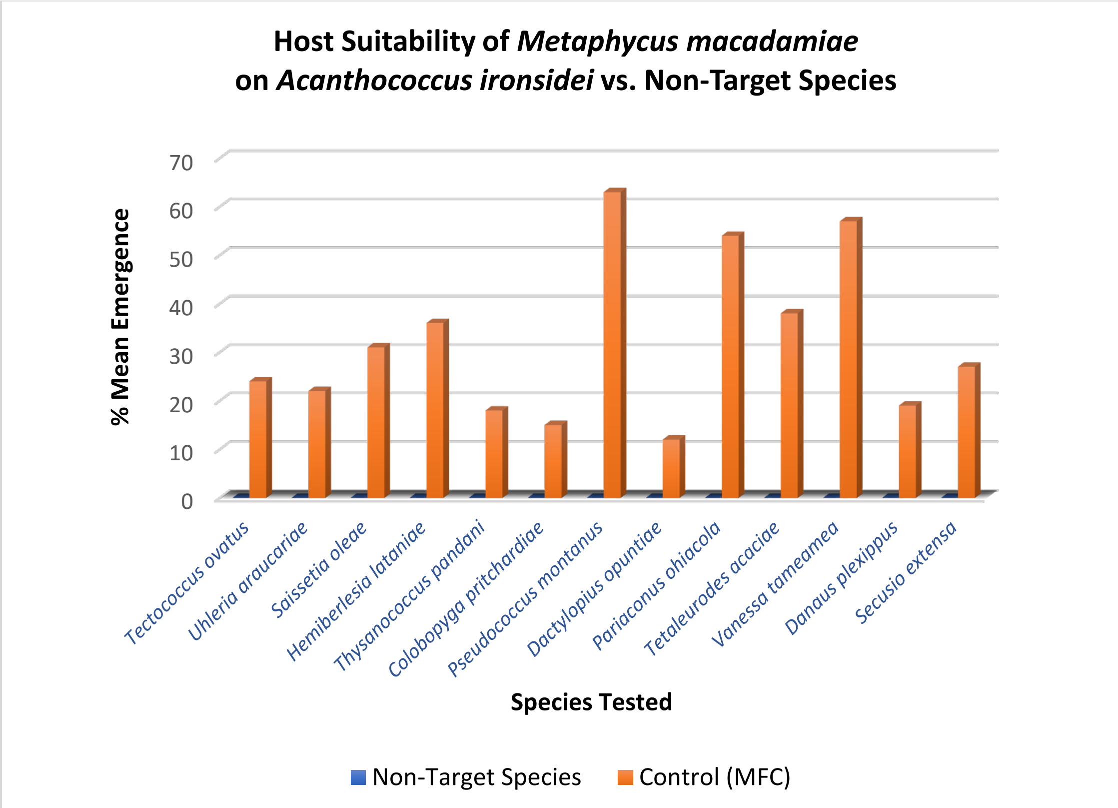


Figure 14. Parasitism rate of *M. macadamiae* on MFC compared with non-target hosts.

5. Affected Environment and Impact Assessment

The release of the MFC parasitoid *Metaphycus macadamiae* will have no negative impact on the natural environment in Hawaiʻi. This parasitic wasp is highly unlikely to produce any negative impact on the flora and fauna of Hawaiʻi, both native and beneficial species. Being monophagous (one single host species), *M. macadamiae* females will exclusively seek MFC nymphs and young adults to host-feed, and young adult MFC to parasitize. MFC will be the only organism in Hawaiʻi that will be impacted by the release of this parasitoid.

5.1. Impact of *M. macadamiae* on non-target hosts: Insects Related to *Acanthococcus ironsidei* in Hawaiʻi

Information regarding insects taxonomically and phylogenetically related to MFC is included because closely related species have the highest potential to be attacked by *M. macadamiae.* There are four species representing four separate genera in the family Eriococcidae known to be present in Hawaiʻi, including *A. ironsidei* (Nishida 2000, García Morales et al. 2016, Matsunaga et al. 2019). All species are adventive to Hawaiʻi. *Rhizococcus coccineus* (Cockerell, 1894) is a pest on cactus spines that is reported only from Kauaʻi. *Uhleria araucariae* (Maskell, 1879) is a pest which infests the needles of *Araucaria* spp. The most recent genus and species establishment of the Eriococcid family in Hawaiʻi is *Tectococcus ovatus* Hempel, 1900, a biological control agent purposefully released in 2011 targeting the invasive strawberry guava

(*Psidium cattleianum* Sabine, 1821) in Hawaiʻi. Both *U. araucariae* and *T. ovatus* were included in our non-target host screening assays with *M. macadamiae.* Neither of these non-target species were affected by the parasitoid.

5.2. Insects Related to *Metaphycus macadamiae* in Hawaiʻi

Seven species of *Metaphycus* are recorded as established in Hawaiʻi; none are native. *Metaphycus clauseni* (Timberlake, 1918), *M. helvolus* (Compere, 1926), and *M. luteolus* (Timberlake, 1916) were purposefully released as biological control agents of scale insects and mealybugs in Hawaiʻi, but establishment is unknown for all three species. *M. alberti* (Howard, 1898), *M. anneckei* Guerrieri & Noyes, 2000, *M. claviger* (Timberlake, 1916), *M. eruptor* (Howard, 1881), *M. flavus* (Howard, 1881), *M. portoricensis* (Dozier, 1926), and *M. stanleyi* Compere, 1940 were unintentionally introduced into the state but are most are known to be beneficial natural enemies of scale insect pests in Hawaiʻi.

5.3. Interactions with Established Natural Enemies and Biocontrol Agents

Several ladybeetle (Coleoptera: Coccinellidae) predators and one parasitoid, *Encarsia lounsburyi* (Hymenoptera: Aphelinidae), are known natural enemies of MFC in Hawaiʻi, but their impacts alone are insufficient to suppress MFC populations. The addition of *M. macadamiae* to the assemblage of natural enemies exploiting MFC will increase the impact on MFC at the population level, and hopefully exert adequate pressure on populations so that the pest population density is reduced to tolerable levels not causing economic damage.

5.4. Potential Impact to Threatened and Endangered (T & E) Species

Host specificity testing in the HDOA-PPC Insect Containment Facility show that *M. macadamiae* will only attack the target pest *A. ironsidei*. There will be no impact on any other insect or other fauna, or even flora in Hawaiʻi. There are no T & E species closely related to MFC in Hawaiʻi, further minimizing any potential for unexpected impacts in Hawaiʻi once *M. macadamiae* is released.

5.5. Potential of *Metaphycus macadamiae* to Act as a Hyperparasite

Metaphycus macadamiae is a newly described species therefore no records exist in the scientific literature. Other members of this genus are only known as primary endoparasitoids of scale insects, and a few species of the Encyrtidae family are recorded to parasitize eggs of some lepidopterans.

5.6. Potential Impacts on the Human Environment

Metaphycus macadamiae will pose no negative impacts to the human environment if it is released in Hawaiʻi. This microscopic parasitoid is just a fraction of the size of a sesame seed and cannot sting humans. It is harmless to humans and all other animals except MFC.

6. Impacts on Cultural Values

The Synergistic Hawai'i Agriculture Council (SHAC) prepared a Cultural Impact Assessment (CIA) for the proposed statewide release of *Metaphycus macadamiae*, which is attached as Appendix C. The CIA report was prepared in adherence with the Office of Environmental Quality Control (OEQC) *Guidelines for Assessing Cultural Impacts*, adopted by the Environmental Council, State of Hawai'i, on November 19, 1997, and pursuant to Act 50, approved by the Governor on April 26, 2000. In general, CIA studies are intended to inform environmental studies that are conducted in compliance with HRS Chapter 343. The purpose of a CIA is to gather information about the practices and beliefs of a particular cultural or ethnic group or groups that may be affected by the actions subject to HRS Chapter 343.

The primary focus of the CIA and its interviews were to identify any utilization of macadamia for Hawaiian cultural practices or community concerns over environmental impacts from the statewide release of *M. macadamiae*. Interviews included questions not just about macadamia, but larger areas and cultural practices that could be affected by the release of *M. macadamiae*.

The interviewees consulted did not explicitly oppose the use of biocontrol. Several praised the successful introduction of *Eurytoma erythrinae* to control the invasive erythrina gall wasp, *Quadrastichus erythrinae*, and therefore saving our native wiliwili trees. However, most of them expressed some concern that *Metaphycus macadamiae* could attack plants and other animals, especially in the absence of the target pest.

M. macadamiae will not 100% eliminate the target pest, it will supress infestations of MFC on macadamia trees to more manageable levels, below economic injury levels. Classical biological control is not a single silver bullet, but is a self-sustaining, long-term natural form of pest control, which maintains populations within more or less regular upper and lower limits over time.

Metaphycus macadamiae will not parasitize plants. Encyrtid wasps are host-specific parasitoids of other insects and are not physiologically able to feed and develop on plants.

As discussed in section 4.6.1., *Metaphycus* species are host specific to scale insects, particularly Diaspididae and Coccidae, with two reports of the genus parasitizing Aleyrodidae. For this reason, our non-target host tests focus on scale insects found in Hawai'i, including the most closely related endemic species. No-choice tests were conducted to simulate the absence of MFC, attempting to "force feed" non-target species to *M. macadamiae*. All individual parasitoids died with no evidence of feeding, female probing, or oviposition in/on any non-target hosts tested. Because *M. macadamiae* did not feed on, oviposit, or parasitize any closely related non-target speices presented, nor did they exhibit any interest in any other scale insect family, Lepidoptera, or psyllid presented in no-choice tests, results show that this biological control agent prefers the target pest (MFC), even in the absence of this host.

Based on the information from the cultural-historical background and from the interviews of community members, it is the assessment of this study that no negative impacts on cultural values are anticipated from the release of *Metaphycus macadamiae* on the human environment in Hawaiʻi.

7. Public Involvement and Agency Coordination

This Draft EA will be released for agency and public comment during a 30-day public review period, following publishing in the Environmental Review Program bulletin, The Environmental Notice. Feedback and comments received during that period would be reviewed and incorporated, as applicable, within the Final EA. Responses to all substantive comments will be provided in the Final EA. Additional consultation was done (Appendix C) through the Cultural Impact Assessment prepared by Synergistic Hawaiʻi Agriculture Council for the proposed action.

HDOA will continue to work with partners, other agencies, stakeholders, and surrounding communities throughout the permitting process. HDOA and partners have worked closely with the Hawaii Macadamia Nut Association. A letter of support can be found in Appendix D.

8. Determination

Section 11-200-12 of the HAR sets forth the criteria by which the significance of environmental impacts shall be evaluated. The following discussion restates these criteria individually and evaluates the project's relation to each.

1. The project will not involve an irrevocable commitment or loss or destruction of any natural or cultural resources.

The proposed action deals with specific interactions between the biological control agent (*Metaphycus macadamiae*) and the target pest insect (MFC) and will not involve irrevocable commitment or loss or destruction of any natural or cultural resources.

2. The project will not curtail the range of beneficial uses of the environment.

The proposed action involves specific interactions between the biological control agent and the target pest insect and is not expected to curtail any beneficial uses of the environment.

3. The project will not conflict with the State's long-term environmental policies.

The proposed action is expected to benefit the environment by reducing the negative impact caused by MFC on macadamia nut trees, providing a non-chemical, long-term, and sustainable method of pest control. Thus, benefiting the State's natural environment. This is in line with the State's long-term environmental policies.

4. The project will not substantially affect the economic or social welfare of the community or State.

The proposed action involves specific interactions between the biological control agent and the targeted pest species and is expected to positively impact the economic and social welfare of the community or State by supporting local farmers and the macadamia nut industry in Hawaiʻi.

5. The project does not substantially affect public health in any detrimental way.

The proposed action involves specific interactions between the biological control agent and the target invasive pest macadamia felted coccid. The biological control agent is a stingless wasp and will not impact public health.

6. The project will not involve substantial secondary impacts, such as population changes or effects on public facilities.

The proposed action involves specific interactions between the biological control agent and the target pest and is not expected to cause substantial secondary impacts.

7. The project will not involve a substantial degradation of environmental quality.

The proposed action deals with specific interactions between the biological control agent and the target pest insect and is expected to improve environmental quality by reducing the direct and indirect negative impacts caused by MFC to the environment.

8. The project will not substantially affect any rare, threatened, or endangered species of flora or fauna or habitat.

The proposed action deals with specific interactions between the biological control agent and the target MFC and will not affect rare, threatened, or endangered species or flora, fauna, or habitat.

9. The project is not one which is individually limited but cumulatively may have considerable effect upon the environment or involves a commitment for larger actions.

The proposed action does not involve a commitment for larger actions, and the cumulative effect is expected to be beneficial by reducing the direct impact of this invasive species on macadamia nut trees and the indirect impact by reducing use of harmful pesticides in the environment.

10. The project will not detrimentally affect air or water quality or ambient noise levels.

The proposed action involves specific interactions between the biological control agent and the target species and is not expected to affect air or ambient noise levels.

11. The project will not affect or will not likely be damaged by being located within an environmentally sensitive area such as floodplains, tsunami zones, erosion-prone areas, geologically hazardous lands, estuaries, fresh waters or coastal waters.

The proposed action involves specific interactions between the biological control agent and the target pest insect and will not affect and is not located within an environmentally sensitive area.

12. The project will not substantially affect scenic vistas or viewplanes identified in county or state plans or studies.

The proposed action will not affect scenic vistas or viewplanes identified in county or state plans or studies. The proposed action involves specific interactions between the biocontrol agent and pest insect.

13. The project will not require substantial energy consumption.

The proposed action involves specific interactions between the biological control agent and the target pest species and will not require substantial energy consumption. The proposed action will provide sustainable and natural pest control, decreasing overall energy consumption used in current pest control operations.

8.1 Conclusion

For the reasons above, and in consideration of comments received during early consultation, the HDOA has concluded that the proposed project will not have a significant impact in the context of HRS Chapter 343 and Section 11-200-12 of the HAR and has determined an Anticipated Finding of No Significant Impact (AFNSI) with the DEA.

9. References

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APPENDIX A: POLASZEK ET AL. 2020

Metaphycus Macadamiae (Hymenoptera: Encyrtidae) – A Biological Control Agent of Macadamia Felted Coccid *Acanthococcus Ironsidei* (Hemiptera: Eriococcidae) In Hawaii

PLOS ONE

RESEARCH ARTICLE

Metaphycus macadamiae (Hymenoptera: Encyrtidae) – a biological control agent of macadamia felted coccid *Acanthococcus ironsidei* (Hemiptera: Eriococcidae) in Hawaii

Andrew Polaszek[1]*, John S. Noyes[1], Stephen Russell[2], Mohsen M. Ramadan[3]

1 Dept of Life Sciences, Natural History Museum, London, England, United Kingdom, **2** Core Research Laboratories, Natural History Museum, London, England, United Kingdom, **3** Division of Plant Industry, Plant Pest Control Branch, Hawaii Department of Agriculture, Honolulu, Hawaii

* a.polaszek@nhm.ac.uk

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Abstract

A new species of encyrtid wasp, *Metaphycus macadamiae* Polaszek & Noyes **sp. n.,** (Hymenoptera: Encyrtidae: Encyrtinae) is described as a solitary endoparasitoid of the invasive macadamia felted coccid, *Acanthococcus ironsidei* (Hemiptera: Eriococcidae) in Hawaii. This parasitoid is native to Australia, and the species description is based on material collected from a *Macadamia integrifolia* Maiden & Betche (Proteaceae) plantation in New South Wales, Australia, the native region of the host tree and insect. It is described here because it is a potential biological control agent against this pest where it has recently invaded Hawaii and South Africa.

Introduction

Macadamia felted coccid (MFC), *Acanthococcus ironsidei* (Williams, 1973) (Hemiptera: Eriococcidae), is an Australian species, first found in Hawaii in 2005. On the Big Island, *A. ironsidei* has been found at Honomalino in South Kona. No infestations have been reported on the other neighbouring islands [1]. Host plants are restricted to smooth and rough-shelled macadamia *Macadamia integrefolia* and *M. tetraphylla*, respectively [2]. The species has become a problem in orchards where infested propagating material has been introduced, and where natural enemies do not keep it under control. Sometimes infested trees can be detected by a dull bronze colour in the foliage. In 2013 a species of the encyrtid parasitoid wasp genus *Metaphycus* was introduced from Australia into selected areas of Hawaii as an attempt at classical biological control of *E. ironsidei*. The new species is described below both to facilitate identification in the future, and to provide the formal nomenclature essential for all future work with this parasitoid.

Hawaii is the third largest producer of macadamia nuts in the world after Australia and South Africa. The macadamia nut industry is one of the top five agricultural commodities for the state. It is a vital part of the agricultural economy, with approximately 18,000 acres

Competing interests: The authors have declared that no competing interests exist.

harvested on the Big Island of Hawaii, and farm value for the 2017–2018 crop is estimated at $53.9 million [3].

Host plants of *A*. *ironsidei* are restricted to macadamia [2, 4]. Adult females are immobile, resembling mealybugs, and lay their eggs within felted sacs that enclose their bodies. The life cycle takes approximately four weeks in Hawaii, and many overlapping generations are produced [5].

MFC is a severe pest of macadamia infesting all above-ground parts of trees, including the nut husks, and causing leaf malformation, discoloration and die-back of large parts of the tree [4, 6]. Heavy infestation causes death of young seedlings, reduction in nut production, and severe damage can eventually kill affected mature trees. Ironside [4] also mentioned that dense infestations could cause flower drop and subsequent reduction in nut setting.

MFC was initially found infesting macadamia trees at Honomalino, South Kona on the Big Island of Hawaii in February 2005. It is now expanding its distribution to Pahala and Paauilo throughout northern and eastern plantations. If not controlled, MFC will continue to threaten the entire macadamia nut industry in Hawaii. Recent state-wide surveys show that the other five Hawaiian islands are free of infestation.

In small to moderate sized trees, MFC infestations can be managed effectively using sprays of horticultural oils, a practice that has been used during outbreaks in Australia. Chemical control is expensive and potentially damaging to the environment, and most farmers in Hawaii would prefer not to spray. However, with the dense canopy in Hawaii's orchards, the MFC populations appear to thrive, and local natural enemies are less common than in other areas. Imidacloprid root-drench application appears to be ineffective, and there are concerns relating to honeybee impact, as bees are commonly deployed for pollination in the orchards (Mark Wright, UH, personal communication).

Local predators and parasitoids may be helping to suppress the scale, but control at population level is not effective and needs to be enhanced by other selective parasitoids. Several extant natural enemies associated with MFC were observed in Hawaii including five species of predatory beetles, and the aphelinid parasitoid, *Encarsia lounsburyi* (Berlese & Paoli) [7]. Several entomopathogenic fungi kill *A*. *ironsidei* under laboratory conditions, but quantitative field studies are still pending [8].

Following a classical biological control approach, surveys in the native region to discover the key natural enemies suppressing MFC populations are essential for the Hawaii Department of Agriculture (HDOA) biocontrol program. MFC is less of a problem in Australia than in Hawaii, and specific natural enemies are thought to be an important mortality factor. The Plant Pest Control Branch (HDOA) considered that classical biological control could offer a long-term solution for suppression of MFC. In December 2013, HDOA initiated a foreign exploration to Australia to search for natural enemies of MFC. Macadamia and MFC are native to Australia, and therefore it was the most likely place for locating host-specific parasitoids. An encyrtid wasp, *Metaphycus* sp., was collected and shipped for host specificity tests in the HDOA Insect Containment Facility. Morphology-based identification (by JSN) revealed the species to be undescribed, and this was later confirmed by sequencing of two gene fragments, partial mitochondrial CO1 and ribosomal 28sD2. The new species is described below both to facilitate identification in the future and to provide the formal nomenclature essential for all future work with this parasitoid.

Materials and methods

Specimen depositories: Abbreviations

ANIC: Australian National Insect Collection, CSIRO, Canberra, Australia.

BPBM: Bernice P. Bishop Museum, Honolulu, Hawaii.
NHMUK: Natural History Museum,. London, UK.
USNM: United States national Museum, Washington D.C., USA.

Collection

In November 2013, a survey was undertaken by MMR in Alstonville, NSW, Australia Australia (28˚51' 20.14"S, 153˚26'31.40"E), where *Metaphycus* was dissected from MFC infested leaves of *Macadamia integrifolia*. Two shipments of infested macadamia leaves were collected and shipped to Hawaii. Infested leaves were taken from different trees that were not known to be sprayed, and these leaves produced adult *Metaphycus* wasps. A colony was initiated from 55 founder *Metaphycus* adults reared on seedlings infested with MFC at the HDOA Insect Containment Facility (Honolulu). The colony is still active, and wasps are currently used to conduct studies on host range and biology.

Morphological study

Morphological terminology and the format for the species description follow Noyes [9].

Abbreviations are as follows: AOD = largest diameter of anterior ocellus; AOL = minimum distance between posterior ocellus and anterior ocellus; EL = eye length; EW = eye width; FV = minimum width of frontovertex; FVL = length of frontovertex from occipital margin to top of antennal scrobes as seen in dorsal view; FVS = width of frontovertex a little above top of scrobes at a point where eye margin changes from being virtually straight to distinctly curved; FWL = fore wing length; FWW = fore wing width; GL = gonostylus length; HW = head width measured in facial view; HWL = hind wing length; HWW = hind wing width; MS = malar space (minimum distance between eye and mouth margin); MT = mid tibia length OCL = minimum distance between posterior ocellus and occipital margin; OL = ovipositor length; OOL = minimum distance between eye margin and adjacent posterior ocellus; POD = largest diameter of posterior ocellus; POL = minimum distance between posterior ocelli; SL = scape length; SW = scape width.

Card-mounted specimens were observed with a Leitz Dialux binocular microscope at magnifications ranging from 20-80x. Slide-mounted specimens were observed with a Leitz Dialux 20 microscope at magnifications ranging from 40-400x.

Images were generated as follows: Fig 1 (Holotype habitus: Canon DSLR with 100 mm macrolens, processed with HeliconFocus stacking software with final editing in Adobe Photoshop CC. Figs 2 & 3: Canon DSLR with 10x Mitutoyo objective, processed with HeliconFocus stacking software with final editing in Adobe Photoshop CC. Figs 4–13 Leitz Dialux 20EB compound microscope using Nomarski Differential Interference Contrast illumination, photographed with MicroPublisher 5.0 RTV camera; scanned sections stacked and combined using Synoptics AutoMontage® software, and final images edited with Adobe Photoshop CC®.

DNA sequencing

Genomic DNA extraction was undertaken using the protocol in Polaszek *et al* [10] and Cruaud *et* al. [11], which leaves the sclerotized parts of the specimen intact. Specimens were then critical point dried and card-mounted, with selected individuals then dissected and mounted in Canada balsam on microscope slides.

As the Folmer primer pair LCO1490/ HCO2198 [12] does not perform well in many chalcid wasp taxa [13–15], especially in those with suboptimal DNA extracts [16], a shorter than standard CO1 sequence was obtained of 555 bp after trimming the primer sequences and poor-

Fig 1. *Metaphycus macadamiae* female holotype, habitus (photo by N. Dale-Skey–specimen subsequently slide-mounted).

https://doi.org/10.1371/journal.pone.0230944.g001

read ends. The 28S D2 fragment was amplified with the primers D23F (5′-GAG AGT TCA AGA GTA CGT G-3′) [17] and 28Sb (5′-TCG GAA GGA ACC AGC TAC TA-3′) [18, 19]. After trimming the primer sequences and poor-read ends, the resulting contig from 7 forward and 8 reverse sequences was 444 bp. All reactions were carried out in 25 μl reaction volume containing 5 μl of template DNA, 2.5 μl of 10× PCR buffer, 0.75 μl of 50 mM MgCl2, 0.2 μl dNTPs solution (25 mM each), 1.25 μl of each primer (10 μM), 0.3 μl Taq polymerase (5u/μl Biotaq, Bioline), and PCR grade water to final volume. The PCR cycle for the 5' end of the standard barcode region consisted of an initial denaturation step of 94˚C for 2 min, followed by 40 cycles of 94˚C for 30 s, 40˚C for 60 s and 72˚C for 30 s, and a final extension step of 10 min at 72˚C. For the 3' end of COI and for 28S the conditions where similar except for annealing at 41˚C for 50 s and 55˚C for 30 s respectively.

Both DNA strands were sequenced at the Natural History Museum Life Sciences DNA Sequencing Facility (London) using the same primers used for the PCR. Forward and reverse sequences were assembled and corrected using Sequencher version 4.8. Identical partial sequences were obtained for 8 individuals for 28S, and 3 individuals for CO1. These have been deposited in Genbank under accession nos MN933670 (CO1) and MN934351 (28S), respectively.

Nomenclatural acts

The electronic edition of this article conforms to the requirements of the amended International Code of Zoological Nomenclature, and hence the new names contained herein are available under that Code from the electronic edition of this article. This published work and the nomenclatural acts it contains have been registered in ZooBank, the online registration system for the ICZN. The ZooBank LSIDs (Life Science Identifiers) can be resolved and the associated

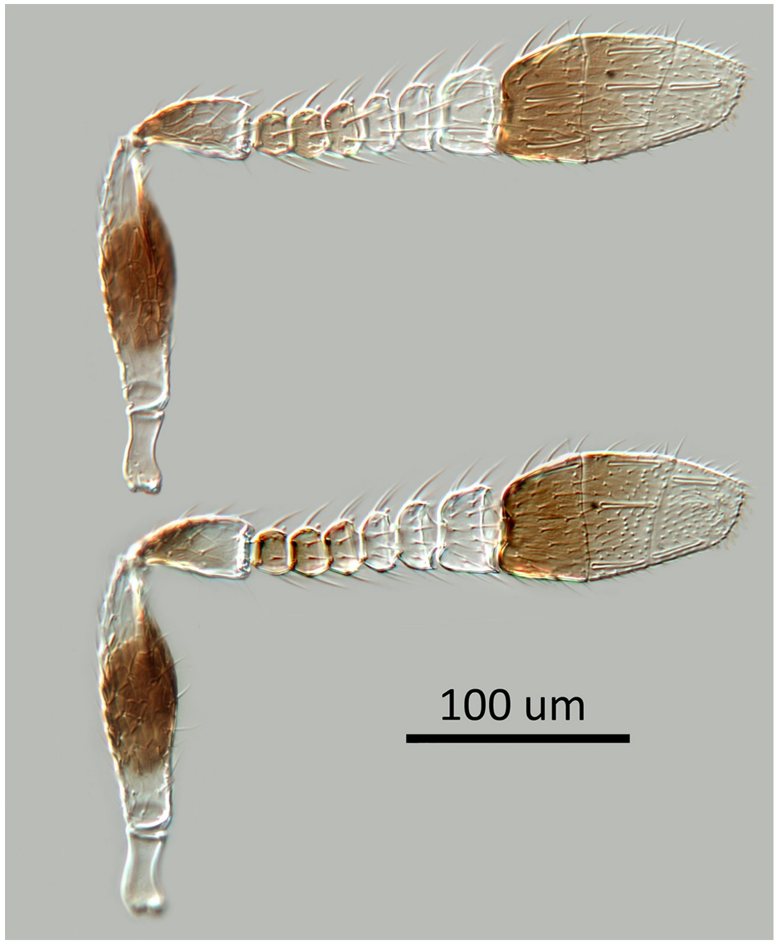

Fig 2. *M. macadamiae* female holotype, antenna, inner and outer aspects.

https://doi.org/10.1371/journal.pone.0230944.g002

Fig 3. *M. macadamiae* female holotype, fore and hind wings.

https://doi.org/10.1371/journal.pone.0230944.g003

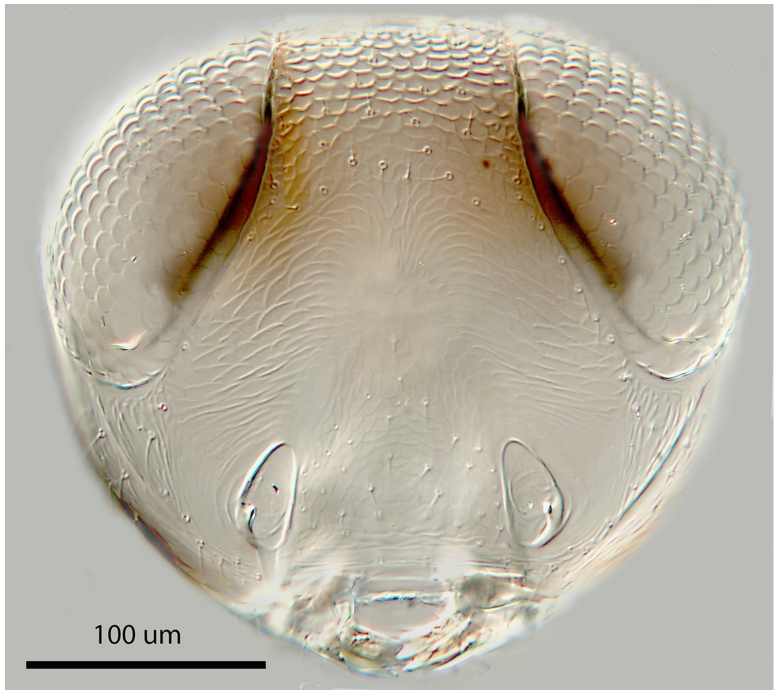

Fig 4. *M. macadamiae* female holotype, head, frontal view.

https://doi.org/10.1371/journal.pone.0230944.g004

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Description

Metaphycus Mercet. Metaphycus Mercet, 1917:138. Type species: Aphycus zebratus Mercet, by monotypy, as subgenus of Aphycus Mayr.

Metaphycus Mercet, 1925:28. Generic status.

Synonyms include *Aenasioidea* Girault, *Aenigmaphycus* Sharkov & Voynovich, *Anaphycus* Sugonjaev, *Erythraphycus* Compere, *Euaphycus* Mercet, *Mercetiella* Dozier, *Melanaphycus* Compere, *Mesaphycus* Sugonjaev, *Notoencyrtus* De Santis, *Ooaphycus* Girault, *Tyndarichoides* Girault and *Xenaphycus* Trjapitzin [20].

Diagnosis. Length 0.5–1.8 mm; robust and squat species, rarely slender and elongate; body largely orange, yellow to brown or black (they may be shiny), never with metallic lustre, antenna usually with black and white or yellow parts or segments, fore wing hyaline to partially or uniformly infuscate, legs yellowish or with brown to black segments, tibiae frequently with dark rings. Head with occipital margin sharp, frequently with shallow grooves lateral to outer margin of torulus; mandible mostly broad with 3 short, subequal teeth, but occasionally slender with two or three unequal teeth. Pronotum short, broadly triangular in dorsal view, mesoscutum wider than long, notaular lines variable in length from virtually absent to complete and reaching posterior margin; scutellum never with an apical flange that overhangs the propodeum medially; fore wing generally about 2.5X as long as broad and with uniform setation, submarginal vein reaching about half way along wing, marginal and postmarginal veins very

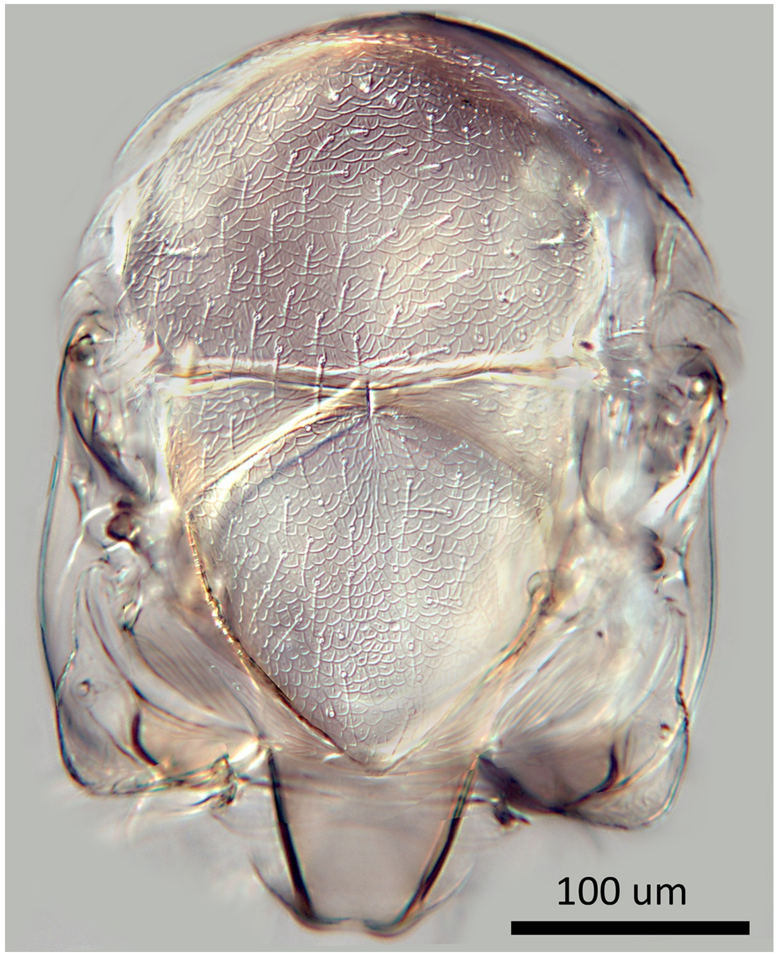

Fig 5. ***M. macadamiae*** **female holotype, dorsal mesosoma.**

https://doi.org/10.1371/journal.pone.0230944.g005

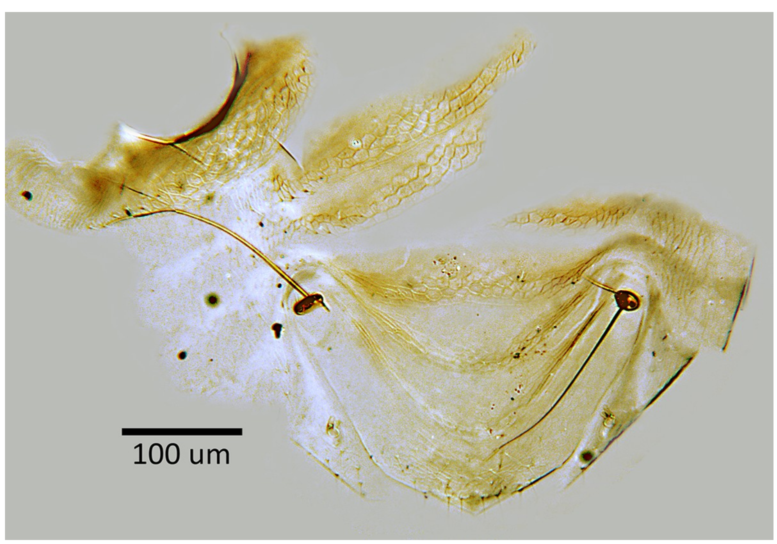

Fig 6. ***M. macadamiae*** **female holotype, metasomal terga.**

https://doi.org/10.1371/journal.pone.0230944.g006

Fig 7. *M. macadamiae* female holotype, ovipositor.

https://doi.org/10.1371/journal.pone.0230944.g007

short, stigmal vein well developed, longer than marginal and postmarginal veins together; linea calva interrupted in posterior third by a few setae, or completely closed at this point; mid tibial spur about as long as mid basitarsus, rarely significantly shorter. *Female*: antenna almost always 11-segmented (1163), rarely with clava 2- segmented; scape cylindrical to strongly expanded and flattened. Gaster with hypopygium reaching half way along gaster to more or less reaching its apex; outer plates of ovipositor not reflected upwards posteriorly; gonostylus free, in most cases not exserted or only slightly so. *Male*: generally darker and with more uniform colour in respect to that of corresponding female. Antenna 9-segmented (1161), with setae longer than in female; toruli very often with associated pores.

Comments. Females of *Metaphycus* that have the ovipositor slightly exserted may be confused with *Aphycus* (Mayr). In *Aphycus*, the linea calva of the fore wing is always clearly entire and the outer plates of the ovipositor are reflected upward posteriorly to connect loosely with the syntergum.

Distribution. Of the 466 described species of *Metaphycus* [21] three species are more or less cosmopolitan *(helvolus*, *lounsburyi* and *flavus)*, 80 are Afrotropical, 208 are Neotropical,

Fig 8. ***M. macadamiae*** **female, lateral habitus.**

https://doi.org/10.1371/journal.pone.0230944.g008

48 are Nearctic, 87 are Palaearctic (including 53 from Europe), 26 are Oriental, and 23 are Australasian, with several species being found in more than one region.

Hosts. *Metaphycus* species are mainly reported as solitary or gregarious parasitoids of soft scales (Hemiptera: Coccidae) (e.g. *Coccus*, *Ceroplastes*, *Saissetia* spp.) and diaspidids (Hemiptera: Diaspididae). A few species have been reported as parasitoids of kermesids (Hemiptera: Kermococcidae), asterolecaniids (Hemiptera: Asterolecaniidae), kerrids (Hemiptera: Kerridae), eriococcids (Hemiptera: Eriococcidae), cerococcids (Hemiptera: Cerococcidae), mealybugs (Hemiptera: Pseudococcidae), whiteflies (Hemiptera: Aleyrodidae) and triozids (Hemiptera: Triozidae) [21].

Biocontrol. Species of the genus play an important role in the natural regulation of scale insect pests, and as a result nearly 30 species have been released in various parts of the world for control of soft scale (Hemiptera: Coccidae) and armoured scale (Hemiptera: Diaspididae) pests of agriculture. The use of *Metaphycus* species in biocontrol programmes has been

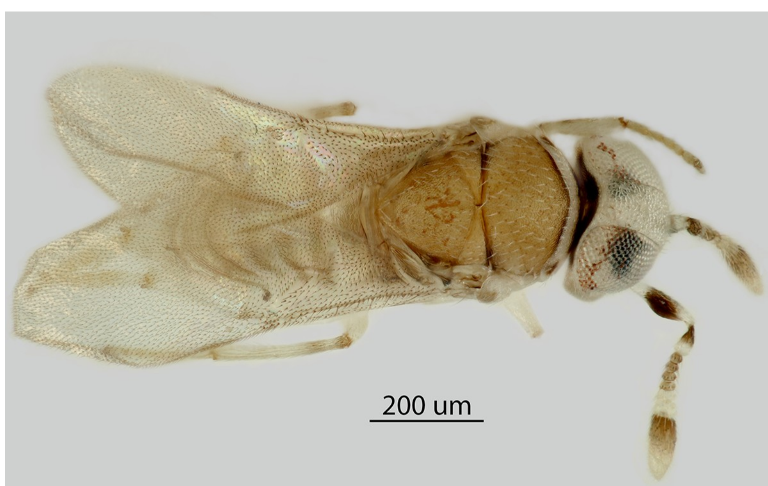

Fig 9. ***M. macadamiae*** **female, dorsal habitus.**

https://doi.org/10.1371/journal.pone.0230944.g009

Fig 10. *M. macadamiae* male, lateral habitus.

https://doi.org/10.1371/journal.pone.0230944.g010

summarized [20, 22], and a detailed compilation of data is available [21]. In general, the most successful introductions have been from southern Africa into California for the control of soft scale pests on *Citrus* with the best known of these being the release of *M. helvolus* (Compere) in 1937 for the control of *Saissetia oleae* (Olivier, 1791) (Hemiptera: Coccidae). This has been estimated to have saved the California citrus industry at least $70m prior to 1979, with an annual saving of over $2m [23]. The same species has proved to control successfully a number

Fig 11. *M. macadamiae* male, dorsal habitus.

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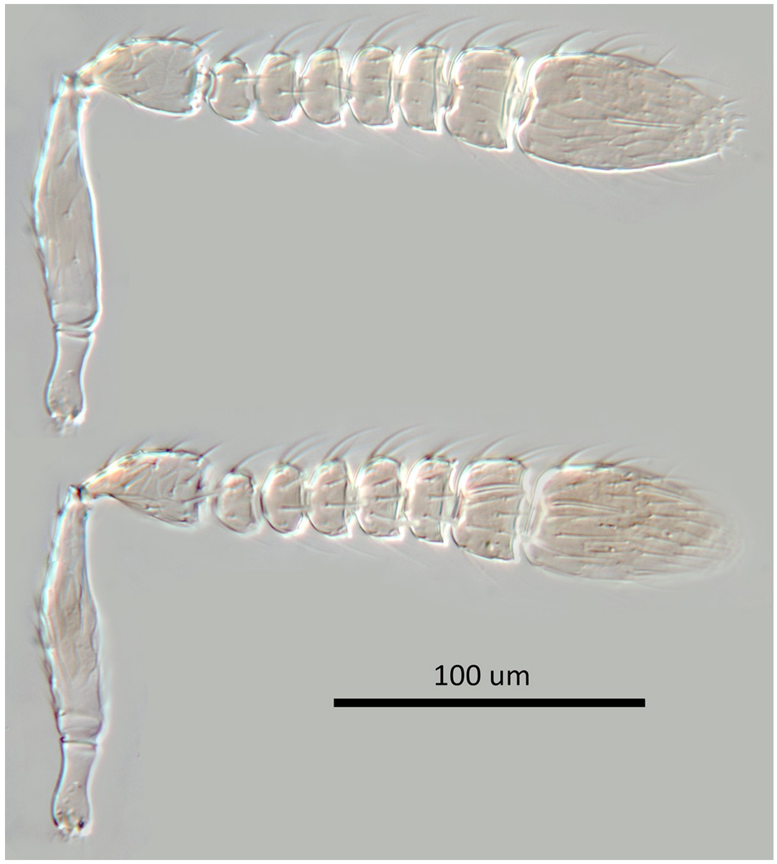

Fig 12. *M*. *macadamiae* male antenna, inner and outer aspects.

https://doi.org/10.1371/journal.pone.0230944.g012

Fig 13. *M*. *macadamiae* male genitalia.

https://doi.org/10.1371/journal.pone.0230944.g013

of *Saissetia* spp. virtually everywhere it has been released for pest control throughout the world.

Identification. Several keys have been published to the species of *Metaphycus*: African species [24], South African species [25–27], Central Asian species [28], Italian species [29], European species [20], Palaearctic species [30], Indian species [31], all of them based on the distinction of species groups using the palp formula [32]. Some of these keys are based largely on characters which may be unreliable (e.g. colour of funicle segments, very small differences in relative width of scape) or difficult to evaluate (e.g. relative length of frontovertex). Other character states that may prove useful in the identification of species are the presence or absence of subapical setae on the 2nd valvifer, the presence or absence of lateral antennal grooves, the shape of the antennal scrobes and the structure of the ovipositor and shape of the hypopygium. Unfortunately, most of these characters can be observed only on well prepared slide-mounted material which makes the reliable identification of a number of species very difficult.

***Metaphycus* macadamiae Polaszek & Noyes sp. N.** urn:lsid:zoobank.org:act:0668979-C-A7BF-4600-B54C-82E1B5941743

Figs 1–13

Morphology. Female (holotype, Fig 1): length, including ovipositor, 0.76mm, excluding ovipositor, 0.73mm (critical point dried specimen).

Colour: Head mostly white with occiput above foramen dark brown and gena with a slightly elongate pale brown mark between base of mandible and eye; mouth margin with a slender brown mark above base of mandible and another below torulus; antenna (Fig 2) with radicle white; scape white with a broad median band about half its length on both inner and outer surfaces, connected ventrally but narrowly separated dorsally; pedicel brown in proximal half, distal half white; funicle with F1-F2 pale brown, F3 slightly paler, F4-F6 white; clava pale brown in proximal half, apex pale yellow; pronotum white with paired sublateral brown spots on posterior margin and a pair of larger submedian subtriangular marks on neck; mesoscutum (Figs 5, 8 and 9) pale orange with posterior margin narrowly dark brown adjacent to axilla; axilla and scutellum pale orange; metanotum dusky pale orange; tegula translucent white, apex pale grey; side and venter of thorax white; mesoscutum and scutellum clothed in numerous, moderately long, translucent setae; coxae and legs white to very pale yellow, mid and hind tibiae each with an extremely faint pale brown subbasal ring; fore wing hyaline, venation pale yellow; propodeum medially pale orange but pale orange-brown in lateral third towards spiracle, side white; dorsum of gaster slightly dusky pale orange with syntergum white, side and venter white; gonostylus white.

Morphology: Head 3.5x as wide as fronovertex, slightly shiny on frontovertex, sculpture coarse and fairly regularly reticulate, of mesh size hardly smaller than eye facet; ocelli forming an angle of about 43˚; antenna (Fig 2) with scape about 2.9X as long as broad; F1-F5 subequal and transverse but increasing very slightly in width distad, F6 clearly longer and larger; funicle with linear sensilla only on F6; clava apically rounded; eye slightly overreaching occipital margin; upper temple rounded in facial view; frontovertex hardly less than one-third head width, with inner eye margins diverging slightly anteriorly, with narrowest point about level with posterior ocelli; scrobes deep, U-shaped, meeting dorsally, interantennal prominence dorsally rounded; lateral antennal groove absent; antennal torulus separated from mouth margin by slightly less than its own length; mandible broad with three short, more or less equal, acute teeth; palp formula 2–2. Relative measurements: HW 64, FV 21, FVS 20, FVL 35, POL 7, AOL 10, OOL 1.5, OCL 2, POD 4, AOD 4, EL 36, EW 29, MS 20, SL 28, SW 9.5.

Thorax with notaular lines absent externally, but visible anterolaterally on slide-mount; dorsum of thorax shiny with sculpture on mesoscutum similar to that of frontovertex, but shallower and composed of smaller cells, sculpture of scutellum about as deep as that on mesoscutum; side of propodeum more or less naked; fore wing venation and setation as in Fig 3. Relative measurements: FWL 165, FWW 66; HWL 110, HWW 21.

Gaster with ovipositor slightly exserted, the exserted part about 0.15X as long as gaster or 0.7X as long as mid tibial spur; gonostyli together cylindrical and proximally about 2X as deep as diameter of base of mid tibial spur; apex of last tergite shallowly rounded; hypopygium reaching about 0.6X along gaster, broadly subtriangular and about 2X as broad as long; second valvifer with 1 or 2 subapical setae. Relative measurements: OL 64, GL 13 [MT 58].

Variation. The overall length of the female varies from about 0.63–0.78mm and the head varies from about 3.0–3.6X as wide as the frontovertex.

Male (Figs 10–13): length 0.46–0.66mm. Structurally very similar to female except structure of antenna and genitalia.

Colour: Head mostly pale orange with occiput above foramen dark brown; frontovertex with a triangular brown mark delimited by occipital margin and anterior ocellus; gena and temple pale pink with posterior margin brown from base of mandible to about level of lower eye margin; mouth margin very narrowly margined brown; scrobal area very pale yellow; antenna (Fig 12) with radicle white; scape very pale yellow, almost white; pedicel brown in proximal half, distal half off-white; flagellum pale brown; pronotum very pale yellow with paired sublateral brown spots on posterior margin and a pair of larger submedian subtriangular marks on neck; mesoscutum, axilla and scutellum orange-brown; metanotum dusky orange; tegula white with apex brown; side and venter of thorax white; mesoscutum and scutellum clothed in numerous, moderately long, translucent pale brown setae; coxae and legs white to very pale yellow, mid and hind tibiae each with an extremely faint pale brown subbasal ring; fore wing hyaline, venation pale yellow; propodeum medially pale orange but pale orange-brown in lateral third towards spiracle, side white; dorsum of gaster orange-brown with syntergum slightly dusky pale orange, side and venter white.

Morphology: Head about 2.4–2.6X as wide as frontovertex with inner eye margins diverging slightly anteriorly; antennal torulus with from 1 to 4, widely spaced, associated pores along inner margin; antenna as in Fig 12 with scape about 2.7X as long as broad, F1-F5 anneliform, subequal, F6 largest and slightly transverse, only F6 with linear sensilla. Phallobase (Fig 13) about as long as aedeagus with a single subapical, seta on each side and each digitus with a single apical hook; aedeagus about 0.5X as long as mid tibia. Relative measurements (slide-mounted specimen): HW 61, FV 24, SL 22, MT 49.5, AL 23.5.

Hosts. A parasitoid of *Acanthococcus ironsidei* (Williams) (Hemiptera: Eriococcidae) on *Macadamia integrifolia* Maiden & Betche (Proteaceae).

Distribution. Australia (New South Wales), Hawaii (introduced).

Material examined. Holotype ♀, HAWAIIAN ISLANDS, Oahu, Pawaa, Hawaiian Dept. Agric. Insect Containment Facility, May 14 2015, lab reared *Eriococcus ironsidei* F18 generation (J. Yalemar), original collection AUSTRALIA, NSW, Alstonville, ex *Eriococcus ironsidei* on *Macadamia integrifolia* Tax. coll. #15–228; 19.xi.2013/26.xi.2013 and Tax. coll. #15–229 25.xi.2013/7.xii.2013 (M. Ramadan). Paratypes: HAWAIIAN ISLANDS, 9♀, 9♂, same data as holotype. Holotype in ANIC, paratypes in BMNH, BPBM and USNM.

Comments. The female of *Metaphycus macadamiae* has a unique combination of diagnostic characters in the genus: 2–2 palp formula; body generally white to pale orange with occiput and pronotum marked dark brown; clava proximally dark brown with apex pale yellow; head mostly white with occiput above foramen dark brown and gena with a slightly elongate pale brown mark between base of mandible and eye; scape white with a broad median band about half its length on both inner and outer surfaces, connected ventrally but narrowly separated dorsally; fore wing hyaline; legs white to very pale yellow, mid and hind tibiae each with an extremely faint pale brown subbasal ring; metanotum dusky pale orange; scape about 2.9X as long as broad; funicle with linear sensilla only on F6; head 3.0–3.6X as wide as the frontovertex; ovipositor about 5X as long as gonostylus.

Of the 30 or so species of *Metaphycus* that have been reared from Eriococcidae worldwide, only two belong to the *alberti* species group (both maxillary and labial palps 2-segmented), i.e. *brachypterus* (Mercet) and *deluchii* Viggiani, both from Europe. These differ significantly from *macadamiae* in having the mid and hind tibiae each with a pair of distinct dark brown rings, the head about 4X as wide as the frontovertex and the scape about 3.X as long as broad. *Metaphycus brachypterus* also has the mouth margin and gena brown and *deluchii* has linear sensilla on F5.

Of the remaining species of *Metaphycus* belonging to the *alberti* group, the most similar in general appearance and habitus is *helvolus* Compere, females of both species being generally yellow in appearance with the scape broadened and flattened and mostly dark brown, apex of clava pale yellow, occiput and pronotum marked dark brown, mid tibia with a faint brown subbasal ring, funicle with linear sensilla only on F6, and male with pores scattered along inner margin of torulus. The female of *macadamiae* differs from *helvolus* in having a brown streak on the gena, and the scape about 3X as long as broad, whereas in *helvolus* the gena is completely pale yellow and the scape is 2.5X as long as broad. The male of *macadamiae* differs from that of *helvolus* in having fewer than five pores along the inner margin of the torulus, and the funicle segments are nearly 2X as broad as long, whereas in *helvolus* there are at least 10 pores and the funicle segments are subquadrate.

In the key to the Hawaiian *Metaphycus* species [33], *macadamiae* runs to couplet 6 which includes "sp. near *claviger*" and *alberti* (Howard). It runs best to "sp. near *claviger*" because the scape is said to be about 3X as long as broad whereas in *alberti* the scape is said to be about 4X as long as broad (actually about 2.5X as long as broad in *claviger* and 3X as long as broad in *alberti*). As both *alberti* and *claviger* are very similar to *macadamiae* and probably originate from Australia, *macadamiae* is compared to both below.

Females of *macadamiae* differs from those of *alberti* and *claviger* in being smaller, generally less than 0.8mm long (mostly at least 1mm long in *alberti* and *claviger*), having a pale brown mark on gena (absent in *alberti* and *claviger*), linear sensilla only on F6 (F5 and F6 in *alberti*); head, side and venter of thorax white (orange in *alberti* and *claviger*), mid and hind tibiae each with a pale brown subbasal ring (legs immaculate in *alberti* or *claviger*), head usually about 3X as wide as the frontovertex (rarely as much as 3.6X, but at least about 3.8X *alberti* or *claviger*) and ovipositor slightly longer than mid tibia (about 0.8–0.9X as long in *alberti* and *claviger*). Males differs from those of *alberti* and *claviger* in having the scape virtually uniformly white (pale orange with a distinct pale brown median band in *alberti* and with dorsal and ventral margins brown in *claviger*), from *claviger* in having the gena pale pink (brown in *claviger*), from *alberti* in having at most only 4 pores along inner margin of torulus that do not extend past upper margin (at least 8 in *alberti* some of which extend past upper margin) and from *claviger* in having F6 strongly transverse, only about 0.6X as long as broad and only slightly larger than F5 (in *claviger* subquadrate, nearly as long as broad and much larger than F5).

Molecular analysis. The paucity of DNA sequences for *Metaphycus* species in GenBank or elsewhere, coupled with the relative shortness of our sequences have precluded the need for any phylogenetic or even phenetic analyses. A Genbank BLAST of our 444 bp 28S ribosomal sequence suggests some proximity to *M. helvolus* (assuming correct identification), which is also suggested by morphology (see above). The top 8 similar sequences are all *Metaphycus* species. *M. helvolus* in Genbank has 97% query cover with 94% identical bases, suggesting quite some genetic distance. Our 555 bp COI contig of 6 sequences BLASTs to "Encyrtidae sp." with

91% query cover and 92% identity. It would appear that *M macadamiae* is not closely related to any species with sequences currently deposited in Genbank.

Comparison of *Metaphycus macadamiae* with *M. dispar* (Mercet). To the untrained eye, as was revealed during the review process of this paper, some superficial similarity between *M. macadamiae* and *M. dispar* could be considered. The main and obvious differences in their appearance are listed below. Also worthy of consideration are the facts that *M. dispar* is known only from Coccidae, is a Palaearctic species (introduced into Califormia), and does not occur in Australia.

M. dispar differs notably from *M. macadamiae* in having linear sensilla on F5; the gena and mouth margin lack brown marks; the notauli reach almost reach half way down the mesoscutum. It is also distinctly paler and in general larger.

Other differences are as follows (the condition in *M. macadamiae* is given first, with *M. dispar* following in parentheses in red typeface):

Female: Head mostly white (yellow/pale orange) with occiput above foramen dark brown and gena with a slightly elongate pale brown mark between base of mandible and eye (yellow/pale orange); mouth margin with a slender brown mark above base of mandible and another below torulus (yellow/pale orange); antenna with radicle white (brown); scape white with a broad median band about half its length on both inner and outer surfaces, connected ventrally but narrowly separated dorsally (continuous); mesoscutum pale orange (dark orange); metanotum dusky pale orange; tegula translucent white, apex pale grey; side and venter of thorax white (pale orange); mid and hind tibiae each with an extremely faint pale brown subbasal ring (only mid tibia with pale ring).

Male: Antennal torulus with from 1 to 4, widely spaced, associated pores along inner margin (cluster of c9 pores ventro-laterally); antenna with only F6 with linear sensilla (F5+F6).

Discussion

Host specificity tests and biological studies in Hawaii will be published elsewhere when nomenclature of this parasitoid is officially published. We anticipate that *M. macadamiae* will be a useful agent in the biocontrol programmes against MFC in Hawaii and South Africa. In April 2017 severe infestations of MFC were observed in the Barberton valley in Mpumalanga, South Africa. The impact of this new pest on the local macadamia industry may take some years to reach the infestation level in Hawaii. However, it is an important quarantine organism and researchers are advocating care to prevent the movement of infested plant material to reduce the risk of spreading the pest amongst orchards. Although it was initially thought the infestation was contained in Barberton where the pest was first found, it spread within a month to White River plantations about 63 Km north of Barberton, presumably through infested plant material.

Spread in Hawaii is relatively slow, and the scale tends to stay in the same tree. But observations in White River contradict this as there was considerable spread to adjoining trees. South African Entomologists are waiting for the release of *M. macadamiae* in Hawaii to get a starter colony for their studies (https://macadamiasa.co.za/2019/02/19/beware-the-felted-coccid/.

Supporting information

S1 Video.
(AVI)

S2 Video.
(AVI)

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Author Contributions

Conceptualization: Andrew Polaszek.

Data curation: Andrew Polaszek, John S. Noyes.

Formal analysis: Andrew Polaszek, John S. Noyes, Stephen Russell.

Funding acquisition: Andrew Polaszek.

Investigation: Andrew Polaszek, Mohsen M. Ramadan.

Methodology: Andrew Polaszek.

Project administration: Andrew Polaszek.

Resources: Andrew Polaszek, Mohsen M. Ramadan.

Software: Andrew Polaszek.

Visualization: Andrew Polaszek.

Writing – original draft: Andrew Polaszek.

Writing – review & editing: Andrew Polaszek, John S. Noyes, Stephen Russell, Mohsen M. Ramadan.

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APPENDIX B: YALEMAR ET AL. 2023

Prospects for Biological Control of Macadamia Felted Coccid in Hawaii with *Metaphycus macadamiae* Polaszek & Noyes, a New Encyrtid Wasp Native to New SouthWales, Australia

insects

Article

Prospects for Biological Control of Macadamia Felted Coccid in Hawaii with *Metaphycus macadamiae* Polaszek & Noyes, a New Encyrtid Wasp Native to New South Wales, Australia

Juliana A. Yalemar [1], Amber P. Tateno-Bisel [2], Stacey G. Chun [1] and Mohsen M. Ramadan [1,*]

1 Plant Pest Control Branch, Division of Plant Industry, Hawaii Department of Agriculture, 1428 South King Street, Honolulu, HI 96814, USA; juliana.a.yalemar@hawaii.gov (J.A.Y.); stacey.g.chun@hawaii.gov (S.G.C.)
2 CDFA Fruit Fly Rearing Facility, 41-650 Waikupanaha Street, Waimanalo, HI 96795, USA; amber.tateno@cdfa.ca.gov
* Correspondence: mohsen.m.ramadan@hawaii.gov

Simple Summary: The macadamia felted coccid (MFC), *Acanthococcus* (=*Eriococcus*) *ironsidei* (Williams) (Hemiptera: Eriococcidae), is an invasive pest that has devastating impacts on the macadamia nut tree, in Hawaii and South Africa. MFC is a scale insect native to Australia where it has been recorded from smooth- and rough-shelled macadamia variants. Feeding causes discoloration and distortion of plant foliage, premature flower and nut drop, branch die back, and substantial reduction in nut production. Heavy infestations cause severe damage and death to large portions of trees. A survey conducted by Hawaii Department of Agriculture in New South Wales (NSW), Australia, found the undescribed endoparasitoid *Metaphycus* species is an important biotic factor for MFC. The parasitoid was imported to Hawaii for host specificity tests using closely related hemipterans, scale insect species, and other species of importance in Hawaii. Results indicated that this parasitoid is monospecific to MFC. This promising natural enemy was described as the new species, *Metaphycus macadamiae* Polaszek & Noyes sp. n (Hymenoptera: Encyrtidae). Laboratory parasitism averaged 30.2%, and parasitoids can feed on their hosts. Field parasitism in Australia is 32.7%. Several coccinellid predators and the aphelinid parasitoid, *Encarsia lounsburyi*, are local natural enemies of MFC in Hawaii, but their impacts alone are insufficient to suppress MFC populations. Introduction of biological control by release of *M. macadamiae* is expected to result in an effective long-term, sustainable solution for controlling MFC on macadamia nut trees in Hawaii or other infested areas in South Africa.

Abstract: Macadamia felted coccid (MFC), *Acanthococcus ironsidei* (Williams) (Hemiptera: Eriococcidae), was first discovered in 2005 on the Island of Hawaii. Host plants are restricted to *Macadamia* species, with *Macadamia integrifolia* Maiden & Betche (Proteaceae) being grown in Hawaii for nut production. Approximately 6839 hectares macadamia nuts are harvested in Hawaii with an estimated farm value of USD 48.8 million (2019–2020 records). Exploration in Australia started in November 2013 for the evaluation of potential parasitoids being host specific for introduction into Hawaii. A dominant solitary endoparasitoid of MFC from New South Wales was discovered and described as *Metaphycus macadamiae* Polaszek & Noyes sp. n (Hymenoptera: Encyrtidae: Encyrtinae). Biology and host specificity testing were conducted at the Hawaii Department of Agriculture, Insect Containment Facility, on nine hemipteran and three lepidopteran eggs. Results indicated that *M. macadamiae* is host specific to MFC. There has been no evidence of parasitism or host feeding on any of the non-target insect hosts that were tested. Parasitoid emergence from the control (MFC) averaged 30.2% compared to 0% on non-target hosts. A low rate of parasitoid emergence in the laboratory (average 30.2%) and an increased rate of MFC nymphal mortality was due to adult feeding. Field parasitism reached up to 32.7% emergence in Alstonville, New South Wales, Australia. We report on the parasitoid performance in native Australia, rearing biology, host specificity testing, and the extant natural enemies associated with MFC in Hawaii. A petition to release this parasitoid for the biocontrol of MFC in Hawaii is pending. Once permitted for release, the colony will be shared with South African Mac Nut Association for their biocontrol program of this invasive pest. They will conduct their own testing before approval for release.

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1. Introduction

The *Macadamia* genus is native to Australia and has been used for the commercial production of macadamia nuts in Hawaii for more than 80 years [1]. Two species of *Macadamia* have been used, primarily the smooth-shelled variety, *M. integrifolia* Maiden & Betche, and the rough-shelled variety, *M. tetraphylla* L.A.S. Johnson (Proteaceae) [2].

Commercial production of macadamia in Hawaii has grown exponentially to be the third most valuable crop, ranked as a commodity, in Hawaii after production of coffee, *Coffea arabica* L. (Rubiaceae), and seed corn, *Zea mays* L. (Poaceae) [3]. Typically, approximately 6475 hectares of macadamia nuts are harvested annually on the Island of Hawaii with an estimated farm value for the 2017–2018 crop of USD 53.9 million [4].

Macadamia felted coccid was first intercepted in 1954 on macadamia species imported into Hawaii [5]. Establishment did not occur until MFC was found infesting macadamia trees in South Kona, island of Hawaii, in February 2005 [6]. The MFC is a native Australian insect with plant hosts restricted to *Macadamia* varieties used for commercial production [2,5]. It infests all above-ground parts of trees and causes yellow spots on the leaves, die back on young seedling, and reduction in nut production [7–9]. Heavy infestation causes severe damage and eventual death of affected trees [10] (Figure 1).

Figure 1. (**A**) Australian macadamia orchard (NSW), in November 2013, with MFC as a minor pest, (**B**) Hawaii macadamia orchard 2005 severe infestation, (**C**) MFC infestation on leaves and nuts in Hawaii, and (**D**) infestation of stems in Hawaii.

Macadamia felted coccid was established and has already spread across the island of Hawaii. In 2023, a survey was conducted by the Hawaii Department of Agriculture, and no infestation was found on the other major Hawaiian Islands (Kauai, Maui, and Oahu Islands) (HDOA-PPC, survey reports, 2023). Natural dispersal rates of this pest are very low, and distribution tends to occur primarily within infested trees [11]. In 2014, estimates on one farm indicated that as much as half a million pounds of wet in-shell macadamia nuts were lost because of MFC. According to USDA National Agricultural Statistics Service, the highest quantity of macadamia nuts, i.e., 6879.6 hectares, is harvested in Hawaii, and the farm value for the 2017–2018 crop was estimated at USD 53.9 million [4,12,13].

MFC belongs to the Family Eriococcidae with members that resemble mealybugs. The adult female is white to yellow brown and averages 0.7 × 1.0 mm in size [9], Figure 2A,B. Adult females are immobile and lay their eggs within felted sacs that are enclosed in their abdomens. A female lays 18–97 eggs during her lifetime of ≥50 days [14,15]. When the eggs hatch, the tiny crawlers move about, thus, spreading by wind or by hitchhiking. Long distance dispersal is mainly by passive transport of infested propagative material such as grafting budwood, scion wood cuttings, and potted nursery trees [9]. The life cycle takes six weeks in the summer (23.8–29.4 °C), and many overlapping generations are produced [16]. The female feeds by inserting her needle-like mouth parts into plant tissues and ingesting the sap (Figure 2B). Adult males are smaller in size, have wings, and do not feed, and their sole purpose is to mate with the females (Figure 2C).

Figure 2. (**A**) MFC mature female, dirty white to pale yellow, scale about 1.5 mm in length, with a raised circular opening at the posterior end, (**B**) female MFC orange in color, showing long stylet mouth parts (arrow), (**C**) honeydew produced on leaves by the nymphs of MFC (arrows honeydew and male white nymphs), and (**D**) *Metaphychus macadamiae* larval stage dissected from female MFC.

In November 2013, the Hawaii Department of Agriculture, Plant Pest Control Branch (HDOA-PPC) initiated a foreign exploration in Australia to search for natural enemies of MFC. The host plants, *Macadamia* species, are native to Australia; therefore, it was the most likely place for potential natural enemies to be located. The HDOA-PPC believed that classical biological control may offer a long-term option for suppression of MFC. An encyrtid wasp, *Metaphycus* sp. (Hymenoptera: Encyrtidae), was collected as the dominant parasitoid and shipped to Hawaii in November 2013, propagated, and evaluated in the HDOA Insect Containment Facility (ICF). No other parasitoids emerged from this Australian collection. Many species of the genus *Metaphycus* have been used successfully in biological control programs against hemipteran pests with some great success in controlling the scale insects [17,18]; therefore, the unknown species of *Metaphycus* seemed like a potential biocontrol agent to control MFC.

Preserved specimens were sent to Dr. Andrew Polaszek and Dr. John S. Noyes of the Natural History of Museum, London, United Kingdom, for description of this new species [19]. The wasp was described in 2020 and named as the new species, *Metaphycus macadamiae* Polaszek & Noyes sp. N. (Hymenoptera: Encyrtidae: Encyrtinae), a tiny solitary endoparasitoid. The female is light yellowish in color and is about 0.8 mm in length (Figure 3A,B). The male is dark in color and is approximately 0.6 mm in length (Figure 3D). The female lays a single egg inside each mature female host where it hatches, and the larva grows and develops, thus, killing the host in the process (Figure 2D). Females also host feed on MFC immatures [19]. No information was available on the host range of *M. macadamiae* in the scientific literature because it was a species not known to science. Host information of *M. macadamiae* from Australia is provided only by collections from *A. ironsidei* on *M. integrifolia* during the 2013 HDOA survey for MFC natural enemies.

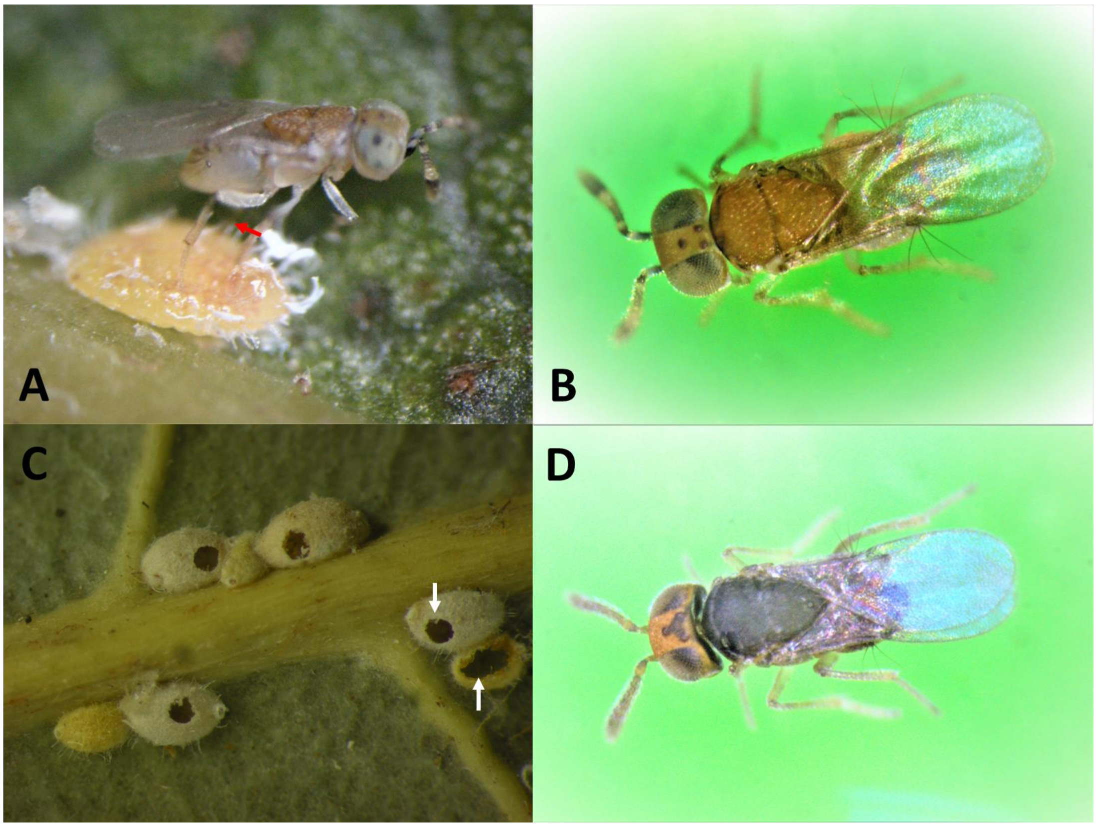


Figure 3. (**A**) Female *M. macadamiae* probing the host for oviposition (arrow showing ovipositor), (**B**) habitus of female *M. macadamiae*, 0.63–0.78 mm in length, (**C**) MFC with circular parasitoid exit holes (upper arrow) versus predation chewing holes (lower arrows), and (**D**) habitus of darker male *M. macadamiae* smaller in size, 0.46–0.66 mm in length.

In order to evaluate *M. macadamiae* as a prospective agent for the biocontrol of MFC in Hawaii, the life history, longevity, and fecundity was studied since this is a newly described species. Also host specificity testing was conducted to determine the host range of *M. macadamiae* and identify potential non-target insect hosts closely related to MFC. The objective was to determine whether *M. macadamiae* would have any negative impact on non-target insects in Hawaii either by feeding and or by ovipositing in the absence of its natural host MFC. Here, we report these findings: parasitoid performance in the native region, and extant natural enemies of MFC in Hawaii. Also, for permission purposes from state officials and USDA-APHIS, the Environmental Assessment for *M. macadamiae* has been drafted and is currently under evaluation.

2. Material and Methods

2.1. Insect Containment Facility Settings and Rearing Conditions

All biology and host specificity testing for *M. macadamiae* was conducted in the HDOA Insect Containment Facility. Wasps were reared for 10 generations before testing began. The Insect Containment Facility was 22.0 ± 1.0 °C at night and 34.0 ± 2 °C during the day, with 60–80% RH and 13L: 11D photoperiod. The purpose was to determine if this parasitoid would have any negative impact on other non-target insects in Hawaii.

Older nuts of macadamia were collected from the field and propagated in 2 L black plastic pots with drainage holes and saucer (17 cm top Ø, 12 cm base Ø, 13 cm height). Pots were held under 75% shade, and seeds germinated within 6–7 weeks. Seedlings were held until they acquired their 3rd or 4th set of leaves, before they were ready to be exposed to MFC infestation. Infested macadamia branches were brought back from the field (South Kona, 19°08′06.64″ N, 155°50′39.5″ W, 516 m) and placed on pots between seedlings. Infested seedlings took 7–8 weeks to obtain enough MFC infestation after which they were exposed to the parasitoid. Two to three pots of infested macadamia seedlings were placed in collapsible lightweight aluminum cages (30 × 30 × 60 cm) with clear vinyl doors and 70 mesh chiffon covered rear and top sides.

2.2. Host and Parasitoid Rearing

Initial parasitoid cohorts originated from infested macadamia from New South Wales, Australia. Founder cohorts were 55 wasps established in the Containment Facility, Honolulu, Oahu Island (21°17′56.00″ N, 157°50′19.69″ W, 6 m). Twenty newly emerged females and ten males were released in each cage for oviposition. A few drops of honey were smeared on the top and sides of each cage for adult feeding. Water was provided in a cup (Deli container with lid, and a cotton wick, 470 mL). After 15 days, newly emerged parasitoids were collected and used for exposure to new MFC-infested seedlings. Parasitoids were reared continuously in the HDOA Insect Containment Facility that was 22.0 ± 1.0 °C at night and 34.0 ± 2 °C during the day, with 60–80% RH and 13L: 11D photoperiod, under fluorescent light plus natural sunlight through window glass panels to facilitate mating of parasitoids [20]. The colony was reared for 10 generations before host testing was conducted.

2.3. Life History, Longevity, and Fecundity of M. macadamiae

2.3.1. Life History

Oviposition was examined by placing excised MFC-infested macadamia foliage inside a Petri dish (14.5 cm Ø × 2.0 cm height plastic Petri dishes) with *M. macadamiae* adults and observing them under a dissecting microscope (Trinocular Stereo Microscope with top and bottom lights). Wet filter paper was added to keep the leaf moist. Information on the duration of the life cycle was determined by keeping track of the first day of exposure to MFC and the first day of parasitoid emergence.

2.3.2. Longevity

Adult longevity was determined by collecting newly emerged parasitoids and placing them in 10 mL vials. Vial covers were modified to include a 5 mm Ø hole in the center, covered with a fine mesh cloth. Honey was dotted on the cloth as food. Parasitoids were examined daily for mortality. A total of 20 males and 25 females were collected and held in such vials at 5 parasitoids per vial separated by sex.

2.3.3. Fecundity

Fecundity studies were based on the female potential fecundity, potential reproductive output of an individual female over its lifetime. Newly emerged females were collected and held individually in 10 mL vials and were fed honey. Ten females at each desired age (<1–5-week-old) were dissected in saline solution, and their mature eggs were counted. Mature ovarian eggs are recognized as characteristic ovarian encyrtid eggs with a double-bodied shape, consisting of two ovoid bulbs connected by a narrow tube [21] (Figure 4). The counts reflect the potential fecundity because they are mature ovarian eggs that parasitoids can produce.

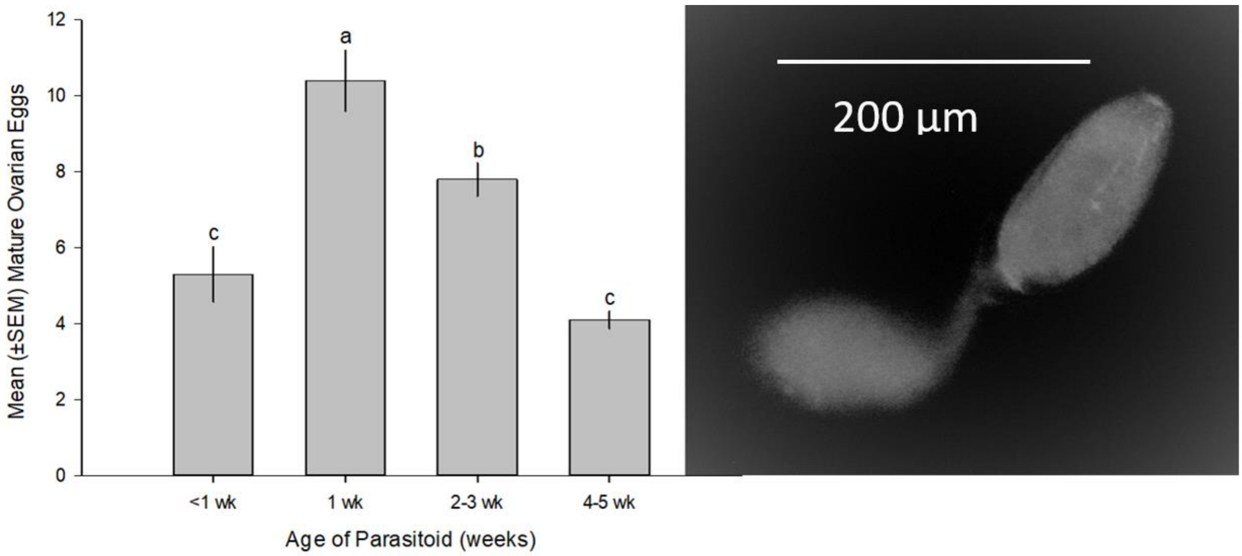


Figure 4. *M. macadamiae* potential fecundity, and ovarian maturation peaked at one-week old female. The image is a mature stalked egg typical of encyrtiform ovarian egg and is two-bodied, with a stalk tube between the two bulbs. Comparisons were performed using Tukey–Kramer HSD (ANOVA: $F_{3,36}$ = 21.8233, $p < 0.0001$). Bars topped by different letters, are significantly different.

2.4. Host Specificity Testing

Two genera in the family Eriococcidae, both adventives, are listed in the Hawaiian Terrestrial Arthropod Checklist that has all adventive members [22]. The genus *Acanthococcus* in Hawaii has one listed member, *Acanthococcus araucariae* (Maskell), a pest found on needles of *Araucaria* spp. (Araucariaceae). The second genus, *Eriococcus,* has only one listed species, *Eriococcus coccineus* (Cockerell), now moved to *Acanthococcus coccineus* (Cockerell), a new name by Miller and Gimpel 2000 [10], which is a pest on cactus (Cactaceae) that was reported only in Kauai Island. A recent addition to the eriococcid family in Hawaii is *Tectococcus ovatus* Hempel, a weed biological control agent released in 2012 to control Strawberry Guava, *Psidium cattleianum* Sabine, (Myrtaceae), Table 1, and is included in host specificity testing.

Table 1. *Metaphycus macadamiae* (Hymenoptera: Encyrtidae) host specificity study with non-target insects and macadamia felted coccid (MFC), *Acanthococcus ironsidei*, as the control.

Non-Target Insect Hosts and Host Plants					Mean% Parasitism Based on *Metaphycus emergence* and Non-Target Dissections (*n* = 3)		
Scientific Name, Order, and Family	**Stage Tested**	**Status**	**Source**	**Host Plant and Infested Plant Part Used**	**MFC (Control) % *M. macadamiae* Emergence**	**Total Non-Target Insects Dissected**	**Non-Target Insects % Parasitism**
Tectococcus ovatus (Hempel) Hemiptera: Eriococcidae	Adult and Nymph	Biocontrol agent	Lab-reared HDOA, Oahu	*Psidium cattleianum* Whole plants and seedlings	6.7	200	0
Acanthococcus araucariae (Maskell) Hemiptera: Eriococcidae	Adult and Nymph	Immigrant	Field collected, Molokai	*Araucaria* sp. Cuttings	17.5	420	0
Thysanococcus pandani (Stickney) Hemiptera: Halimococcidae	Adult and Nymph	Immigrant	Field collected, Maui	*Pandanus tectorius* Whole plants	21.7	300	0
Colobopyga pritchardiae (Stickney) Hemiptera: Halimococcidae	Adult and Nymph	Endemic	Field collected, Hawaii	*Pritchardia* sp. Cuttings	15.2	500	0
Dactylopius opuntiae (Cockerell) Hemiptera: Dactylopiidae	Adult and Nymph	Biocontrol agent	Field collected, Oahu	*Opuntia ficus-indica* Cuttings	11.7	1100	0
Saissetia oleae (Oliver) Hemiptera: Coccidae	Adult and Nymph	Immigrant	Lab-reared HDOA, Oahu	*Erythrina variegata* Whole plants and seedlings	30.6	1642	0
Pseudococcid montanus (Erhorn) Hemiptera: Pseudococcidae	Nymphs and pupae	Endemic	Field collected, Oahu	*Freycetia arborea* Cuttings	62.5	354	0
Pariaconus ohiacola (Crawford) Hemiptera: Triozidae	Nymphs and pupae	Endemic	Field collected, Oahu	*Metrosideros* sp. Cuttings	54.3	300	0
Tetraleurodes acaciae (Quaintance) Hemiptera: Aleyrodidae	Egg	Immigrant	Field collected, Oahu	*Erythrina variegata*, Seedling	38.3	300	0
Vanessa tameamea (Eschscholtz) Lepidoptera: Nymphalidae	Egg	Endemic	Lab-reared PEPS, UHM	*Pipturus albidus* Eggs placed on filter paper	57.3	55	0
Danaus plexippus (L.) Lepidoptera: Nymphalidae	Egg	Naturalized	Field collected, Oahu	*Colotropis gigantea* Foliage	19.4	30	0
Secusio extensa (Butler) Lepidoptera: Erebidae	Egg	Biocontrol agent	Lab-reared HDOA, Oahu	*Senecio madgascariensis* Foliage			

A total of twelve insect species were tested against *M. macadamiae* of which nine are economically important and endemic members of the Hemiptera: Sternorrhyncha (e.g., Aleyrodidae, Coccidae, Dactylopiidae, Eriococcidae, Halimococcidae, Pseudococcidae, and Triozidae). Some members of these families are reported hosts of *Metaphycus* spp. [23]. Additionally, some encyrtids may attack lepidopteran eggs [24]; therefore, we included three representatives of the Order Lepidoptera in our tests, i.e., one endemic *Vanessa tameamea* (Eschscholtz), one naturalized nymphalid, *Danaus plexippus* (Linnaeus), and one beneficial arctiid moth, *Secusio extensa* (Butler), released in Hawaii to control the fireweed, *Senecio madgascariensis* Poir., and *Delairea odorata* Lem. (Table 1).

Infested branch cuttings collected from the field or infested plant seedlings reared at the HDOA Insectary containing non-target insects were exposed to *M. macadamiae* for host specificity testing. A plant or plant cutting infested with one of the non-targets was placed in a (30 × 30 × 60 cm) collapsible metal cage and exposed to naïve newly enclosed groups of ten females and five males of *M. macadamiae* in each cage and held until parasitoids died. In another cage, an MFC-infested macadamia seedling was placed, and the same number of parasitoids were released inside the cage. Host specificity evaluations were based on no-choice tests. All host plants contained all stages nymphs and pupae of non-target insects. After one month, non-target insects were dissected and examined for evidence of parasitism. Three infested leaves were randomly picked from each control, and the number of MFC on each leaf was tallied and examined for parasitism. Parasitism was determined by the presence of parasitoid circular exit holes (Figure 3C), unemerged parasitoid cadavers, and dead MFC due to parasitoid probing marks. Parasitism in the control replicates was determined with adult parasitoid emergence and parasitoid circular exit holes. In the case of the tested lepidopteran eggs, plant parts containing eggs were collected and placed in Petri dishes (2.0 cm height × 14.5 cm Ø). Five females and five males of *M. macadamiae* were released inside each Petri dish. Unhatched eggs were examined under a dissecting microscope for evidence of probing or oviposition which left traces of recognizable blacken melanized oviposition scars. All tests were replicated three times.

2.5. Parasitoid Field Performance in Australia

M. macadamiae was dissected from MFC on infested leaves of *Macadamia integrifolia* collected in Alstonville, NSW, Australia. Two batches of infested macadamia leaves were collected from different trees that were not known to be sprayed with insecticides, and subsequently shipped to HDOA ICF. One consignment was obtained on 19 November 2013 (*n* = 150 infested leaves, 28°51′20.14″ S, 153°26′31.40″ E, 136 m), from Alstonville, NSW, Australia, and Department of Primary Industry of Australia and another batch of (*n* = 130) infested leaves, on November 25, 2013, from the same locality (28°49′13.51″ S, 153°23′44.65″ E, 168 m). MFC individuals collected on the infested macadamia leaves yielded only adult *M. macadamiae* wasps. Mean numbers of MFC/leaf, % parasitism by *M. macadamiae*, and % predations were recorded from leaves and petioles (*n* = 30) of infested leaves. Parasitism and predation rates were determined by shape of parasitoid exit holes or predation chewing holes. Dominant predators on the trees were photographed, and one species was identified using keys of Australian Lady Beetles [25]. Parasitism was determined by counting the MFC with circular holes of parasitoid emergence (Figure 3C, white arrows), and predation was determined by the larger oblong irregular holes on scales (Figure 3C).

2.6. Extant Natural Enemies in Hawaii

Relative abundance of local natural enemies of MFC on three orchards on the island of Hawaii; Pahala, South Hilo (19°08′08.35″ N, 155°50′44.78″ W, 503 m); Honokaa, North Hawaii (20°04′5.07″ N, 155°28′19.92″ W, 476 m); and Honomalino, South Kona (19°08′06.64″ N, 155°50′39.5″ W, 516 m) were studied by counts of parasitoids and predators on sticky traps. Ten randomly selected infested trees per orchard were designated. Yellow sticky traps set for flying insects (5 cm wide × 15 cm length) with glue on one side were placed one per tree on infested branches at ≤2 m above ground. Traps were replaced every month, and numbers of parasitoids and predators stuck on traps were microscopically tallied as means ± SEM of parasitoids and five species of coccinellids/trap/month/orchard during twelve months of 2015. *Encarsia lounsburyi* (Berlese & Paoli) (Hymenoptera: Aphelinidae), a parasitoid of male MFC, and *Curinus coeruleus* Mulsant (Coleoptera: Coccinellidae) were the dominant parasitoid and ladybeetle in macadamia fields, respectively, during this survey [12].

2.7. Statistical Analysis and Vouchers

For studies on field parasitism in Australia, an analysis of variance was used to assess the potential significance of differences in the number of parasitoids produced by the *M. macadamiae* parasitism, % parasitism, and % predation. Means were separated with Tukey's standardized range honestly significant difference test and unequal variances Welch's *t*-test at $p = 0.05$ level [26]. Percentage data were transformed arcsine $\sqrt{}$ proportion before analysis. Voucher specimens and paratypes of *M. macadamiae* were placed in the insect reference collection of the HDOA, the Bernice P. Bishop Museum, Honolulu, Hawaii, and the Department Life Science Collections of the Natural History Museum, London. Vouchers specimens are deposited in Australian National Insect Collection, CSIRO, Canberra, Australia, United States National Museum, Washington D.C., USA, and the Hawaii Department of Agriculture insect collection [19].

3. Results

3.1. Life History, Longevity, and Fecundity of M. macadamiae

3.1.1. Life History and Longevity

Adult emergence ranged from 12–21 days after MFC exposure to parasitoids depending on temperature. In the summer, June–August, maximum indoor temperature ranged 31.9–32.2 °C, when days were warmer males were seen emerging as early as 12 days after exposure. *M. macadamiae* can have multiple generations per year under laboratory conditions.

M. macadamiae females had on average a longer lifespan compared to the short-living males. Mean ± SEM of female longevity was 32.9 ± 3.1 d and that of male longevity was significantly shorter at 8.3 ± 1.4 days ($t = 7.1679$, df = 32.57, $p < 0.0001$).

3.1.2. Fecundity

Number of mature ovarian eggs in ≤1 week-old females seen in dissections ranged 3–10 eggs with a mean ± SEM of 5.3 ± 0.73 mature eggs. Maximum egg production peaked at 14 ovarian eggs in one-week-old females with a mean of 10.4 ± 0.8 mature eggs per female and declined thereafter to 7.8 ± 0.4 and 4.1 ± 0.2 as the female aged to 2–5-week-old (Figure 4). This indicated that *M. macadamiae* is a synovigenic species that produces mature eggs throughout its adult life and resorbs eggs at an older age ($F_{3,36} = 1.823$; $p < 0.0001$).

3.2. Host Specificity Testing

Host specificity study proved that *M. macadamiae* is specific to MFC. There was no parasitoid emergence from any of the twelve non-targets tested. Moreover, dissections revealed no evidence of parasitism nor host feeding on non-targets. Although parasitism rates varied between controls, all had some degree of emerged parasitoids, ranging 6.7–62.5% (Table 1).

3.3. Field Parasitism Evaluation of M. macadamiae in Australia

The rate of parasitism in the field ranged 21.2–32.7% in Alstonville, during the November 2013 sampling. Predation reached a mean of ≥5% with two recognized predators. Mean infestation ranged 16.7–19.9 MFC/infested leaf during November 2013. Parasitoids perform better on leaves, with a higher parasitism rate on leaves than petioles (Figure 5).

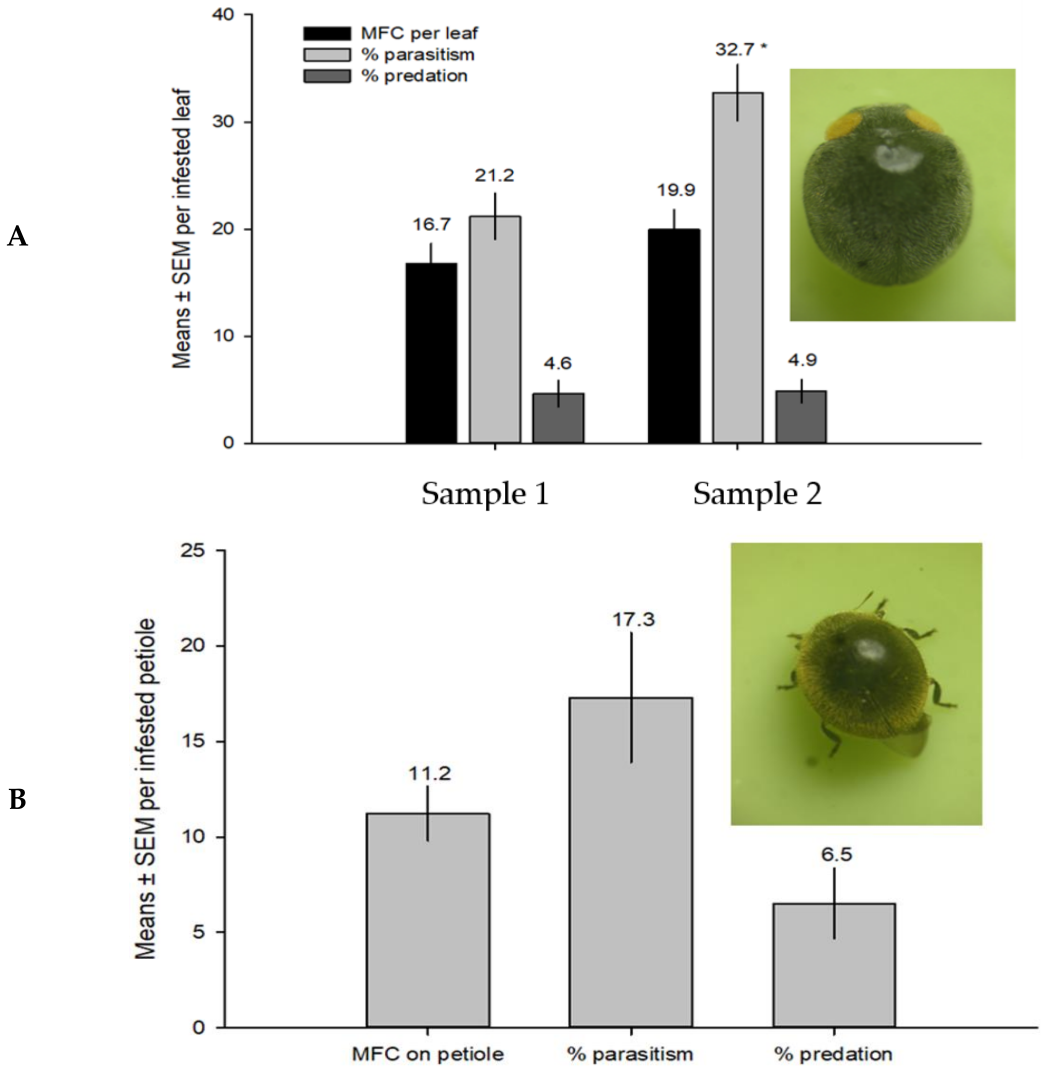


Figure 5. Field infestation by MFC, and *M. macadamiae* performance on (**A**) leaves and (**B**) on petioles parasitism and % predation, during November 2013, at Alstonville, NSW, Australia. Two dominant predators, with only one species identified, and inset bottom is *Rhyzobius ventralis* (Erichson). (*) significantly different ($p < 0.05$).

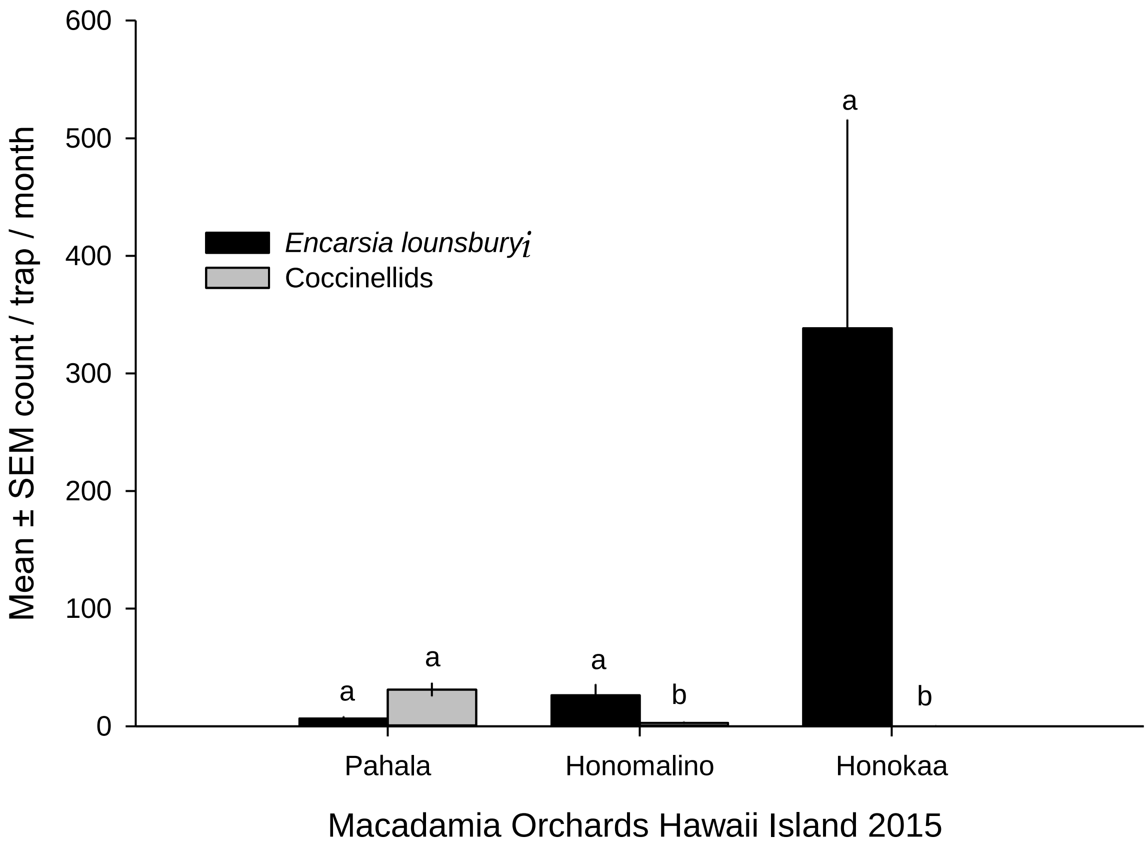
3.4. Extant Natural Enemies of MFC in Hawaii

Several coccinellid predators and the aphelinid parasitoid, *Encarsia lounsburyi*, are known natural enemies of MFC in Hawaii, but their impacts alone are insufficient to suppress MFC populations. The average count of trap catches per month in three macadamia orchards on the island of Hawaii during 2015 showed that the parasitoid *E. lounsburyi* is thriving especially in Honokaa Orchards. In comparison, predation with coccinellid counts were significantly low (Figure 6).

The Pahala site had no significant differences between the densities of *E. lounsburyi* and *C. coeruleus*, whereas Honomalino had mean count differences of 25 parasitoids to 5 predators, measured as individuals/trap/month. Honokaa had no incidence of *C. coeruleus*, and only *E. lounsburyi* was present with mean counts above 300 individuals/trap/month (Figure 6).

(**A**)

(**B**)



(**C**)

Figure 6. Relative abundance of extant natural enemies of MFC on three orchards on the island of Hawaii during 2015. Values are means ± SEM of parasitoids and five coccinellids per sticky trap per month placed on infested macadamia trees. (**A**) *Encarsia lounsburyi* (Hymenoptera: Aphelinidae) on MFC male scale. White male scale is about 1.0 mm long. (**B**) *Curinus coeruleus* (Coleoptera: Coccinellidae), a dominant lady beetle on macadamia fields. (**C**) Parasitoid or predator bars topped with same letters in three orchards are not significantly different ($p > 0.05$).

4. Discussion

Field surveys of natural enemies in macadamia nut orchards on the island of Hawaii revealed the presence of several predatory coccinellid beetles (*Halmus chalybeus* (Boisduval), *Rhyzobius forestieri* (Mulsant), *Sticholotis ruficeps* Weise, and *Telsimia nitida* Chapin), and the parasitic wasp *Encarsia lounsburyi*, associated with MFC [15]. The parasitic wasp, *E. lounsburyi*, was first found associated with MFC infestations on the island of Hawaii in 2005 [27]. *E. lounsburyi* is recorded to parasitize a range of diaspidid scale insects and is not host specific to MFC like the Australian *M. macadamiae* [28]. All species of Diaspididae are adventive in Hawaii [22].

Local natural enemies in Hawaii may play a minor part in reducing numbers of MFC, but do not prevent populations from reaching damagingly high densities. They are considered generalists, and their impacts on high MFC infestations are inadequate to reduce the pest populations below economically injurious levels. With the high MFC populations that are typical in Hawaii, macadamia nut orchards biocontrol is hopeless without an effective specialized agent [29]. Our laboratory studies show that MFC parasitism rate with *M. macadamiae* can range from 11 to 62% (Table 1), higher than estimates from field parasitism in Australia (21–33% parasitism). In addition, female wasps host-feed on MFC nymphs, thereby adding to the mortality of MFC attributable to the wasp. The addition of *M. macadamiae* to the assembly of natural enemies exploiting MFC will hopefully decrease pest population levels so densities of MFC are reduced to tolerable levels as in the native Australia.

Metaphycus macadamiae is a newly described species. No records of performance exist in the scientific literature. Other members of this genus are known as primary endoparasitoids of scale insects, and a few species of the Encyrtidae family parasitize eggs of some lepidopterans [30].

Historically, three species of *Metaphycus* have been released in Hawaii from previous biological control introductions, i.e., *Metaphycus clauseni* (Timberlake), *M. helvolus* (Compere), and *M. luteolus* (Timberlake), and were purposefully released as biological control agents of soft scale insects and mealybugs in the period 1934–1964. The parasitoids originated from California, but the establishment is unknown for the three species [22,31]. Additionally, seven *Metaphycus* species were accidently introduced to Hawaii and recorded as natural enemies of scale insect pests on major Hawaiian Islands: *M. alberti* (Howard), *M. anneckei* Guerrieri & Noyes, *M. claviger* (Timberlake), *M. eruptor* (Howard), *M. flavus* (Howard), *M. portoricensis* (Dozier), and *M. stanleyi* Compere. All seven species were established on various islands [22,31]. No non-target parasitism of native insects in Hawaii was recorded by *Metaphycus* species since their first introduction in 1934 [31].

In 2017, MFC was found severely infesting macadamia nut trees in Barberton valley, Mpumalanga province, South Africa [32,33], where it is also a devastating pest to the country's macadamia nut producing industry, due to the rapid spread within a month to White River Macadamia orchards, presumably through infested plant material [34]. South Africa has been the world's largest producer of the macadamia since the 2010s [35,36].

A starter colony of *M. macadamiae* (200 wasps) was hand-carried from Hawaii to a South African quarantine facility for propagation The colony arrived in good condition (Dr. Mark Wright, University of Hawaii at Manoa, unpublished). Unfortunately, this culture was lost before any permission to release in the field. In addition to our information on host testing, South Africa may need to consider study specificity on other introduced eriococcid species of South Africa (i.e., *E. coccineus* Cockerell, *E. araucariae* Maskell, *E. leptospermi* (Maskell), and the native species *Calycicoccus merwei* Brain [37].

In Australia, MFC is only a problem in newly infested localities until natural enemies catch up to exert adequate control [9]. The infestation and rate of parasitism from the sampled leaves indicated that *M. macadamiae* is the dominant natural enemy. *M. macadamiae* seems to perform better on leaves showing higher rates of parasitism than on petioles and stems. Infested leaves may be more attractive to the parasitoids because of higher MFC density and presence of honeydew drops on leaves (Figure 5).

The longevity of the adults of *Metaphycus* species is known to be influenced by available food sources of insect hosts and sucrose availability of adult diet. Non-fed adults did not survive past the second day, while honey-fed individuals lived more than six days in some species [38]. In our laboratory experiment, the MFC-infested leaves would provide a sugar diet content to the parasitoid. This may also happen in the field without dependence on flowering plants for nectar (Figure 2C). Still, female *M. macadamiae* are observed to partake in insect host feeding. They were observed to penetrate the young hosts by ovipositor and then to feed on oozing fluid from immature MFC. Females do not use these young, shriveled individuals for oviposition. Host feeding increases parasitoid longevity and their potential fecundity in naïve wasps [38]. Similar results of longevity of *Metacphycus* spp. indicate non-ovipositing females lived on average about eight days, whereas ovipositing females lived on average about five days [39].

Insect growth regulators (IGR) and horticultural oils insecticides are currently used to help control MFC in Hawaii. Some of these insecticides have negative impacts on natural enemies that are present in orchards, such as Coccinellidae and parasitoids. Based on studies by Gutierrez-Coarite et al. 2017 [15], insecticide treatments with IGR compounds are appropriate when MFC populations are high, whereas horticultural oils combined with natural enemies are most effective when populations are low. The use of chemicals to control MFC may negatively impact the extant natural enemies in macadamia orchards and honeybees. Honeybees are essential for pollination in macadamia fields. Therefore, a specific parasitoid like *M. macadamiae* is desirable.

Cultural control is an essential component of the integrated pest management system utilized by macadamia orchards in Hawaii. Keeping macadamia nut trees healthy by maintaining the right soil moisture, fertilizing, cleaning, and pruning helps defend them against MFC infestation. In addition, MFC infestation is heaviest in shaded sites within the orchards and on trees with sucker shoots [7,28]; hence, trees need to be pruned and cleaned regularly to prevent build-up of MFC populations. However, cultural management alone is insufficient to reduce MFC impacts.

5. Conclusions

Like several other *Metaphycus* species released in previous biological control programs, this endoparasite wasp is highly unlikely to produce any adverse effect on the fauna of Hawaii, both native and beneficial introduced species including the lepidopteran eggs. Being a monophagous species, *M. macadamiae* females will exclusively seek MFC nymphs for host feeding, and young adult MFC for oviposition. MFC and macadamia crops are expected to be the only organism in Hawaii that will be affected by the release of this parasitoid. Observations in the native region indicate that *M. macadamiae* is restricted to MFC hosts reaching up to 33% parasitism in Australian fields, making MFC a minor pest of *Macadamia*. Host specificity testing in the HDOA-PPC Insect Containment Facility demonstrated that *M. macadamiae* will only attack the target pest *A. ironsidei*. There are few immigrant pest species closely related to MFC existing in Hawaii, further minimizing any potential for unexpected impacts in Hawaii once *M. macadamiae* is released. This report of host specificity and parasitoid performance should support decision making for release permits in Hawaii or infested regions in South Africa. The parasitoid was unable to successfully emerge or feed on any tested non-target species.

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APPENDIX C: CULTURAL IMPACT ASSESSMENT FOR PROPOSED STATEWIDE RELEASE OF *METAPHYCUS MACADAMIAE* TO CONTROL MACADAMIA FELTED COCCID

Cultural Impact Assessment for Proposed Statewide Release of *Metaphycus macadamiae* to Control Macadamia Felted Coccid

Principal Investigators
Suzanne Shriner
Joan Obra
Krista Johnson

Synergistic Hawaii Agriculture Council
190 Keawe St, Suite 25
Hilo, Hawaii, 96720
info@shachawaii.org
808-365-9041

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Introduction

At the request of the University of Hawaiʻi (UH), the Synergistic Hawaiʻi Agriculture Council (SHAC) conducted a Cultural Impact Assessment (CIA) for the proposed statewide release of *Metaphycus macadamiae* (Hymenoptera: Encyrtidae). Used as a biocontrol in macadamia, *M. macadamiae* is a tiny wasp that targets and parasitizes the macadamia felted coccid (MFC) *Acanthococcus* (previously *Eriococcus) ironsidei* (Hemiptera: Eriococcidae).

This CIA and its interviews were designed to identify any utilization of macadamia for cultural practices or community concerns about environmental impacts from the release of *M. macadamiae*. It is a companion document to an Environmental Assessment drafted by Hawaiʻi Department of Agriculture (HDOA) and UH and was prepared in adherence with the Office of Environmental Quality Control (OEQC) *Guidelines for Assessing Cultural Impact*, adopted by the Environmental Council, State of Hawaiʻi, on November 19, 1997 and pursuant to Chapter 343 of the Hawaiʻi Revised Statutes as well as the 2019 revisions to HAR Chapter 11-200.1.

Proposed Action

Biological control (biocontrol) is a component of an integrated pest management strategy. It is defined as the reduction of pest populations by natural enemies and typically involves an active human role (Flint, 1998). Classical biocontrol is the selection and introduction of a natural enemy of an invasive plant or insect pest, and then "reuniting" of this natural enemy with the invasive pest to provide long-term, cost-effective, and sustainable pest management. Both State and Federal agencies have been cooperating on biocontrol activities to minimize the threat of invasive pests in Hawaiʻiʻs natural environment. Selection of a biocontrol for potential release undergoes a multi-step regulatory process to ensure native plants, insects, or traditional and customary practices are not impacted by the introduction.

Macadamia integrifolia and *Acanthococcus ironsidei*

The macadamia (*Macadamia integrifolia*) is an introduced plant to Hawaiʻi. Indigenous to the west coast rainforests of Australia, it is the only native Australian plant to attain the status of a commercial food crop (Hamilton, et al. 1983). It was first introduced to Hawaiʻi in 1881 (Shiguera et al. 1984), with further introductions by the Territorial Department of Agriculture between 1891 and 1895. At the time of introduction, the nut had no commercial uses due to the hardness of the shell. The early trees were primarily planted for windbreaks or as an ornamental "delicious oddity" by island residents. The fallen nuts were noted to attract puaʻa (pigs), and also hunters in search of puaʻa.

Attempts at creating a commercial crop occurred several times before taking hold. In 1919, the Hawaiʻi Agricultural Experiment Station in Makiki Valley distributed seedlings to coffee farmers to supplement their income. However, coffee prices remained high through the 1920's and interest declined in the Kona districts (Hamilton et al., 1959). The exception was a commercial farm with locations on Oʻahu (Tantalus) and Hawaiʻi Island (Keauhou). To facilitate further interest in the crop, the 1927 Territorial Legislature exempted macadamia lands from taxation for five years.

The early years were characterized by the challenge of developing machinery to crack the hard shell without crushing the nut inside, as well as experiments in cooking, salting and flavoring the nutmeat. This went hand in hand with an expansion of field research at the Hawaiʻi Agricultural Experiment Station, and the identification of varieties that were best suited for growers and consumers. Small-scale marketing and crop development continued until critical mass was reached in 1945. At that time, a UH graduate and agriculturist, Leon Thevenin, brought samples of processed nuts to the annual meeting of the Hawaiian Sugar Technologists. It has been described as a "historic date" for interest in the crop (Shiguera et al. 1984).

The island of Hawaiʻi hosted the expansion of the industry. In 1948, Castle & Cooke planted the first major orchard in Keaʻau, with 1,000 acres. Their brand was credited with popularizing the nut to the consumer. In the early 1960's, 3,500 acres were planted in Honomalino under the Mac Farms label. The Pāhala area was planted by C. Brewer, peaking at 2,000 acres. All of these regions are still heavily planted in macadamia, although ownership has changed over time.

In addition to the large plantation agribusinesses, family growers such as Joe Kamagaki and the Oue brothers expanded acreage in the Kona districts. These, and many other growers around the island, operated their own mills and sold nuts into the Oʻahu chocolatier market. With the rise of the tourism market and *omiyage*, these confections earned Hawaiʻi the reputation as the "home of the macadamia nut" (despite its Australian origins). To this day, chocolate-covered macadamias are a sought-after gift item by visitors and residents alike.

The nut's popularity grew among farmers, who considered macadamia as a more price-stable crop than coffee and other cyclical commodity crops. Historically, the nuts were in short supply, whereas coffee had boom-and-bust cycles. This led to a rise in small family farm orchards, peaking at 19,300 acres in 1995 (NASS 2021). The demand was noted globally as well, with Australia and South Africa developing significant industries of their own. The rise in competition from the foreign crops has led to more price instability as of late.

Macadamia continues to be an economically important crop, with 16,800 acres in production across the state and a farmgate value of $49 million in 2021. According to the most recent agricultural census, there are 835 farms. The majority of commercial growers are smallhold, with 612 farms operating on less than five acres of land, and are considered socially-disadvantaged by the USDA (NASS, 2017).

Figure 1: Commercial macadamia field in North Kohala, Island of Hawaiʻi
Photo courtesy of Nathan Trump

In late February 2005, a commercial plantation in South Kona noted a new insect infestation. University of Hawaiʻi staff tentatively identified it as the macadamia felted coccid (MFC) *Acanthococcus* (previously *Eriococcus*) *ironsidei* (Hemiptera: Eriococcidae). The USDA confirmed the identification through their lab in Beltsville, Maryland (HDOA, 2005). It is assumed the pest arrived in the 1990's on scion wood, used for grafting. By 2009, it had spread throughout Hawaiʻi Island, with economically damaging infestations in many locations (Wright and Conant 2009).

Like its host tree, the MFC is native to Australia, and infests all above-ground parts of the tree (Ironside, 1978). It is a minor pest in its native provenance, and there is a scarcity of published literature pre-dating its Hawaiʻi discovery (Gutierrez-Coarite, et al. 2019). The sap-sucking insects can stunt and distort new growth, causing dieback of entire branches in cases of high insect density. Young foliage with a high rate of photosynthesis on macadamia nut trees is essential for the development of nuts, and the accumulation of oils in them (Stephenson, 1990). In Australia, insecticidal oils are applied for MFC control when an outbreak occurs; however, natural biological control by *Metaphycus sp*. (Hymenoptera: Encyrtidae) is usually sufficient to prevent economic losses in commercial settings (Wright and Conant 2009).

Figure 2: Infestation of MFC appear as a thick crust on nut and branches
Photo source: themacadamia.co.za

A. ironsidei is currently the only macadamia pest in Hawaiʻi that requires consistent and aggressive management. Left untreated, it can reduce yields by 60%. Treatment with standard insecticides adds a significant cost for management in terms of equipment, fuel, labor, water and insecticide purchases that growers were not incurring prior to the invasion and spread of MFC. There are also concerns with the use of insecticides in terms of environmental impacts on non-target species and groundwater. (Gutierrez-Coarite, et al., 2020).

Hawaiʻi – Historical and Cultural Background

PRE-SETTLEMENT

GEOGRAPHICAL

The Hawaiian Islands lie in the middle of the vast Pacific Ocean located approximately 2,500 miles from the nearest continent on the Earth. Islands rose individually to the surface as the Pacific Plate drifted north-northwest over a lava hot spot creating these new land masses. The youngest and most southern island in the chain, Hawaiʻi, is thought to be about 400,000 years old. Niʻihau and Kauaʻi to the northwest end of the main Hawaiian islands are aproximated to be about 3-5 million years old. The newest formation south of Hawaiʻi island, Lōʻihi, will most likely reach the surface in 50,000 years. Kure Atoll to the far northwest of the archipelago is one of the atolls still above water, close to 30 million years old (Olson, 2004). The islands are host to many diverse climate zones and the largest mountain on the planet, Mauna Kea on Hawaiʻi island, standing at 39,000 feet (14,000 metres) if taken from measurement at its sub-surface base to its summit (Wylie, 2015).

The main and most populated islands in the Hawaiian-Emperor Chain are Hawaiʻi, Maui, Kahoʻolawe, Lānaʻi, Molokaʻi, Oʻahu, Kauaʻi and Niʻihau. The Papahānaumokuākea Marine National Monument, established in 2006, extends from Nihoa northwest to Kure Atoll. Stretching over 1,350 miles and covering 582,578 square miles, it is one of the largest marine conservation areas on Earth, offering both environmental and Native Hawaiian cultural protections (Papahānaumokuākea Marine National Monument).

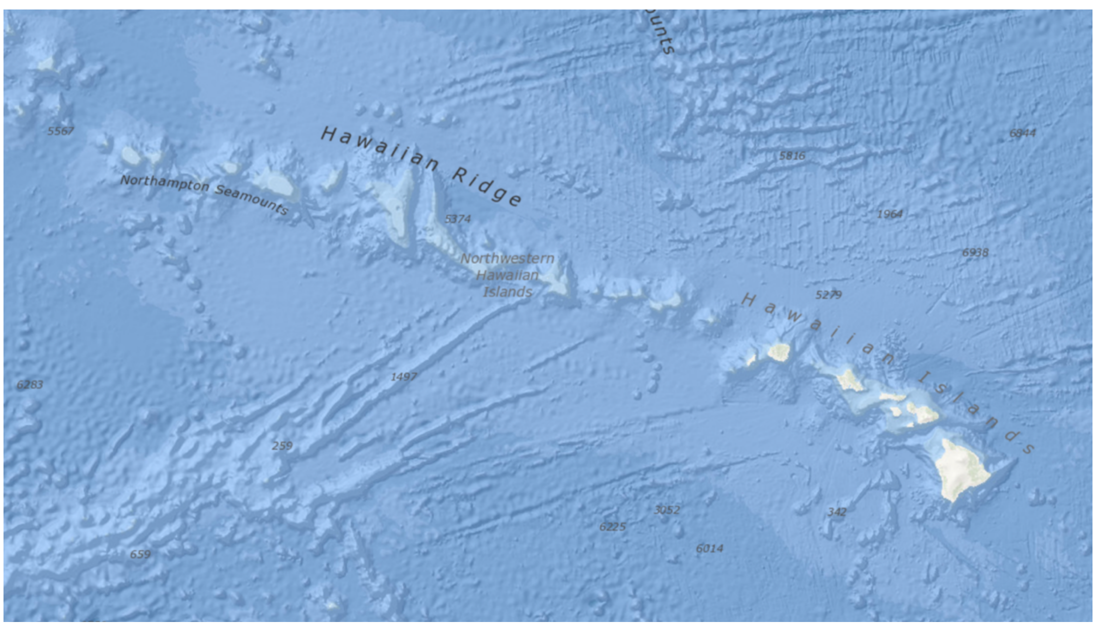

Figure 3: Map of the Hawaiian Archipelago
NOAA

PLANTS AND ANIMALS

The position of these islands on the planet created space in which flora and fauna developed unimpeded and unchallenged. Various birds, trees, plants, and creatures of the sea and land made their way by air or water here to thrive on the shores and slopes of this volcanic chain, creating an abundance of life (Olson, 2004). This life would eventually come to support the Polynesians who made their way across the Pacific to the many island groupings in one of the most rapid settlement excursions known to humans.

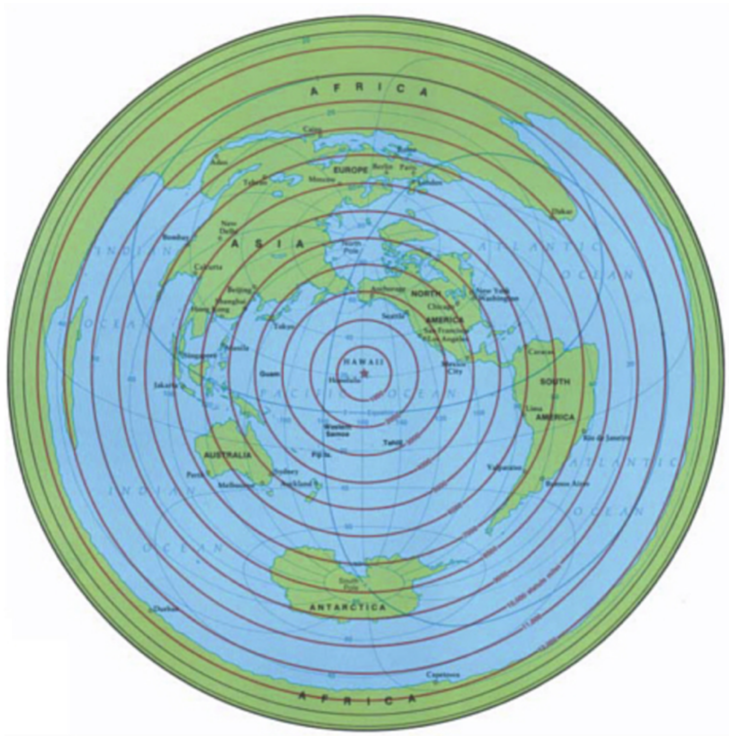

Figure 4: Azimuthal equidistant projection map Hawaii (Armstrong, 1983)

Prior to the arrival of the Polynesians, Hawaiʻi lay untouched except for the natural forces of tsunami, earthquakes, hurricanes, drought and even blizzards atop the peaks of its highest mountains. The plants, animals and insects that made their way here established themselves and became some of the most unique species on the planet. Although similarities can be seen with their counterparts on the continents, many developed interesting new characteristics. Typical protective defense systems in place in these organisms on the continents were lost over time as there were no predators nor competitors to challenge them (Olson, 2004). Stinging nettles on the mainland of North America, for example, has a relative here in Hawaiʻi known as māmaki (*Pipturus albidus*). Māmaki has lost the stinging leaf its mainland relative is known for, however still carries the same usages in medicinal remedies (Bishop Museum, 2021).

Early examples of these pre-settlement species include fern spores, koa, pōhuehue (beach morning glory), snails, and insects most likely from North America. Tradewinds that prevail from the Northeast and storms from the South most likely helped propel them to the Hawaiian islands (Dunford et. al, 2013). Once here, as mentioned above, many lost their natural defenses due to lack of predation and continually diversified, adapting to the wetlands and drylands of the islands.

Plants existing pre-settlement:

Koa, pūkiawe, māmaki, ‘a‘ali‘i, olonā, ‘uki‘uki, kauila, ‘ōlapa, ‘ākala, maile, māmane, ‘ōhelo, ‘ūlei, hāpu‘u, ‘ilima, alahe‘e, alani, ‘ōhi‘a lehua, mokihana and wiliwili (Dunford, et. al. 2013).

SETTLEMENT & PRE-EUROPEAN CONTACT

There is dispute as to the actual dates of arrival of the Polynesians who settled the Hawaiian islands. Current archaeological carbon dating points to 1000 CE as the approximate date of first settlement in the islands although ranges from 800-1200 CE are possible (Kirch, 2011 and Cordy 2000). Two possible sources for the voyagers who made their way to Hawai‘i are the Marquesas (Nu‘uhiwa) c. 900 CE and Tahiti (Kahiki) c. 1200 CE (Dunford et. al. 2013).

Polynesian settlers sailed with many plants and animals on their wa‘a (canoes). The history of settlement is also the history of agriculture, and of species introduction. During the pre-contact era up to about 1450 CE, when migration seems to have slowed perhaps due to the Little Ice Age (Dunford, et al. 2013), several species were introduced.

Species introduced by Polynesians:

pua‘a (pig), moa (chicken), ‘īlio (dog), ‘iole (rat)

kō (sugar cane), 'ohe (bamboo), niu (coconut palm), kalo (taro),
kī (ti), pia (Polynesian arrowroot,), uhi (yam)
Pi'a (Five-Leafed yam), mai'a (banana), 'ōlena (turmeric)
'awapuhi (wild ginger), 'awa (kava), 'ulu (breadfruit)
wauke (paper mulberry), pa'ihi (nasturtium), auhuhu (Fish Poison
plant), kukui (candlenut tree), hau (hibiscus), milo (Portiatree)
kamani (Alexandrian laurel), 'ōhi'a 'ai (mountain apple)
‘uala (sweet potato), kou (Cordia wood), noni (Indian mulberry)
ipu (Bottle gourd) (Dunford, et. al. 2013 and St. John et. al 1980).

The introduction of these new species provided great sustenance for the kanaka maoli (Hawaiians) (Dunford et. al. 2013). These species, however, also began to encroach upon the endemic pre-settlement species. Puaʻa dug up rooted vegetables and "the main source of destruction of the native forests was the introduction of the Polynesian rat, *Rattus exulans*" (Athens et. al, 2002). Prehistoric avian species also suffered from the rat but also from human settlement as initially forests where the birds resided were burned and cleared for agricultural development by the settlers.

LAND DIVISIONS AND SOCIETAL STRUCTURE

"Hawaiian integrated farming systems evolved and proliferated within a unique socio-cultural context" (Costa-Pierce, 1987).

AHUPUAʻA

Islands in the Hawaiian language (ʻōlelo Hawaiʻi) were called mokupuni. Mokupuni were divided into moku (districts) and within these moku were created smaller areas called ahupuaʻa (Williams, 1997). In some ahupuaʻa there were even smaller areas: ʻili kūpono and ʻili ʻāina (Dunford et.al, 2013 and Cordy, 2000). Most important, however, were the ahupuaʻa.

Ahupuaʻa usually ran from mauka to makai (mountain to ocean) with possible smaller ones that didnʻt have this feature. Residents worked and gathered within their ahupuaʻa which were designed to provide resources for them from upland crops to ocean provisions (William,1997).

There were three distinct areas within these ahupuaʻa: uka, which included mountain and upland areas; kula, the flat and sloping plains and fields; and kai, the seashore and sea environment sometimes up to a mile offshore (Williams, 1987). Frequently the uka and kula zones would be terraced cross-slope to retain soil and prevent erosion. However, this pattern was notably different in the dry Kona region, where kua'iwi, or stone ridges, ran mauka-makai in a diverse matrix of crops (Lincoln, 2014).

The Kona Field System was considered a marvel by early European visitors, and was indicative of the intensive agricultural activity and horticultural expertise of Hawaiian farmers. Archibald Menzies, a botanist who traveled with Captain George Vancouver, wrote in 1794:

> "On leaving this station, we soon lost sight of the vessels, and entered their breadfruit plantations…The size of the trees, the luxuriance of their crops and foliage, sufficiently show they thrive equally well…The space between the trees did not lay idle. It was chiefly planted with sweet potatoes and rows of cloth plant (wauke). As we advanced beyond the breadfruit plantations, the country became more and more fertile, being in a high state of cultivation…In clearing the ground, the stones were heaped up in

ridges between the little fields and planted on each side, either with a row of sugar cane or the sweet root of these island (ti)…so that even these stony uncultivated banks are by this means made useful to the proprietors, as well as ornamental to the fields they intersect. The product of these plantations, besides the above mentioned, are the cloth plant, taro, and sweet potatoes…The whole field is generally covered with a thick layer of hay, made from the long coarse grass or the tops of sugar cane, which continually preserves a certain degree of moisture in the soil that would otherwise be parched by the scorching heat of the solar rays…Their fields in general are productive of good crops that far exceed in point of perfection the produce of any civilized country within the tropics."

Figure 5: Kua'iwi mauka-makai wall in a Hōnaunau field. Height is 2 ft, width is 12 feet.

The kuaʻiwi system is still evident today, and forms the backbone of land in use for agriculture and macadamias in South Kona.

Within each ahupuaʻa area, crops were cultivated for specific microclimate zones. Uka provided trees and plants used for canoe-building, weaponry, tools, cloth (kapa), cordage, lei and feathers for aliʻi clothing collected from the native birds in these upland forests. The kula plains grew most of the food plants including maiʻa (at the fringes of uka), kalo, ʻulu, ʻuala and uhi. Kukui for oil, ipu for gourds, kī for capes and pili grass for thatched roofing were also grown in the kula areas. Finally, kai was where Hawaiians resourced fish (iʻa), salt (paʻakai), limu (seaweed), coconut, hau, hala and noni. The kai sections, especially in leeward areas where the water was calm and shallow, sometimes were host to the loko iʻa (fish pond). These loko iʻa housed Hawaiian fish farms which are being revitalized even today (Dunford et. al, 2013 and Williams, 1997).

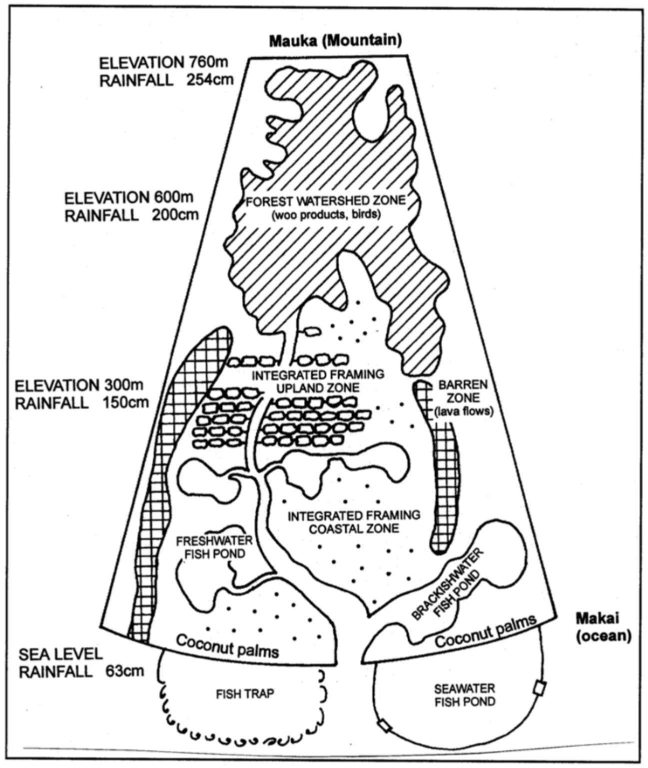

Figure 6: Example of individual ahuapuʻa configuration (Davidson-Hunt, 2021)
Adapted from Costa-Pierce (1987)

Governance of these ahupuaʻa followed a distinct chain of command. Mokupuni were led by an aliʻi nui (high chief). Each moku, or district, within the mokupuni was governed by an aliʻi ʻai moku (lesser chief). Ahupuaʻa divisions within a moku were controlled by the aliʻi ʻai ahupuaʻa who in turn had konohiki (headmen) to oversee the people (makaʻāinana) farming and caretaking the lands. Sometimes the aliʻi ʻai ahupuaʻa and konohiki were the same person (Dunford et. al, 2013).

LAND TENURESHIP

Most of the population chose to live in small villages on non-agricultural land near the shore or clustered around bays where the air was warm and dry (Dixon, 1789). Hawaiian settlements developed around not just the environmental landscape, but also in accordance to societal organization of the aliʻi, konohiki and makaʻāinana (Kirch, 2011). Farming was usually done by a family unit known as an ʻohana. These family relationships were core to the pre-contact farming practices and of great significance to the Hawaiians (Costa-Pierce, 1987). ʻOhana created and maintained complex agricultural systems "that connected agricultural watersheds to oceanic environments" (Costa-Pierce, 1987).

The traditional management system for the early Hawaiians was based on strict kapu, laws meant to preserve societal order. These kapu pertained to aspects of daily life which included practices in religion, ways of eating, areas one was allowed to enter and times of harvest and gathering to name just a few. Some of these kapu were so strict they carried the penalty of death (Dunford et. al, 2013). In general practice, the ʻauhau (taxes) were gathered during the Makahiki (gathering time for collecting taxes with focus on more celebratory aspects of life versus war) (Iʻi , 1959).

The concept of land ownership viewed through Western culture is far different from the Hawaiian socio-cultural understanding of ownership. The makaʻāinana worked the land for the aliʻi ʻai moku who oversaw the district in turn for the aliʻi nui. In essence, it was a system of feudal tenureship with freedom to move within the ahapuaʻa and with the responsibility to pay your taxes in the form of food and animals once a year to the aliʻi (Handy & Pukui, 1998).

This idea and practice of tenureship is what would help contribute to the downfall of the Hawaiian farming practices. It would also provide the opening for Westerners, post-contact, to permanently change the landscape and traditional lifestyle and welfare of the Hawaiian people.

EUROPEAN CONTACT & THE HISTORIC PERIOD

"With the general demise of native Hawaiian society, the majority of Hawaiian integrated farming systems fell into disuse and disrepair" (Costa-Pierce, 1987).

The arrival of Captain James Cook to the islands in 1778 CE heralded immense change for the Hawaiian people who had lived for approximately a millenia without contact except from other occasional Polynesian voyagers (Kirch, 1998).

The next most significant person in the initial contact years was Captain George Vancouver who had served as an officer to Cook. Returning in 1791 leading the second British expedition, he made several trips to the islands bringing cattle (pipi), goats, geese, sheep and oranges (Speakman & Hackler 1989 and Hawaiʻi Dept. Of Agriculture). Eventually, mangoes, papaya, plumeria, coffee and lychee would also be introduced in the early nineteenth century (Dunford et. al, 2013).

After Cookʻs arrival to Hawaiʻi, the islands became a stopping point and eventual base for Western political and economical expansion into the Pacific and Asia. Landscape and cultural changes sailed in with the explorers, New England whaling industry and the missionaries who arrived in its wake. Over time, the raising of the new crops and animals they introduced to Hawaiʻi would contribute to the undermining of the traditional farming practices (Lâm, 1989). Development of imported agricultural in the Hawaiian islands increased rapidly during the early nineteenth century. The increase in the foreign population and creation of whaler ports on several of the islands produced a new supply and demand chain that would forever alter the islands.

'Iliahi (sandalwood) became a major commodity in 1810 heralding the increased economic investment by foreigners. Eventually when the sandalwood trade waned, the damage to the traditional subsistence economy had been done. The whaling industry as well now had a foothold in the islands and the aliʻi had incurred massive debt to the foreign investors. By 1826, the first gunboat incidence occurred when the U.S. Navy moored in Honolulu harbor attempting to forcefully collect on these aliʻi debts.

The whaling industry impacted traditional Hawaiian lifestyles in many areas. The cash economy began to supplant the previous subsistence economy. Hawaiians began to relocate to the now town and city centers for work, with many men signing on to the whaling ships. Agriculture turned to growing crops to be sold to the peoples inhabiting these areas and to provision all the trade and merchant vessels at port. Disruption of the agriculutral farming systems that had served Hawaiʻi for a millenia seriously impacted the traditional socio-cultural basis for the kanaka maoli. It would pave the way for the end of land tenureship and the evolution of private property rights especially to be held by foreign entities (Kent, 1993).

THE GREAT MAHELE OF 1848 and THE KULEANA ACT OF 1850

Foreign economic disruption of the traditional subsistence trade practices led to a cultural clash related to the concept of land ownership. Hawaiians' utilization of a method of tenureship approach to the land was in opposition to and undermined the Western cultures' idea of right to privately own land which placed great value both economically and politically on this type of usage.

Between 1839 and 1845, major shifts occurred within the Hawaiian political system in response to decades of foreign influence. Hawaiʻi was recognized as a consitutional monarchy by France, Belgium and Great Britain; the Bill of Rights was drawn up, and a constitution was signed in 1840 (Kamakakau, 1992). Several other pieces of legislation followed which would lead to the privatization of land ownership. The Act to Quiet Lands Titles was the first in 1844, initiating ten years of land ownership transformation. The Act created a Board of Commissioners to oversee the process of the division of lands between the king and his subjects. It also opened up the potential, perhaps not intentionally, for foreign buyers to gain a foothold into land ownership in Hawaiʻi.

The Great Māhele spanned the years of 1845 to 1855 culminating in The Great Māhele Act of 1848 and the Kuleana Act of 1850. The 1848 act relocated one third of the lands to the king, which would be known as crown lands, another one third to the konohiki or chiefs and the last third to the makaʻāinana. Importantly, the initial Māhele did not change the tenureship concept for the makaʻāinana (Lâm,1989).

The Resident Alien Land Ownership Act of July, 1850 and the Kuleana Act of August, 1850 would effectively be the instruments to commit the final severance. The Resident Alien Act gave foreigners the right to own land privately. The Kuleana Act gave Hawaiians two years to pay for and complete surveys on land that they were currently using but only up to 0.25 acre. Most Hawaiians did not understand nor took advantage of, nor perhaps weren‘t financially able, to take advantage of this process. At the end of the two years only 8,200 kuleana parcels were recognized and awarded which amounted to less than 1% of the lands (Lâm 1989). Combined, these two acts, whether good-intentioned or not, effectively ended traditional land use in the Hawaiian islands.

The rise of the plantation in coordinance with the sugar trade was a direct result of these processes. Labor and land were restructured to maximize profits in the hands of the owners of these plantations. These owners would eventually play a large part in the overthrow of the Hawaiian kingdom in the late nineteenth century (Kent 35-6).

IMPACT OF INTRODUCED DISEASES

Prior to outside contact, Hawaiians had already suffered greatly from warfare, famine and infant mortalities. However, the economic and socio-cultural changes brought upon Hawai‘i were only part of the process of the change in society. For a long period of time, Hawai‘i enjoyed the separation from the outside world and along with that, freedom from newly transmitted diseases. That changed with the arrival of Cook in 1778 and led to a steep decrease in Hawaiian population over the next century (Bushnell,1993).

Sailors on the voyaging ships introduced several venereal diseases, followed by tuberculosis in 1786. By 1804, Hawai‘i saw its first large epidemic of what was most likely typhoid fever. Leprosy made its way to the islands by 1823 (Kamakau, 1992). There were continual outbreaks from 1826-57 derived from insect-borne disease, venereal disease and epidemics from inbound ships. An American warship brought in measles to Hilo in 1848 killing off 1/3 of the population. Several outbreaks of colds and flus occurred and by 1853 smallpox had arrived.

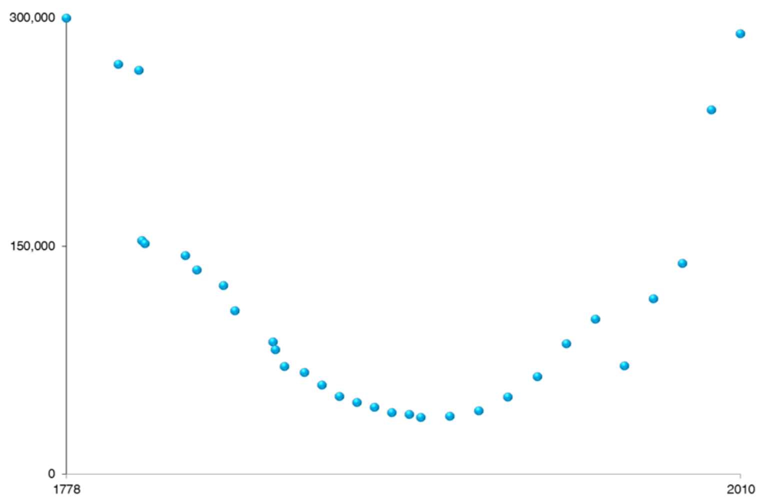

Figure 7: Map showing population decrease
(Office of Hawaiian Affairs, 2017)

Decimation of the native Hawaiian population in the nineteenth century along with changes in the laws governing land ownership, created a space into which foreign investment and eventual political policy would lay the foundations for the modern era in Hawaiʻi.

AGRICULTURE IN THE POST-CONTACT ERA

The rise of foreign influences and trading ports saw a divergence in the agricultural production of each island.

Oʻahu, Maui and Kauaʻi followed similar paths during the period from the late 1790ʻs through the 1850ʻs. Whaling ports were the main drivers for change on these three islands and Honolulu, Lahaina and Kōloa Harbors became major resupply points for ships.

OʻAHU

The first half of the nineteenth century saw a diversification of imported food crops, supplanting the traditional crops that had been grown by the Native Hawaiians. As was similar on the other islands, imported crops were grown to resupply the visiting ships and cater to changing tastes in a rapidly diversifying population. The rise in a cash economy supplanted the traditional subsistence and ʻohana-based structure.

The sugar industry was king during the mid-1800ʻs but as the twentieth century fast approached, sugar began to wane economically. Other potential crops were explored for both local use and exportation. Specific to Oʻahu, the plains of Wahiawā had developed an irrigation system and American homesteaders experimented with several crops. These included banana, papaya, fig, olive, orange, mango, pineapple and also coffee and vegetable oils, with pineapple and coffee eventually becoming the focal crops (evols.library).

Modern agriculture on Oʻahu includes more than 40 different crops including pineapple, macadamia, cacao, tropical flowers, coffee, melons, papayas, pumpkins, and bananas. Oʻahu is also home to University of Hawaiʻi and the College of Tropical Agriculture and Human Resources (CTAHR). CTAHR is engaged in the study of and promulgation of agriculture throughout the Hawaiian islands.

KAUAʻI

Waimea was the first point of contact on Kauaʻi for Captain James Cook in January of 1778. The south shore of the island would eventually host the whaling and sugar industries for the better part of the nineteenth century. Kōloa Village and Landing were the main point for distribution of products like sugar, molasses, beef and sweet potatoes to the ships (kauai.gov). Commercial pineapple as an industry navigated from Oʻahu to the neighbor islands, especially Kauaʻi and Maui as the previously-established sugar plantation farming methodology supported the growing and harvesting infrastructure for pineapples (Bartholomew).

Modern crops include papaya, tropical flowers, large kalo (taro) loʻi or ponded fields, and GMO biotech seed crops. GMO corn research fields were implemented on Kauaʻi as early as the late 1960ʻs and remain in rotation.

MAUI

Like Kauaʻi, Mauiʻs agricultural history followed the whaling industryʻs needs from the 1820ʻs to the 1850ʻs. Crops shifted from traditional Hawaiian foods to those desired for the shipsʻ stores. Lahaina on the west side was the main harbor used for the export of goods. Towards the advent of the twentieth century, pineapple became a staple crop and eventually canneries were started on the island (Bartholomew et al., 2002).

Modern agriculture now includes a thriving coffee industry, cattle, pineapple, onions, papayas, tropical flowers, raw sugar, and the GMO biotech seed industry (mauicounty.gov). Efforts to plant macadamia nuts in the former cane lands near Kahului are currently underway.

LĀNAʻI

Lānaʻi has a uniquely different history of agricultural development than the other islands. The population had been decimated by wars within the Hawaiian kingdomʻs expansion under Kamehameha I and remained sparsely populated with subsistence farmers and fishermen. It wasn‘t until Walter Gibson arrived in the 1860‘s and acquired private land that agriculture shifted to more modern crops. Gibson brought ranching to the island which was followed by sugar from 1899-1921. The first pineapples were grown during the latter period of that time, and in 1921, James Dole acquired the island under private ownership. Soon Lānaʻi became known as the pineapple island (lanaichc.org). Pineapple was phased out of production by 1992, due to high labor and land costs. Today, with 91% of the island in private ownership, the focus is increasingly on tourism and resort development instead of major agricultural crops (Land Use Baseline).

MOLOKAʻI

Aquaculture and ranching were mainstays of the transitional agricultural landscape on Molokaʻi. When the Hawaiian Homes Act of 1920 was estabished, many homesteads were created on the north shore in Hoʻolehua. Initially, land was leased out for pineapple production but moved into diversified crops as did the other islands, just at a later rate of change (hdoa.hawaii.gov).

Molokaʻi‘s strong winds and lack of water prevented the larger crop systems from maintaining economic sustainability. Pineapple companies left in the 1970‘s, as did a large portion of the population dependent on their income. Today, Molokaʻi is predominantly Hawaiian by population and the residents do not cater highly to tourism. In the homestead area, foodcrops such as banana, papaya, taro, sweet potatoes and onions are grown (molokai.org). There is a large commercial coffee farm in the Kualapuʻu village area.

The GMO biotech seed companies comprise more than 50% of the crop production on the island and as with other islands, has become a controversial land use issue (molokai.org). The only true port on the island is Kaunakakai on the south shore.

HAWAIʻI

Hawaiʻi island has a rich history in agricultural development, both pre- and post-contact. A variety of ethnographic materials exist for West Hawai'i, primarily because it was the ancestral seat of a powerful line of hereditary chiefs, including Kamehameha. The early European visitors paying their respects to the ruling power in the islands left behind journals and logs as they investigated the Kona and Kohala districts (Greene 1993).

As the largest of the Hawaiian islands, it also is home to an abundance of climate zones and can sustain a wide diversity of crops. About half of the state’s commercial farms are located here (NASS Census, 2017).

Hawaiʻi Island’s forests were host to the majority of the 'iliahi (sandalwood) growth. Kamehameha I controlled much of the trade, but on his death, the trade (and subsistence agriculture as a whole) began to fall apart for the Hawaiians. His kapu on felling young trees collapsed, and the mountains were eventually stripped of most of these trees. His son, Kamehameha II sank into debt as the crop declined and the industry had collapsed by 1830 (hawaiihistory.org). Kamehameha III banned the collection of sandalwood in 1839. This rare and expensive crop is still propagated and harvested on the upland slopes of the west side, albeit in very small quantities (nativeplants.hawaii.edu).

Many varieties of crops were introduced to the island, concurrent with other islands (nativeplants.hawaii.edu). This included oranges and cattle in the 1790's followed by pineapple and coffee by 1810. Commercial crops of mango, rice, eucalyptus and macadamia nuts were all introduced before the turn of the century. Sugar was primarily farmed in the south and east sides of Hilo, Hāmākua and Puna until its economic collapse on the island in the 1990ʻs.

On the Kona side, coffee production moved to the forefront during the mid-1800's and still remains prominent. There are many individual small farms focused on a large variety of crops including chocolate, honey, avocado, tropical fruits and flowers, sweet potato, and kalo. The GMO biotech seed crops also have a presence, mostly on the east side. Parker Ranch, in Kamuela, is one of the largest cattle ranches in the United States.

The island is home to 90% of the commercial macadamia crop. Large macadamia nut farms are located in the Hilo, South Kona and Kaʻū districts. Smaller farms are located throughout the island, particularly in the South Kona district, where it is cross-planted with coffee.

MODERN ERA

The Hawaiʻi of today is a far cry from what it was pre-contact. There are no illusions that life pre-contact was a perfect utopia. However, a Hawaiian such as Kamehameha I might be hard-pressed to see any familiarities of his time in the current era.

At this moment, the islands face many challenges. Hawaiʻi is deeply dependent on a tourist-based economy, which proved fragile during COVID-19 quarantines. Home ownership is virtually impossible for many Kānaka Maoli as housing prices have risen well beyond what is affordable to many residents in a service-based economy. Even the neighbor islands of Hawaiʻi, Maui, Molokaʻi, Lānaʻi and Kauaʻi have seen housing prices rise close to equal of those on Oʻahu. This has led to an exodus of Hawaiians to the mainland United States in search of better jobs and housing opportunities.

On the upside, there is a nascent effort in smaller communities to restructure the economy. The focus is on industries that serve and benefit the community especially in the areas of economic, social and mental welfare. Agriculture is one of the industries that could help alleviate the reliance on tourism. Coffee, avocados, kalo, bananas, papayas, mangoes and pineapples are just a few of these crops that are produced locally. Perhaps with strong support to these farming endeavors, Hawaiʻi can reclaim its inherent agricultural proficiency in order to support a healthier economic base for its social and cultural communities.

Community Interviews

To gain a deeper understanding of the project area, a variety of stakeholders was interviewed for their knowledge of macadamia nuts grown on the Hawaiian islands. As the majority of macadamia nuts are grown on Hawaiʻi Island, most of the interviewees are residents of that island. In keeping with the *Guidelines for Assessing Cultural Impacts* from the State's Department of Health - Office of Environmental Quality Control, interviews concerned not just macadamia nuts on these islands, but larger areas and cultural practices that could be affected by the release of *Metaphycus macadamiae.*

SHAC staff contacted thirteen community members for these interviews via telephone and email. Five declined or didn't answer, while eight others agreed to be interviewed. Each person contacted fits into one or more of the following categories: 1) Native Hawaiian cultural practitioner, 2) macadamia nut farmer in Hawaiʻi, or 3) leader of a nonprofit benefiting a community where macadamia nuts are grown commercially. To solicit additional feedback from members of the public who fit these criteria, a public notice was published on December 1, 2021, in Ka Wai Ola, the Office of Hawaiian Affairs newspaper. No responses were received from the Ka Wai Ola notice.

Following is the list of interviewees and the method of each interview:

Name of Interviewee	(Island) Title, Organization	Method of Interview
Shalan Crysdale	(Kaʻu District, Hawaiʻi Island; Molokai) Hawaiʻi Island Program Director, The Nature Conservancy	Zoom
David Fuertes	(North Kohala District, Hawaiʻi Island) Executive Director, Kahua Paʻa Mua	Telephone
Wayne Kawachi	(Kaʻū District, Hawaiʻi Island) President of ʻO Kaʻū Kākou	Telephone
Kala Mossman	(Kaʻū District, Hawaiʻi Island) Site manager for the Edith Kanakaʻole Foundation	Zoom
Mel A. Johansen	(Kaʻu District, Hawaiʻi Island) The Nature Conservancy Field Coordinator, Kona macadamia nut farmer	
Bryce Nakamura	(Kona District, Hawaiʻi Island) Second generation macadamia nut farmer	Zoom
Hiʻilani Shibata	(Oʻahu) Co-owner, Ka Mahina Project; Lead Cultural Trainer of the Native Hawaiian Hospitality Association	Zoom

Pomai Weigert	(Maui) AgBusiness Consultant, GoFarm Hawaiʻi	Zoom

Each interview started with a short introduction to *M. macadamiae,* including photos of the parasitoid wasp laying eggs in a Macadamia Felted Coccid (MFC). Points emphasized included the following:

- The MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona.
- The inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaiʻi Island.
- The host-specificity tests at the Hawaiʻi Department of Agriculture's (HDOA's) Insect Containment Facility, conducted on MFC as well as 10 other insect species, including seven economically important or endemic members of the Superfamily Coccoidea.
- The study results: After three tests, *M. macadamiae* attacked only the target host by feeding on or parasitizing it.
- The wasp cannot sting humans or animals.

Subsequent questions focused on four areas: 1) each individual's background, cultural and agricultural practices, as well as experiences with pests and plant diseases that impact their cultural and agricultural practices; 2) their knowledge about macadamia nut production and its links to Hawaiian culture; 3) their views about proper methods of pest control; and 4) any additional comments and concerns. SHAC staff prepared draft summaries of participants' interviews for them to review and add revisions. Below are the approved summaries of each interview:

Shalan Crysdale, The Nature Conservancy

Shalan Crysdale, 43, has been working on Hawaiʻi Island for The Nature Conservancy (TNC) since 2009. He began his tenure with TNC as the field coordinator for the Kaʻu Preserve, was promoted to natural resource manager, and is now the Hawaiʻi Island forest program director. As such, he is directly responsible for three units of TNC-owned lands: Kaʻu Preserve, Kona Hema in South Kona, and Kamehame in Kaʻu District.

Of these three, Kona Hema and Kaʻu Preserve have patches of macadamia nuts. Kona Hema has three rows of them at about 2,880 feet above sea level, tended by the adjacent MacFarms, LLC. This location also has an experimental, high-elevation strand of macadamia nuts, at about 3,000 feet above sea level. These trees were planted by longtime agribusiness developer Sally Rice, who currently co-owns consultancies Agricon Hawaii and Agro Resources Hawaii. By contrast, Kaʻu Preserve has about a dozen macadamia-nut trees on the forest's edge, at 2,500-foot elevation. "The forest is starting to smother out those trees," Crysdale said.

Crysdale himself does not have any experience tending macadamia nuts. He notices big sections of dieback on the macadamia-nut trees in Kona, but isn't sure how much of this is due to the Macadamia Felted Coccid (MFC). "It looks like our trees are better off in Kaʻu," Crysdale said. "And then over in Kona, it just looks like they're dealing with more threats over time."

He pointed out the economic importance of the macadamia-nut industry, especially in Kona and Kaʻu. "This is an employer of quite a few people during the picking season," said Crysdale, noting that families often harvest nuts together.

In addition, macadamia-nut farms provide the local topsoil industry with macadamia-nut hulls, a key raw material for making compost, Crysdale said. Compost and topsoil have multiple uses on the Big Island: They replace soil eroded by storms, and they're used by residents in rocky areas, such as Ocean View, to build out landscaping and gardens. "It has been referred to as Black Gold," Crysdale said.

Crysdale had been aware of MFC and different approaches to lessen its impact before being interviewed for this Cultural Impact Assessment. One way to boost the health of the macadamia-nut trees is Korean Natural Farming, as practiced by Nathan Trump and Chris Trump in North Kohala. "It looked like a phenomenally effective approach," Crysdale said. "These trees just look like they're thriving."
For Crysdale, protecting agriculture and ecosystems from introduced pests is "very top priority. What we're dealing with in Hawaiʻi is a rate of extinction that's unparalleled anywhere else in the world. It was a comparative flatline of species lost until these last 200 years."

He pointed out a few pests that have impacted his conservation work: 1) Rats are the number one pest in the forest, especially for forest birds with low-lying nests. 2) Mosquitoes carry avian malaria. 3) Invasive plants, such as strawberry guava and Christmas berry, grow prolifically and crowd out native plants.

There have been advancements in controlling these pests, Crysdale says. Automatic rat traps reset themselves and release just a little non-toxic bait, preventing the accidental poisoning of native birds. Sterilized male mosquitoes mate with female mosquitoes and leave them barren. *Tectococcus ovatus* is a biological control for strawberry guava. But to Crysdale, the best cure is prevention. He would like to see the State invest in more robust inspections and severe penalties.

Crysdale generally is supportive of insect biocontrols because he has witnessed the success of several of them. One is *Eurytoma erythrinae*, a parasitoid wasp of the Erythrina Gall Wasp (*Quadrastichus erythrinae)*. Before the release of *E. erythrinae* as a biocontrol, the Erythrina Gall Wasp was unchecked in laying its eggs in the leaves and stems of *wiliwili* trees, a dryland forest species native to Hawaiʻi. Crysdale recalls *wiliwili* trees with gnarled new growth. Severe infestations resulted in defoliation, or even death.

The release of *E. erythrinae* had an "instantaneous" effect in some areas, Crysdale says. For example, the difference was like "night and day" in Ka'u. New growth looked normal again, and *wiliwili* leaves started growing at South Point on Hawai'i Island for the first time in years.

Another success that he witnessed was the 2013 release of *Secusio extensa,* the Madagascan fireweed moth, to combat Madagascar fireweed – an invasive plant toxic to cattle and horses. According to the Hawaii Department of Agriculture's (HDOA's) estimates, the fireweed took over more than 850,000 acres of pastureland, mainly on Maui and Hawaii Island. (Source: "Biocontrol Moth Released to Fight Invasive Fireweed," Feb 20, 2013). *S. extensa* was so successful at killing fireweed that "you couldn't tell you were looking at the same area" when shown before and after photos, Crysdale said.

Not only did *S. extensa* attack the Madagascar fireweed, it assailed another invasive species: Cape Ivy, also known as German Ivy. The HDOA's 2008 Draft Environmental Assessment noted this possibility. When both invasive pests still were abundant, the population of *S. extensa* was visibly high. Eventually, the populations of Madagascar fireweed and Cape Ivy fell, as did that of *S. extensa*. By Crysdale's estimate, this took less than three years.

Crysdale noted the risks of biological predators: They work better in some areas than others, depending on environmental factors. Plus, imported predators could attack species other than the target, such as *S. extensa* assailing Cape Ivy. "You just don't know until you try the release," he said.

Crysdale reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* He learned about MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. He heard about the inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaii Island. He saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Crysdale learned about the HDOA's host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. He understood that, after the three tests, *M. macadamiae* attacked only the target host by feeding or parasitizing it.

"It sounds like a really promising biocontrol," Crysdale said, noting that the methodology of testing *M. Macadamiae* is "extremely close" to the other parasitoids tested by HDOA or the US Forest Service with which he is familiar. He was glad to see that *M. macadamiae* did not parasitize native coccids in the tests.

"This to me sounds like it's a very thorough approach to how we can continue the macadamia nut industry in Hawaii," he said.

David Fuertes, Executive Director, Kahua Pa'a Mua

David Fuertes, 73, has a long career in agricultural and science education, as well as community service. Currently, he is the executive director of Kahua Paʻa Mua, a 501(c)(3) nonprofit organization founded in 2010 to benefit North Kohala. Kahua Paʻa Mua provides resources for families to grow their own food and nurtures agricultural entrepreneurship. Its programs teach multi-generational families to grow traditional Hawaiian crops and row crops, raise backyard chickens and pigs using Korean Natural Farming, and tend fish and vegetables with backyard aquaponics. During the COVID-19 pandemic, as layoffs impacted the North Kohala community, Kahua Paʻa Mua's ethos of food self-sufficiency helped its residents stay resilient. Families trained in its programs self-organized to plant more crops. They have been growing and giving away hundreds of pounds of beans, cucumbers, bok choy, zucchini, lettuce and poi.

"My purpose is to train the younger ones about agriculture, and at the same time, just enjoy being on the land," Fuertes says.

Fuertes served more than 30 years teaching agriculture in Hawaiʻi's schools. He sat on the Hawaiʻi State Board of Agriculture for eight years. Fuertes is a former Hawaiʻi County Deputy Managing Director, and has served as the Hilo/Hāmākua Community Liaison for the revitalization of plantation communities for the State of Hawaiʻi's Department of Business, Economic Development and Tourism (DBEDT). He also has undergone Korean Natural Farming Certification with its founder, Dr. Cho Han Kyu.

Fuertes, who is Filipino, grew up on Kauaʻi. After being drafted during the Vietnam War, he went to the University of Hawaiʻi. Then he moved to North Kohala in 1975 to teach agriculture at Kohala High School. That area was home to one of the first sugar plantations to fail, Fuertes says. Today, North Kohala's major agricultural footprint is pasture for cattle. Macadamia nut also is a leading agricultural industry in this area, with plantings of about 1,000 unirrigated acres. (Source: Hawaiʻi Statewide Agricultural Land Use Baseline, 2015 and 2020 update.)

Despite Fuertes' extensive experience in teaching agriculture, his work with macadamia nuts is limited. While working at Kohala High, Fuertes tended about 20 macadamia nut trees in the 1970s and 1980s. He and his students harvested the small amount they had and gave it away as gifts.

Then came yield losses on macadamia nut trees in North Kohala, including on Island Harvest, a company that tends about 750 acres of macadamia nuts from three different landowners. Chris Trump, one of the family members behind Island Harvest, says 2005 brought "an infestation of green stink bug that led to an 80% crop failure." (Source: https://christrump.com/about/) Trump learned more about Korean Natural Farming via Fuertes.

"I was more of a facilitator and introduced them to it," Fuertes says. "They were going to remove a lot of dying trees, but instead, went the Korean Natural Farming way." The farm recovered, and now Trump is a leader in Korean Natural Farming.

Throughout his years teaching agriculture, Fuertes has seen many pests attack crops. For example, rust turns cabbage and lettuce to mush. Pickle worm attacks cucumbers and squash. A pumpkin patch expected to yield 80 fruits ended up with only 12. The culprit? A moth that laid its eggs in pumpkin flowers.

Ginger is particularly susceptible to fungal and bacterial infections in wet weather. “When there’s a rainfall and the water is going in that direction, it takes one week and the whole [ginger] field is just devastated,” he says.

For this reason, Fuertes understands the need for both biological and chemical controls. “Biological controls will address the long term,” he says. “If you’ve gotta use chemicals and that’s gonna save the farmers’ crop, then use it. When I say use it, use the chemical that has been proven and registered for that.”

Fuertes reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* He learned about the Macadamia Felted Coccid’s (MFC’s) harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. He read about the inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaiʻi Island. He saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg’s growth into a larva. Fuertes learned about the Hawaiʻi Department of Agriculture’s (HDOA’s) host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. He understood that, after the three tests, *M. macadamiae* attacked only the target host by feeding on or parasitizing it.

“We have to be careful,” Fuertes says. “Hopefully, this wasp controls that particular insect. But when that insect reduces population, what happens next?”

Fuertes is alluding to insects’ ability to adapt to their environment. If the population of MFC drops as expected, he worries that *M. macadamiae* will choose different prey to feed on and parasitize.

Fuertes was heartened to hear that Hawaiʻi has existing insect predators for MFC. Before releasing *M. macadamiae* into Hawaiʻi‘s environment, he advocates trying to increase the population of the islands’ current MFC controls. “Why bring in something else, if we have something that’s working?” Fuertes says. “Can we repopulate those?”

“If we do try to repopulate the existing predators, how long will it take to effectively release them to the farmers?” he adds. “If it takes too long, then I’m OK with using the new one…. Just as long as we can prove that it will be with its own host.”

Wayne Kawachi, President of ‘O Kaʻu Kakou

Wayne Kawachi, now 75 years old, is the president of ʻO Kaʻū Kākou (OKK), a 100% volunteer-run 501(c)(3) non-profit formed in 2006 to benefit the Kaʻū District. Its charitable goals: promote a healthy community through education, culture, and economic opportunity. Projects include funding local scholarships, purchasing life-saving equipment for Kaʻū Hospital, restoring and maintaining four historical cemeteries, growing a community garden, and developing a senior-housing complex in Nāʻālehu.

Kawachi's dedication to community service in Kaʻū is known across the state of Hawaiʻi. In January 2018, at the age of 71, Kawachi personally raised awareness for Nāʻālehuʻs senior housing complex by walking 100 miles – mostly uphill, in rubber slippers – from Paʻauilo to Nāʻālehu. His four-day walk generated $75,000 in donations to support the project.

Kawachi was born and raised in Kaʻū. His father, along with four uncles, moved to Pāhala from Hilo. Kawachi's father worked on the Pāhala sugar plantation of C. Brewer and Co., one of the Big Five companies in Hawaiʻi. His mother was a homemaker.

Kawachi remembers a time before large-scale macadamia nut farming in the Kaʻū District. As a teenager, he foraged underneath the macadamia nut trees growing wild around Pāhala, cracked the nuts with a hammer and rock, and ate them raw. His family didn't have any Japanese cultural traditions based on the macadamia nut.

Kawachi left Kaʻū for about a decade, first to join the U.S. Army, and then to go to college. After returning to Pāhala in the mid-1970s, he spent almost 30 years as a deep-sea fisherman. As part of OKK's projects, Kawachi still is connected to food production. OKK's community garden grows bok choy, onions, cilantro, lettuce, carrots and tomatoes.

Kawachi has watched agriculture change in Kaʻū, from the fall of the sugar plantations to the rise of macadamia nut and coffee farms. C. Brewer's subsidiary, Kaʻū Agribusiness Co., had added macadamia nuts to its Kaʻū plantings before shutting down its Pāhala sugar plantation in 1996.

"They didn't have to wait until '96 to know the sugar was gonna go," Kawachi says. "By the time sugar went out the mac nut trees were pretty big."

After the sugar plantation shut down, the macadamia nut farms were Pāhala's major employer. At about 4,800 acres of plantings in Kaʻū, macadamia nuts have remained one of the area's top agricultural crops. (Source: Statewide Agricultural Land Use Baseline 2015 and 2020 update.) From Kawachi's perspective, the macadamia-nut industry has been positive for his community.

Kawachi was unfamiliar with the Macadamia Felted Coccid (MFC) before this interview. "I never heard of anything destroying [macadamia nut farms]," he says. He hears more about pests damaging Kaʻū coffee, such as coffee berry borer (CBB) and coffee leaf rust (CLR).

In general, Kawachi thinks new measures to control pests should be introduced carefully. "I don't think some of them need to be controlled because there's enough natural control," he says. "When it's devastating you've got to take different measures."

In severe cases, Kawachi leans toward using biological controls. But he also thinks it's sometimes necessary to use both chemical and biological agents.

Kawachi reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* He learned about MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. He read about the inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaiʻi Island. He saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Kawachi learned about the Hawaiʻi Department of Agriculture's (HDOA's) host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. He understood that, after the three tests, *M. macadamiae* attacked only the target host by feeding or parasitizing it.

Given Hawaiʻi's past track record of introducing new species, Kawachi urged caution: "If you go back to what they have done in the fishing industry, they introduced new fish: taʻapeand the roi. They thought the taʻape would be good. It does propagate really fast, but it's not as good as the local fish we have. And they are now overtaking the shoreline and eating the native fish like baby menpachi. A lot of times the study just doesn't go far enough in the future."

Kawachi noted that the tests of *M. macadamiae* are not long-term ones. He worries about the ability of this wasp to adapt to its environment by feeding and parasitizing other insects – especially if it is very successful in killing MFC: "If you took the macadamia pest away, and just leave [*M. macadamiae*] with others, that might force it to feed on other bugs."

"I'm not saying this is a bad decision," Kawachi says of the HDOA's test results. "I hope they have researched this as best as they can. You have to look at 10 years down the road."

"Man wants to solve a problem, but a lot of times they create another," he adds. "For the present, they are solving this problem, but what about the future?"

Konrad "Kala" Mossman, Hawaiian Cultural Practitioner

Konrad "Kala" Mossman, 55, currently is site manager for the Edith Kanakaʻole Foundation. He manages three locations on Hawaiʻi Island:

- Hale O Lono is the birthplace of one of Hawaiʻi's premier aliʻi, Kalaninuiʻīamamao. At this site, Mossman handles tasks such as building and repairing rock walls, maintaining the flow of water into fishponds, and monitoring the stock of fish.

- ʻĪmakakāloa Heiau is located in Kaʻalāiki, Kaʻū. It is a heiau dedicated to Laka, the Hawaiian goddess of hula. A garden of plants associated with hula is kept there. Hula practitioners visit this site to conduct ceremony and protocol. Mossman's major tasks are cutting grass, controlling weeds and maintaining the road.
- Nāpoʻopoʻo is located in Waipiʻo Valley, where Mossman maintains traditional loʻi kalo (taro patches) and its highly sophisticated traditional irrigation engineering.

Mossman originally is from Oʻahu, where he grew up in a farming and spear fishing family. They grew florals, such as leather leaf fern, heliconia and ginger. They also grew their own food, including kalo, sweet potato, ʻulu and Western fruits.

In addition to these cultural practices, Mossman has been carving wood since he was a teenager. His carvings include canoes, bowls and musical instruments. "Any traditional Hawaiian tool, I've probably made it," he says.

Macadamia nut is not a traditional Hawaiian plant, so it is not part of traditional practices, he says. But it can be adapted for use by Hawaiians. For example, Mossman is making macadamia nut oil for his bowls and platters, because it is food safe. "Traditional is kukui nut oil. But I'm using macadamia nut oil," he says. "I would imagine that [macadamia nut] could be used for anything the kukui nut was used for. Kukui nut was used to make candles and fuel to burn to create a torch."

Mossman has grown macadamia nuts at two locations on Hawaiʻi Island. One is in Panaʻewa, where he planted about 40 macadamia nut trees now tended by his son. The other is in Waiʻōhinu, on property formerly owned by his late mother. The Waiōhinu property has about 25 macadamia nut trees. Aside from the macadamia nut oil for his wood carvings, Mossman doesn't process the nuts. Rather, he provides them to a hunter who uses the nuts to set pig traps.

Mossman is unsure about the balance of upsides and downsides of large-scale macadamia nut agriculture in Hawaiʻi. As a subsistence farmer, he grows food that is consumed on island, as opposed to crops largely meant for export.

"Any time we can have land protected as agricultural, it's a plus. We often face the loss of land for profit, not only on this island but all of the islands," he says. "Because I don't know much about the large-scale farming operations, I can't say for certain that there's a downside to them."

Mossman says pests have impacted his cultural practices as a spear fisherman and a wood carver. For example, the introduction of *taʻape* and *roi* has hurt native fish populations. And the Erythrina Gall Wasp (EGW) (*Quadrastichus erythrinae)* once was unchecked in laying its eggs in the leaves and stems of *wiliwili* trees, a dryland forest species native to Hawaiʻi. The trees had gnarled new growth. Severe infestations resulted in defoliation, or even death.

The EGW was spotted on Oʻahu in 2005. At the time of its discovery in Hawaiʻi, this pest already had been identified in multiple Asian countries between Reunion Island and Guam. (Source: State of Hawaiʻi, Department of Agriculture. New Pest Advisory, Erythrina Gall Wasp. Updated December 2008.) It is assumed to have hitchhiked in imports to Hawaiʻi.

The 2008 release of *Eurytoma erythrinae*, a parasitoid wasp of the EGW, significantly checked this pest's growth and helped *wiliwili* trees begin recovery throughout the Hawaiian islands. But there are limits to *E. erythrinae's* effectiveness. The EGW creates small galls on the *wiliwili's* inflorescences and seed pods – which would be better accessed by *Aprostocetus nitens*, a different parasitoid wasp. Environmental review of *A. nitens* currently is underway. (Source: Hawaiʻi Invasive Species Council. Invasive Species: Erythrina gall wasp (*Quadrastichus erythrinae*).)

Mossman recalls a time before the devastation, when *wiliwili* grew along the highway. Even after the release of *E. erythrinae*, *wiliwili* haven't repopulated the highway areas. "You don't see them anymore," Mossman says. "They took quite a hit."

"As a carver, all native woods are important to me," Mossman says. "There are certain implements that I can't make anymore that were only made out of *wiliwili*. It's a very light wood. We use it for floats, *amas* (outriggers) of canoes, for surfboards. Because of its buoyancy in the water, it was utilized for these purposes. Now I use different wood, but it's not as good."

Mossman reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* He learned about MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. He heard about the inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaiʻi Island. He saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Mossman learned about the Hawaiʻi Department of Agriculture's (HDOA's) host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. He understood that, after the three tests, *M. macadamiae* only attacked the target host.

Mossman worries that *M. macadamiae* will adapt to eat other insects if it is successful in eradicating the MFC. Also, as the HDOA's tests were done in captivity, Mossman wondered how these insects would act when released into Hawaiʻi's unique environment. One example, brought up by Mossman: "Do they burrow into our ʻōhia trees?"

"Although they did the tests three times, I feel like that's not enough," Mossman says. "My concern is that we make sure whatever we bring in is not going to cause more harm."

Mel A. Johansen, The Nature Conservancy: Field Coordinator and Kona Farmer

Mel Johansen, 65, is a lifelong resident of Hawaii Island. He lives in the house his father built in

South Kona, in the ahupuaʻa called Papa. Johansen was born into a family that had a love of the outdoors: His great-grandfather emigrated from Norway to Hawaii in 1860, taking a job at Parker Ranch. His grandfather also was a paniolo. And Johansen's father was a forester who worked at Manuka State Wayside Park for 35 years.

"Dad got me interested in native plants," Johansen said. "We used to go on botanizing trips in the forest."

Johansen remembers when Kona's macadamia-nut industry started. In the early 1960s, thousands of acres of tropical dry forest were cleared for macadamia-nut plantings. Tropical dry forest "is one of the rarest forest types in the world now," he said.

For a decade, Johansen worked at MacFarms, LLC, the 3,000-acre macadamia-nut field next to Kona Hema. He ran the maintenance department, repairing factory and field equipment. "I put my kid through private high school with money I earned from mac nuts, so it worked for me for a while," he said.

Then he worked a stint for agribusiness developer Sally Rice, who currently co-owns consultancies Agricon Hawaii and Agro Resources Hawaii. Rice installed the experimental plantings of macadamia nuts and other crops at Kona Hema preserve, which is now owned by The Nature Conservancy. For the past 22 years, Johansen has worked for The Nature Conservancy as Kona Hema's field coordinator.

Johansen also has his own, 35-year-old macadamia-nut farm. His father started it in the early 1960s; Johansen expanded it to cover 10 acres. He has not seen the Macadamia Felted Coccid (MFC) at the farm, but he's sure it's there. "MFC is just one of many diseases or insect pests that affect macadamias," he said.

The last 20 years have brought a variety of diseases and pests. Johansen named some of them: Macadamia Quick Decline, thrips, and scale insects such as MFC. His own macadamia-nut trees suffer from dieback, and he has not been able to identify what is causing it. The newer varieties – such as 344, 741 and 800 – all seem to be affected more by pests, he said. The 246 variety, planted by his father and other old-timers, is much more resistant.

Johansen tried spraying an oil-based insecticide on his 20-foot tall trees. It did improve their health, but he stopped spraying because of the time involved, as well as the product that covered him during application. "This was supposed to be a relatively non-toxic chemical to humans, but you still had to spray it into the trees, and you get a lot of chemical rolling back at you."

Another factor affecting the productivity of macadamia-nut farms is environmental conditions at different elevations, Johansen said. Between 1,000 and 2,000 feet above sea level, production still is good. (His own farm is at 2,000 feet.) MacFarms, LLC, which is three miles away from his farm, sits at 2,500 feet and higher. Johansen noticed a decrease in productivity at that elevation. And at Kona Hema, the experimental plots planted by Sally Rice sit at 3,000 feet. “I took care of them for Sally for a while,” Johansen said. “As it turns out, macadamia nut doesn’t do well that high. It doesn’t flower.”

The number of small, independent farmers in the macadamia-nut industry is shrinking, Johansen said. These are farmers who must sell to the processors. The price paid to them isn’t enough for farmers to make a decent return – especially in light of pressures from MFC and other pests. Plus, it can be difficult to find pickers for this labor-intensive crop. This season, Johansen left his nuts on the ground because it wasn’t financially worth the harvest. Instead of heading to processors, the nuts became feed for wild pigs, which he traps. Baiting wild pigs with macadamia nuts is “a newer cultural practice,” he said. “The pork quality gets really good if they’re feeding on mac nuts.”

The last time Johansen let a crop go was 10-15 years ago. “A lot of farmers are giving up,” he said. As the older ones die, their children sell the land to developers.

Over the years, Johansen hasn’t seen much interest in helping the macadamia-nut industry. He thinks the State could do more. “There’s a lot of opportunity for the State to help independent farmers to form their own coop and create their own processing plant,” he said, noting that the equipment cost of a husker and cracker is cost prohibitive for smaller growers.

He also believes that the State should do a much better job of keeping invasive species out. There have been so many that “you’d be fighting a losing battle to try to take Hawaii back to where it was 200 years ago,” he said.

Johansen was glad to learn that the HDOA was studying *M. Macadamiae* as a predator for MFC. “Having tried to combat invasives with mechanical or chemical controls for most of my life, you’re just fighting a losing battle,” he said. “It has to be a high-tech method of control, and biocontrol seems like a method that could work, given enough precautions to ensure that it doesn't affect other species.”

Johansen offered an example: During his childhood, *Ageratina riparia*, or mist flower, was one of the worst invasive pests in South Kona’s native forests. As a shrub, it would take over the forest floor and suppress native species. *A. riparia* was so thick in areas that it was hard to walk, Johansen said.

The State of Hawaii introduced several controls for this invasive species: a white smut fungus (*Entyloma ageratinae*), a gall fly (*Procecidochares alani*), and a plume moth (*Oidaematophorus beneficus*). The white smut fungus and the gall fly were the most successful biocontrols in Hawaii. (Source: “Biological Control of Mist Flower (Ageratina riparia, Asteraceae): Transferring a Successful Program from Hawaiʻi to New Zealand.”)

Johansen still sees *A. riparia*, but at much reduced rates compared to the 1960s. *P. alani* is controlling *A. riparia's* population by making galls on the plant's stems. "Today you'll see those galls and find the insect pest inside the galls," Johansen said.

Johansen reviewed key points from the July 2020 draft environmental assessment for the field release of *M. macadamiae.* He learned about MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. He heard about the inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaii Island. He saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Johansen learned about the HDOA's host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. He understood that, after the three tests, *M. macadamiae* attacked only the target host by feeding or parasitizing it.

Johansen had no additional questions about the evaluation or release of *M. macadamiae*. "It looks like it has the potential to work and be a big help for farmers," he said. "I think it's worth the risk."

Bryce Nakamura, Kona farmer

Nakamura, 68, is the third generation tending his family's Kona farm. He is descended from Japanese immigrant laborers for Hawaiʻi's sugar industry. His great-grandfather established the family farm on 30 acres of Bishop Estate land overlooking Kealakekua Bay. Their first crop was tobacco, followed by coffee and macadamia nuts.

Before tourism grew, agriculture was the main industry in Hawaiʻi. Back then, anyone who leased Bishop land was required to improve it with agriculture, Nakamura says. It was Nakamura's father who planted the macadamia nut trees, which are more than 50 years old. "When I was in high school, those trees were already adults," he says.

Watching his father work so hard on the farm convinced Nakamura to become a pharmacist. He spent 29 years working at Kona Community Hospital before retiring. But now, the responsibility for tending the family fields rests on him.

Granted, the acreage isn't as much as it used to be. Nakamura's father sold off most of the farm in the early 2000s, leaving 5.5 acres of Bishop Estate land under the family's control. Two acres are planted with interspersed macadamia nut trees and coffee trees. A separate 1-acre plot is planted with only coffee.

When asked if he knew of Native Hawaiian cultural practices that involve macadamia nuts, Nakamura couldn't think of any. His family's own Japanese cultural practices consisted of pounding mochi with a rock his great-grandfather found in Waipiʻo Valley and crafted into a mochi pounding bowl, as well as going to Obon dances. None of these activities have been affected by pests, but his farm certainly has been.

Nakamura has severe pest infestations on his macadamia nut trees. One problem: Insects bore into their trunks, which releases resin and allows a fungus to enter. So far, he says he has lost 60% of his trees during the past five years. This past season, his farm's nut production decreased by 80%.

Before his trees started dying and losing production, Nakamura would harvest 200 bags every three months, as well as higher amounts during the peak season of October to January. "Now I'm lucky to get 200 bags in the whole year," he says.

Upon seeing photos of macadamia nut trees affected by *Acanthococcus ironsidei,* or Macadamia Felted Coccid (MFC), Nakamura recognized the extreme leaf dieback seen in his own trees. "Once the leaves go brown or red on you, it's ready to die," he says. "Within six to eight months, leaves start to turn yellow and the next month it gets worse. Three to four months later, it's all gone."

When asked about the pest controls he uses on his macadamia nut trees, Nakamura explained that he's limited to cultural controls, such as de-suckering and fertilizing his trees. He says chemical control isn't practical for small-scale farmers – especially ones with trees so old. His trees are in the range of 50 feet tall, with trunks that are two feet in diameter. In addition, they're crowded next to one another, with thick canopies. "There's no way you could spray from the ground, unless you have a boom," he says.

Nakamura also is fighting coffee berry borer (CBB) and coffee leaf rust (CLR) in his coffee trees. "At the beginning of the year, the farm looked like a green forest," Nakamura said of his coffee trees. At that point, he was combatting CBB by spraying *Beauveria bassiana*, the fungus that dessicates the beetles upon contact. On the one acre planted only with coffee, he managed to keep the CBB infestation under 5%. But in the field that is macadamia nut trees interspersed with coffee trees, the CBB infestation stubbornly stayed at about 15%. If he didn't spray *B. bassiana* at all, the infection rate in both fields would shoot up to 70%-80%, he says.

Then, in May or June of 2021, CLR appeared on his farm. And now, the damage is so severe that Nakamura is pruning all of his coffee trees. In 2021, the coffee yield was the highest the farm had produced since 2007. Due to CLR, the yield is expected to drop 90-95%.

Based on these experiences, Nakamura says it's a good idea to protect agriculture from pests. He considers both sprays and insect biocontrols to be important in this goal. Subsidies for farmers, such as the federal and state programs that reimbursed coffee farmers for *B. bassiana*, are the best way to motivate growers to use these pest-control methods, he says. He hasn't heard of any subsidy programs for macadamia-nut pest control.

Nakamura reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* He learned about MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. He saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Nakamura learned about the Hawaiʻi Department of Agriculture's tests on 10 insect species other than MFC – and was heartened to learn that *M. macadamiae* only attacked the target host.

As long as *M. macadamiae* doesn't harm native species or populations of beneficial insects, Nakamura has no problem with importing and rearing this parasitoid wasp in Hawaiʻi.

"Tell them to hurry up and let's get started," he says.

Hiʻilani Shibata, Ka Mahina Project and Native Hawaiian Hospitality Association

Originally from Hilo and now living on Oʻahu, Hiʻilani Shibata, 46, is a longtime educator of Native Hawaiian cultural practices and history. She is co-owner of the Ka Mahina Project, which promotes a healthier life through traditions that honor Hina, the Hawaiian moon goddess. Shibata also is lead cultural trainer for the Native Hawaiian Hospitality Association. Previously, she spent 14 years as education manager at the Bishop Museum in Honolulu. Shibata's own cultural practices include *lomilomi* and traditional *hoʻoponopono*.

She also has conducted farmer education, based on her own family's experience with small-scale agriculture. Her husband had a two-acre farm that grew crops such as taro, *ʻulu*, sugarcane and bananas -- just enough to feed family and friends. (They are looking for another plot of land to resume farming.) Over the years, she has seen growth in the number of Hawaiʻi's small and large farms. She hopes to see the establishment of more small ones.

Shibata's extended family doesn't grow macadamia nuts, but some of them have worked as contract labor for the Mauna Loa Macadamia Nut Corp. in Keaʻau on Hawaiʻi Island. Shibata herself has cracked open macadamia nuts for home consumption.

As macadamia nuts were imported from Australia, they are not part of Native Hawaiian cultural practices, Shibata says. "Giving chocolate-covered mac nuts as a gift from Hawaiʻi is not necessarily a positive, because it doesn't have anything to do with Hawaiʻi," she says.

The big plantations of macadamia nuts also don't allow for other plants to grow underneath, which isn't good for the land, she adds. "It's the opposite of the native forests, where everything is 'ohana. Understory up to the fourth story," she says. "The whole biological system is 'ohana. Everyone is working together to grow."

Instead of growing monocultures for export crops, Shibata prefers to see more diverse farms producing food to be consumed on the islands. An increase in local agriculture could reduce imports, which are a major source of invasive species, she says.

Shibata has seen invasive pests affect both agriculture and plants important to Native Hawaiian culture. *ʻUala* and taro are targeted by sweet potato weevil and apple snails, respectively. On her husband's farm, they noticed longneck turtles, poisonous dark frogs, and Japanese eels -- all non-native species. *Wiliwili* trees have been harmed by the Erythrina Gall Wasp. And the leaves of the *hala* tree, used by lauhala weavers, suffer from hala scale.

"Any time a native plant is affected negatively, it will have multiple effects on our culture," Shibata says.

Shibata reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* She learned about the Macadamia Felted Coccid's (MFC's) harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. She saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Shibata learned about the Hawaiʻi Department of Agriculture's (HDOA's) host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. She understood that *M. macadamiae* attacked only the target host in the HDOA's tests.

Shibata is troubled by Hawaiʻi's focus on reacting to invasive species. She would like to see more resources dedicated to preventing their entry to the islands – which would alleviate the need to bring in non-native species such as *M. macadamiae* to control pests. Such resources would include more inspectors for commercial flights, as well as full examinations of military ships and planes.

"We have all the capability as the people of Hawaiʻi and the State to be able to strengthen our biological borders," she says, noting that countries such as New Zealand and Japan have had tighter controls. "At this point, I think it's silly. It's ridiculous that we haven't strengthened them more."

Shibata also worries about what would happen if *M. macadamiae* is very successful in controlling MFC. "That species is not going to just die," she says. "They will adapt to attack something else."

Shibata recognizes that, given the current situation with Hawaiʻi's invasive species, extensively researched parasitoids do play a role. An example is the parasitoid that saved the *wiliwili* trees from the Erythrina Gall Wasp.

"I'm not against what they're trying to do," she says of the HDOA's effort to study *M. macadamiae.* "But there are preventative measures that can be solidified before it gets to this point."

Pomai Weigert, AgBusiness Consultant, GoFarm Hawaiʻi

Pomai Weigert, 39, has a long history in agritourism, agriculture and Native Hawaiian cultural practices. "I was raised mostly in Hawaiian culture," says Weigert, who was taught to preserve and pass on Native Hawaiian ceremonies and prayers, as well as protocols and rituals around asking for permission and giving thanks. In addition, her parents were always advocates for the land-back movement and equality of Native Hawaiian people.

Born in Honolulu, Weigert moved with her mom to Maui at the age of two. She now resides on her family's Hawaiian homestead in Keokea and frequently travels throughout the state for her work. "My career started with tourism, then agritourism, and now it's in building food systems," she says.

Weigert is an AgBusiness consultant for GoFarm Hawaiʻi. She helps farmers on multiple islands with marketing, especially identifying value-added products that have high-sales potential. She also is an adviser for the Hawaiʻi AgriTourism Association. And she works with the Hawaiʻi Tourism Authority on an agritourism initiative.

Weigert's experience with macadamia nuts is as a consumer. As the macadamia nut tree is not a Native Hawaiian plant, she doesn't know of traditional practices with any of its parts. "Mac nuts were never packaged to me as super important to the culture," she says, noting the plantation history of this crop. "It was, 'Mac nuts are super important to the economy.'"

Weigert does not know any farmers growing macadamia nuts. She also hasn't seen any controversies from large macadamia-nut farms affecting their surrounding communities. In fact, she sees opportunities for value-added products from macadamia nuts, such as faux Parmesan cheese for plant-based diets.

Weigert reviewed key points from the July 2020 draft environmental assessment for the field release of *Metaphycus macadamiae.* She learned about MFC's harmful effect on macadamia nut yields, particularly in hot, dry growing areas such as South Kona. She heard about the inability of current controls – chemical, cultural, natural and biological – to manage MFC on Hawaiʻi Island. She saw photos of *M. macadamiae* laying an egg in an MFC, as well as that egg's growth into a larva. Weigert learned about the Hawaiʻi Department of Agriculture's (HDOA's) host-specificity tests on 10 insect species other than MFC, including seven economically important or endemic members of the Superfamily Coccoidea. She understood that, after the three tests, *M. macadamiae* attacked only the target host by feeding or parasitizing it.

Weigert sympathized with macadamia nut farmers experiencing MFC infestations. "60% loss [of yield] is huge," she says. "We can't spray every tree from head to toe. That's not economically viable."

But she also notes that a strict economic view doesn't take other perspectives into account. "Farmers overall are not always concerned with the impacts outside of themselves," she says. "What do the farmers want to do? They're going to want to do whatever to keep their farms going."

Weigert expressed concerns about *M. macadamiae's* ability to expand its dietary and parasitizing practices to other insects – if it is successful at killing off MFC. She noted the limited number of insects in the host-specificity tests and wondered whether the scientists missed other ones that *M. macadamiae* already feeds upon and parasitizes. Weigert also questioned the strategy of introducing new, non-native insects every time an invasive species turns out to be a pest.

She recommends the HDOA consult with villages and towns where *M. macadamiae* is intended for release. Communities across the state are not the same, she notes, so it's important to take each area's opinions into consideration when deciding whether or not to release *M. macadamiae*. "The State is driven by the hand of Oʻahu a lot," she says. " Sometimes when people tell the State they don't want it, the State still does it."

"I hate to speak for a community I don't live in," she adds.

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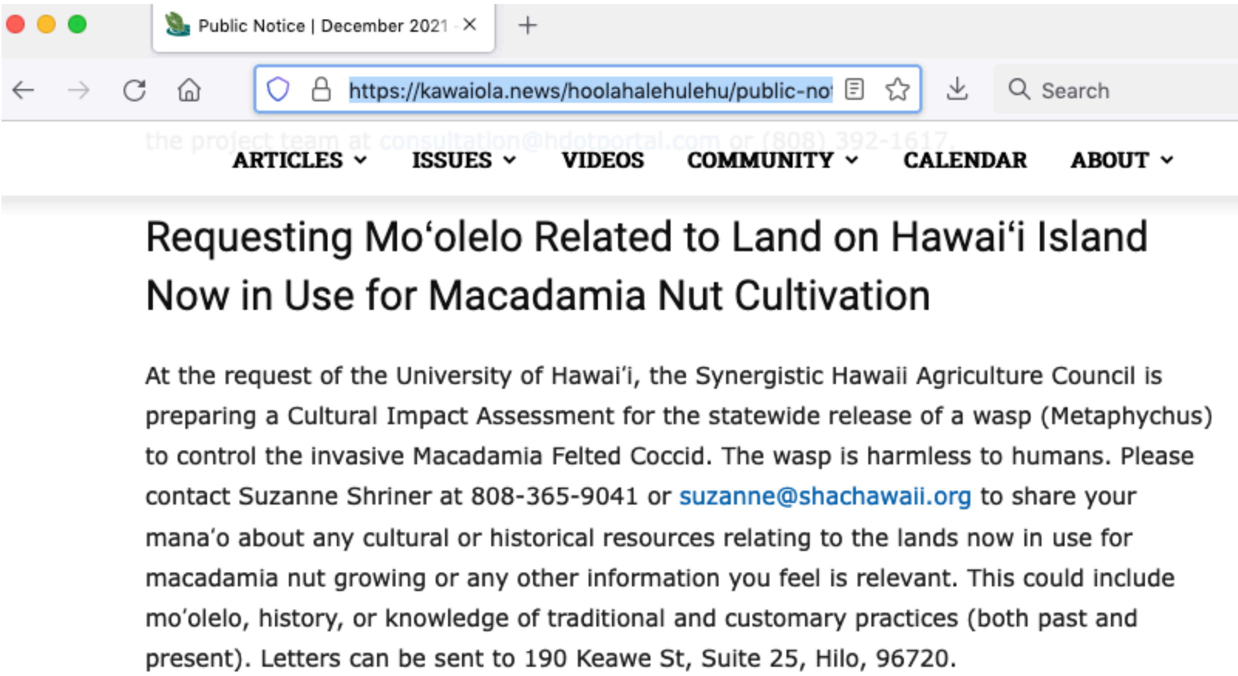
Appendix A: Public Notice



Requesting Mo'olelo Related to Land on Hawai'i Island Now in Use for Macadamia Nut Cultivation

At the request of the University of Hawai'i, the Synergistic Hawaii Agriculture Council is preparing a Cultural Impact Assessment for the statewide release of a wasp (Metaphychus) to control the invasive Macadamia Felted Coccid. The wasp is harmless to humans. Please contact Suzanne Shriner at 808-365-9041 or suzanne@shachawaii.org to share your mana'o about any cultural or historical resources relating to the lands now in use for macadamia nut growing or any other information you feel is relevant. This could include mo'olelo, history, or knowledge of traditional and customary practices (both past and present). Letters can be sent to 190 Keawe St, Suite 25, Hilo, 96720.

Figure 8: Screenshot of online Public Notice. Also published in hard copy. https://kawaiola.news/hoolahalehulehu/public-notice-december-2021/

APPENDIX D: HAWAII MACADAMIA NUT ASSOCIATION LETTER OF SUPPORT

Office of the Chairperson
Hawai'i Department of Agriculture
1428 S. King St.
Honolulu, HI 96814

To Sharon Hurd, Chairperson of the Board of Agriculture,

The Hawaii Macadamia Nut Association (HMNA) offers its full support for the Field Release of *Metaphycus macadamiae* (Hymenoptera: Encyrtidae) for Biological Control of Macadamia Felted Coccid, *Acanthococcus ironsidei*.

The HMNA is comprised of members from all sectors of the macadamia nut industry in Hawaii. Its membership is made up of small and large-scale growers, processors, and distributors, all dedicated to growing the finest macadamia nut in the world.

Macadamia Felted Coccid (MFC) is a damaging invasive pest threatening the existence of the macadamia nut industry in Hawaii. MFC is a scale insect that feeds by inserting its piercing mouth parts into macadamia nut plants and sucking phloem from the plant tissue. Their feeding causes leaves to be distorted, early flower drop, and branch die-back, leading to the death of trees and a substantial reduction in nut production. Yield losses are found to be severe even with relatively low infestations of MFC, particularly in hot dry growing areas like South Kona.

Through the work initiated by the Hawaii Department of Agriculture (HDOA) we feel confident that the release of *Metaphycus macadamiae* will be only beneficial for Hawaii's environment. The HDOA has shown that this parasitoid is specific to MFC and therefore is an excellent candidate for biological control.

Because the MFC is an invasive pest, there are few natural predators effective in controlling its populations. This is why the state-wide field release of *Metaphycus macadamiae* is an important step in controlling populations of MFC on the Big Island and to control infestations should MFC spread to other Hawaiian Islands.

Sincerely,

Barbara Anderson
Secretary
Hawaii Macadamia Nut Association