Macadamia felted coccid impact on macadamia nut yield in the absence of a specialized natural enemy, and economic injury levels

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A R T I C L E   I N F O

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A B S T R A C T

Macadamia nut is among the most important edible crops produced in Hawaii. Macadamia also accounts a significant amount of agricultural land in the state at about 6920 ha of active production. Currently, macadamia has one major insect pest that requires considerably more severe management than others; the macadamia felted coccid, Acanthococcus (previously Eriococcus) ironsidei. Horticultural oils and insect growth regulator insecticides are frequently used to control this pest, without any knowledge of economic injury level currently. This study quantified yield loss and impact on nut quality related to A. ironsidei in Hawaii, on two varieties in two different environments, one mesic, and the other dry. Based on these data, EIL estimates were developed for A. ironsidei on macadamia. There was significant variation in yield loss to A. ironsidei in the two varieties and locations. Some varieties of macadamia nut had severe yield losses under dry-habitat conditions, while others tolerated higher A. ironsidei infestations better, with a lower rate of yield loss. Kernel quality was largely not impacted by A. ironsidei infestation, and reduction in yield was the only impact detected. There were correspondingly variable EILs estimates from the different varieties and environments. The implications of high yield loss in a crop in the absence of a natural enemy of the primary pest are discussed. Results of this study will help to contribute to developing an effective integrated pest management program for A. ironsidei management in Hawaii.

1. Introduction

With the translocation of plants to different parts of the world for agricultural purposes, many pests of those plants are left behind – the crop is able to achieve high productivity in the absence of the impacts from specific pests. In other cases, insects from the native provenance of the plants become invasive in the new range of the crop and cause substantial yield losses in the absence of natural enemies that successfully suppress the pest. This scenario creates the opportunity to assess the potential impact that insects have on plants, but is not evident in their place of origin owing to the actions of natural enemies there. The beneficial impact of highly evolved natural enemies on plant fitness can thus be extrapolated. Macadamia nut (Macadamia integrifolia, Proteaceae) is originally from Australia and is cultivated in a number of other countries. Hawaii was the first place to develop macadamia nuts as a commercial crop. Today, macadamia nuts are grown in Australia, South Africa, Kenya, Guatemala and Brazil. The invasion of Hawaii (and more recently, South Africa, Schoeman and Millar, 2018) by a specialist macadamia nut insect, Acanthococcus (formerly Eriococcus) ironsidei (Hemiptera; Eriococcidae, macadamia felted coccid, MFC) has resulted in substantial yield losses in the industry there, while in Australia, A. ironsidei is a minor and sometimes sporadic pest. It is evidently suppressed through mortality inflicted by a specialized parasitoid wasp in Australia, Metaphycus macadamiae (Polaszek et al., 2020), which has not yet been released in Hawaii as a biological control agent.

Macadamia nut (Macadamia integrifolia, Proteaceae) is one of the most important edible crops produced in Hawaii, with a farm value of $42 million (based on wet-in-shell weight) for the 2018–2019 crop (USDA-NASS, 2019). Approximately 6920 ha of macadamia nut trees are in active production in Hawaii (USDA-NASS, 2019). This represents a significant portion of agricultural land in Hawaii, and therefore the agricultural practices of macadamia nut growers including pesticide
applications may have significant implications for the region in terms of environmental impacts.

The macadamia felted coccid is currently the most significant insect pest of macadamia nut in Hawaii, and has also recently become invasive in South Africa. Macadamia felted coccid was first recorded on the Island of Hawaii in 2005 in a macadamia orchard located in South Kona, and by 2009 its distribution had extended to the east and north areas of the Island (Wright and Conant, 2009). A. ironsidei females develop from egg hatch to adult stage in 32 days and their lifetime can exceed 50 days; males become adults in 16 days and die soon after mating. An individual female can lay up to 97 eggs in its lifetime (Zarders and Wright, 2016). A. ironsidei produces multiple generations per year and population densities typically increase in the drier season in Hawaii (Gutierrez-Coarite et al., 2017).

A. ironsidei primarily infest the trunks and branches of the macadamia tree, and at high population densities, will populate the leaves, racemes, and husks of the nuts. Up to 1700 MFC crawlers per 6.5 cm² (1 square inch) have been recorded on macadamia trees in Hawaii (Gutierrez-Coarite et al., 2019). MFC feed by inserting their mouthparts into the plant and extracting plant fluids. At high infestation levels, their feeding can lead to distorted and stunted tree growth, causing yellow spotting on mature leaves, premature drop of developing fruit, and branch dieback (Jones, 2002) affecting nut production. 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 and Gallagher, 1990). MFC can reduce young healthy foliage when densities are high. The exact extent of yield reduction in relation to MFC density has not been quantified though, and it is essential for developing an effective integrated pest management for the pest.

Control of A. ironsidei using pesticides is difficult considering the size that macadamia trees and canopies can reach (up to >20 m in Hawaii, with dense canopies), making full coverage spray applications that are nearly impossible and expensive. Despite these difficulties, current management programs for MFC in Hawaii rely primarily on insecticide applications, while biological control and cultural management options are being developed. Growers rely on insect growth regulators (pyriproxyfen, Esteem® 35 WP, Valent U.S.A. Corporation, Walnut Creek, CA and buprofezin, Centaur®, Nichino America Inc., Wilmington, DE), in combination with paraffinic horticultural oils (Saf-T-Side®, Lawn and Garden Products, Inc. Fresno, CA and TriTek®, Brandt Consolidated, Inc. Springfield, IL) (Gutierrez-Coarite et al., 2017). There are constraints on the use of the insect growth regulators insecticides, including a 60 day pre-harvest interval of buprofezin, and impacts on non-target species. In addition to limited insecticide options, the dense canopies, access to water, moving heavy equipment throughout the orchards and the costs associated with these factors contribute to reducing the economic sustainability of insecticidal control of MFC. There are resident natural enemy populations that may contribute to reductions in A. ironsidei populations with predation and parasitism of up to 60% and 4.3% respectively (Gutierrez-Coarite et al., 2018). However, their contribution to MFC mortality is inadequate to control this pest when population peaks occur in some seasons of the year. A specialist parasitoid from Australia, Metaphycus macadamiae, is a potential biological control agent that is under consideration for release in Hawaii.

Insecticides have been used to control A. ironsidei in Hawaii with no specific action thresholds in place, and without a thorough understanding of yield loss attributable to MFC. The economic injury level (EIL) is a significant element of determining cost-benefit in integrated pest management (IPM) programs and is an important decision-making instrument in the utilization of pesticides (Shipp et al., 2000). Pedigo et al. (1986) defined EIL as the point where the costs of applying pest control measures are equal to the benefits of the pest management actions. Pest infestations below the EIL do not justify pest control actions; however, economic damage may accrue when the pest populations surpass the EIL. The parameters included in EIL calculations comprise the cost of controlling the pest, actual market price of the product, yield loss rate attributable to the pest, and efficiency of controlling the pest using the management options applied (Higley and Pedigo, 1996). A. ironsidei is currently the only insect pest in Hawaii that requires consistent and aggressive management in macadamia, and it 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 of course also concerns with the use of insecticides in terms of environmental impacts. Development of IPM decision-making tools that will assist in reducing dependence on insecticides for A. ironsidei will be a valuable contribution to sustainable management of MFC.

This study examines the impact of A. ironsidei at a range of population densities on macadamia nut yield in the absence of an effective biological control agent, in two cultivated varieties, and under two different sets of environmental conditions. Further, to provide growers with a decision-making tool for MFC IPM, this study provides estimates for the economic injury level of A. ironsidei in macadamia orchards in Hawaii.

2. Materials and methods

2.1. Field data collection: effects of A. ironsidei on macadamia yield and quality

On-farm trials were established in March 2016 to quantify yield loss attributable to MFC, and to provide estimates of the economic injury level of the macadamia felted coccid. This study was conducted in two consecutive production years (Year 1: 2016–2017 and Year 2: 2017–2018) at two locations on Hawaii island, the Kau and South Kona districts. The annual mean temperature of Kau district is 17 °C, with a maximum of 29 °C and a minimum of 8.9 °C and the mean annual precipitation is 1332.5 mm. The South Kona district annual mean temperature is 27 °C, with a minimum of 20 °C and a maximum of 31 °C, and a mean annual precipitation of 481 mm. The selection of these locations provided a mesic production area with moderate temperatures, and a hot, dry production area. Management of the study sites followed standard grower procedures, with the exception that no A. ironsidei control was applied in the experimental plots at each location.

Two cultivars of macadamia were selected at each location, “Kakea” (HAES 508, or var 508) and “Kau” (HAES 344, or var 344). Twenty trees were randomly selected within a production block for each cultivar at each location; 15 of the trees were naturally infested with A. ironsidei populations from the previous year, and 5 trees with no sign of A. ironsidei infestation (control trees). This sampling design thus provided the opportunity to monitor the effect of a gradient in MFC infestation (see Appendix 1) on nut yield within an otherwise uniform production unit.

Monthly monitoring of A. ironsidei was carried out from March 2016 in the South Kona district and in the Kau district from April 2016. Monitoring numbers of adult A. ironsidei is impractical, as many of the insects present on the tree are often dead exoskeletons of MFC, that can remain on the tree for protracted periods and are not readily distinguished from live coccids without the use of a dissecting microscope (Wright and Vorsino, 2005). We therefore monitored crawler numbers, as they are a more reliable indicator of MFC activity on trees and can be trapped on simple sticky traps. To monitor A. ironsidei crawler stage populations, two branches per tree were selected and double-sided sticky tape (3 M Center, St. Paul, MN) bands of 1.27 cm width were placed around each branch over a previously lightly sanded band on the bark and collected after a week. The number of A. ironsidei crawlers trapped on 5.08 cm length of each tape (6.5 cm² total, 1 square inch) was determined using a microscope for each sampling.

Yield data were recorded during the 2016-17 and the 2017-18 harvest seasons between September and May. Yields were hand harvested from the ground below trees at 8 to 10-week intervals and recorded as
mass of wet-in-shell per tree, per cubic meter of canopy, to standardize for variation in tree size. Tree crown volume was calculated using three values: 1) crown spread, 2) crown thickness, and 3) crown form (CF). Crown spread is the diameter of the crown, crown thickness is the height from the base of the crown to the top of the tree, and the crown form of the canopy was assumed to be an irregular ellipsoid (Charles-Edwards et al., 1986) as:

\[ \text{Crown volume} = (\text{CF}) \times (\text{crown thickness}) \times (\text{mean crown spread})^2 \]

where crown form is calculated as \( \text{CF} = (\pi \times \text{crown shape ratio})^2 / 4 \) (Charles-Edwards et al., 1986).

Nut quality was determined using a sub-sample of 50 randomly selected nuts per tree. After husking, macadamia nuts were desiccated in an oven at 30 °C for 7 days, followed by 40 °C for 7 days, and finally 3 days at 70 °C (Wall and Gentry, 2007). The dry mass of the sampled nuts was documented, and individual nuts were weighed and cracked. Kernels were weighed and then floated to calculate the percentage of kernel recovery and kernel defects were recorded based on visual evaluation (Hamilton and Ito, 1984).

### 2.2. Statistical analysis

An index of *A. ironsidei* density per tree was derived by calculating the mean number of *A. ironsidei* crawlers per two 6.5 cm² samples on each evaluation date, and then accumulated for each tree per year. Linear regression analyses (JMP Pro 14, SAS Institute, Carey, NC) were used to evaluate the effects of *A. ironsidei* density on macadamia yield and quality. For each harvest season, linear regression analyses were performed using accumulated *A. ironsidei* density on sampling strips per year for each tree as the independent factor and four dependent factors: yield, percentage of kernel recovery, percentage of defective kernels and individual kernel weight.

### 2.3. Economic injury level (EIL) calculations

EILs for each site and cultivar were calculated to estimate the *A. ironsidei* densities that justifiably pesticide application, using the formula

\[ \text{EIL} = \frac{\text{CN} \times \text{YPL}}{\text{N} \times \text{P}} \]

where \( C \) = the cost of control per unit (US$/ha), \( N \) = pest density (*A. ironsidei* density), \( Y \) = yield (anticipated yield in kg/ha), \( P \) = actual price per unit of yield (US$/kg), and \( L \) = the percentage reduction in crop yield for every unit of pest density (% reduction in crop value for every unit of *A. ironsidei*) (Pedigo et al., 1986). The cost of control (C) was estimated as $395.2/ha based on the conventional production practice of applying pyriproxyfen (Esteem® 35 WP) and paraffinic oil (TriTek®) for control. Pyriproxyfen is applied at a rate of 350 g/ha at a cost of $135.85/ha of product. Pyriproxyfen is only effective at controlling the crawler stage of *A. ironsidei*, it does not effectively control *A. ironsidei* adults. To control the adult stage of this pest, growers mix pyriproxyfen with paraffinic oil at a cost of $111.15/ha. Cost of control includes labor ($49.4/ha) and equipment ($98.8/ha). This one-time application cost of these products assumes 100% control of *A. ironsidei*. The cost includes labor ($49.4/ha) and equipment ($98.8/ha).

For the sake of simplification of calculations, a mean MFC crawler density (N) of one *A. ironsidei* per sticky tape trap (6.5 cm²/tree) was used for the estimates - in other words, yield loss per MFC crawler trapped was used in the formula.

Yield (Y) value was estimated as the anticipated yield in kg/ha. Average expected yield was estimated using the y-intercept on the regressions of macadamia yield and *A. ironsidei* density for each cultivar and study site. Price (P) was determined at $2.2/kg based on a 2-year average return to macadamia growers documented by the USDA National Agricultural Statistics Service (2018).

The percentage reduction in crop value (L) was determined by the relationship of *A. ironsidei* density to crop yield using a regression equation for each cultivar and location (Table 2). For example the resulting equation for the yield mass lost in var 508 in Kau (\( y = -0.016x + 70 \)) meaning that for every one *A. ironsidei* crawler captured on the tape, there is a 0.016 kg yield decrease per tree; dividing this value by the y-intercept value of 70 kg provides an estimate of yield loss of 0.00023% (yield component of L) for every increase of one crawler per 6.5 cm²/tree (Fig. 1A).

Following the approach of Haviland et al. (2015), data from 2016 to 2017 were used for EIL evaluations because the relationship between yield and *A. ironsidei* (Fig. 1) was highly significant for that harvest season compared with the 2017–2018 season (Table 2).

### 3. Results

#### 3.1. Effects of *A. ironsidei* on macadamia yield and quality

Different ranges in *A. ironsidei* densities were observed in trees at each location and by cultivar during the two years of the study (Table 1). Var 508 was less infested with *A. ironsidei* in South Kona than in Kau in both years of the study, and *A. ironsidei* infestation in var 344 was 2.4-fold higher in South Kona compared with Kau, but only in the first year of the study (Table 1). Field observations throughout the study confirmed that yield loss estimates could be directly related to *A. ironsidei* since no other pests were observed to be causing significant losses in the two years of the study, e.g. *Nezara viridula*, which can also cause premature nut-drop and reduced kernel quality were not observed in significant numbers.

During the two years of the study yields per tree ranged from 35 to 101 kg (wet-in-shell) per tree in var 508 in the Kau district and in the South Kona district from 13 to 101 kg (Table 2). Average yields varied by harvest season, and generally lower yields were observed during the second year of the study in both varieties and at both locations, for reasons that remain unclear.

Linear regression analyses of yield against *A. ironsidei* density resulted in significantly negative relationships in 2016–2017 and 2017–2018 harvest seasons for both varieties and both locations (Table 2). The significant regressions had \( R^2 \) values ranging from 0.20 to 0.55 (Table 2), suggesting that other factors contributed considerably to yield loss, particularly in the South Kona study sites, which are typically considerably drier than the Kau sites. Cultivar × environment interactions may have played an overriding role in determining yield under the more inclement conditions in South Kona. However, all regression analyses of yield as a function of MFC infestation levels that were used in the EIL development were highly significant (Fig. 1). Var 344 had relatively similar yield in un-infested trees (34 ± 6 kg per tree, mean ± 95%CI) compared with var 344 trees in Kau (21 ± 5 kg per tree mean ± 95%CI), yet at the South Kona site, they harbored a greater range in numbers of MFC infesting them, but a significantly lower yield loss rate (Fig. 1; comparison of slopes: \( F_{6,72} = 25.16; P < 0.0001 \). Differences in mean yield per tree are shown in Appendix 1, showing the consistent trend for control trees to have significantly greater yields than moderately to heavily infested trees.

For the Kau trees, a negative relationship between yield and *A. ironsidei* infestation level was observed in var 508 in both years of the study (Table 2). A similar negative relationship was recorded for var 344 at Kau. A slight reduction in kernel recovery was observed in year 2 of the study, with a 0.20% reduction in kernel recovery for every 10 *A. ironsidei* crawlers (Table 2). No other significant effects were observed in the quality of kernel for the two varieties in the Kau District (Table 2). In South Kona, yields of both varieties were negatively related to *A. ironsidei* infestation rates in both years of the study at the South Kona location (Fig. 1C and D). Cultivar 508 had a dramatic and significantly higher (comparison of slopes: \( F_{6,72} = 25.16; P < 0.0001 \)), rate of yield reduction relative to MFC infestation level compared to the Kau var 508 trees (approximately 4× the yield loss rate) (Fig. 1C). Regressions of quality parameters (kernel recovery, kernel defects, individual kernel...
There was considerable variability in estimated EIL among locations and years for both A. ironsidei varieties, ranging from 15 MFC crawlers per tree on sampling sticky tape traps (var 508) to 246 per tree crawlers per tree on sampling sticky tape traps (var 344) in the Kona study sites (Table 3). In South Kona, the estimated EIL was an accumulated 65 MFC per tree crawlers per tree on sampling sticky tape traps (var 344) in the Kona study sites (Table 3). In the Kau Study sites, the estimated EIL was an accumulated 65 MFC per tree crawlers per tree on sampling sticky tape traps (var 508) and 55 crawlers per tree on sampling sticky tape traps for var 344 (Table 3).

### 3.2. Economic injury levels

Economic injury levels (EIL) were estimated using the formula developed by Pedigo et al. (1986) as described above. Estimated EIL values using the parameters listed above are shown in Table 3. The estimated EIL values should be interpreted as the accumulated number of crawlers per year involving pests and their parasitoids that suppress the MFC population under natural conditions reduced the selective pressure on the plant to adapt resistance mechanisms to A. ironsidei. From an evolutionary perspective, it is interesting to note that while total mass of fruit (seeds) was reduced by MFC feeding in the absence of suppression by a specialized natural enemy, individual seed mass and quality was unaffected. The total number of seed produced by infested trees was reduced, which should impose a fitness cost on infected trees, unless seeds complete for limited germination space once dispersed from the parent tree. It is possible that the presence of a parasitoid that suppresses the MFC population under natural conditions reduced the selective pressure on the plant to adapt resistance mechanisms to A. ironsidei, thus resulting in high susceptibility of cultivated trees to this tiny insect when no effective biological control is present. This may be a case of indirect defense of the plant host, where the tree might produce stimuli that attract natural enemies of the herbivore when attacked (Pearse et al., 2020). Indirect defenses are considered to be among the most effective defenses for plants against herbivorous insects (Janssen et al., 1998). If the tri-trophic interaction between macadamia nut, A. ironsidei, and its parasitoid is such a case, further research should consider the possibility that cultivated varieties may have differential attractiveness to parasitoids of A. ironsidei, as attractiveness to the insects may be under genetic control in the plants (e.g. Zust and Agrawal, 2016).

The difference in impact of MFC feeding on the different varieties examined under different environmental conditions was striking. Tresing in the more mesic Kau site had a similar rate of yield reduction attributable to MFC. In the drier Kona area, while both varieties had similar yield levels in trees not infested with MFC, the rate of yield loss in Var 508 was substantially larger than in the Kau site with lower infestation levels. Conversely, in var 344, even with inordinately high

### Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Cultivar</th>
<th>Year</th>
<th>Mean (±SE)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kau</td>
<td>508</td>
<td>2016-2017</td>
<td>60 ± 12.9</td>
<td>0.0-211</td>
</tr>
<tr>
<td></td>
<td>344</td>
<td>2017-2018</td>
<td>38 ± 8.8</td>
<td>0.9-160</td>
</tr>
<tr>
<td>South Kona</td>
<td>508</td>
<td>2016-2017</td>
<td>15 ± 4.2</td>
<td>0.0-67</td>
</tr>
<tr>
<td></td>
<td>344</td>
<td>2017-2018</td>
<td>7 ± 1.7</td>
<td>0.2-30</td>
</tr>
<tr>
<td>Kau</td>
<td>508</td>
<td>2016-2017</td>
<td>51 ± 14.5</td>
<td>0.0-196</td>
</tr>
<tr>
<td></td>
<td>344</td>
<td>2017-2018</td>
<td>53 ± 15.2</td>
<td>2.0-292</td>
</tr>
<tr>
<td>South Kona</td>
<td>508</td>
<td>2016-2017</td>
<td>124 ± 29.3</td>
<td>1.0-497</td>
</tr>
<tr>
<td></td>
<td>344</td>
<td>2017-2018</td>
<td>8 ± 1.3</td>
<td>1.0-23</td>
</tr>
</tbody>
</table>

### 4. Discussion

The primary mechanism for yield loss associated with A. ironsidei is their feeding activity, limiting nutrient sources for nut development, as well as likely causing premature nut-drop in trees where the flowering racemes were infested with high MFC densities. Heavily infested trees would also experience branch-die back and may become susceptible to infestation by stem boring Scolytinae, further weakening trees (M.G. Wright unpublished data). Nut quality parameters were unaffected, with the exception of a very minor kernel recovery reduction (0.20%) in one year, at one location, in one cultivar. Reduced nut yield is likely the result of the perennial presence and feeding habit of A. ironsidei, which mostly occurs on the main trunk and branches of the tree. While A. ironsidei can be found on the husks of the macadamia nut, it does not penetrate the kernel during feeding, and therefore does not cause physical damage to the kernel that might impact quality parameters. The primary mechanism for yield loss associated with A. ironsidei, as attractiveness to the insects may be under genetic control in the plants (e.g. Zust and Agrawal, 2016).
infestation levels, the rate of yield loss was low. This underscores the significance of understanding growing conditions on susceptibility to damage from sap-sucking insect pests, and is an aspect that should be considered with care when developing pest management programs (Camacho et al., 2015). Further, with regard to the unexplained variability in yield loss in the different sites, variable success of honeybees placed in orchards to provide pollination services may have been a contributing factor, as well as factors such as variability in moisture available to trees within orchards.

EIL estimates: Different methods to estimate economic injury levels has been used by other researchers, including different damage indices and developmental stages of the pest. Jemsi (2007) used pest density on leaf surface to calculate the economic injury level in the grape leaf miner *Syringospis temperatella* Led. (Lep: Elachistidae), while Bahrami et al. (2003) and Naranjo et al. (1996) quantified the number of individuals per plant for the whitefly, *Bemisia tabaci* (Hem: Aleyrodidae). The numbers of trapped insects was used an indicator of pest density for EIL estimation by Kovanci et al. (2005); similarly, we used the number of *A. ironsidei* crawlers trapped on double sided sticky tape as a correlate of pest density in the present study.

This formula shown in Table 3 can be used to calculate EILs for any value of anticipated yields and changes in management costs. Haviland et al. (2015) described this EIL formula can be adjusted to accommodate yield and control cost modifications for *Ferrisia gilli* Gullan in pistachio orchards, and the same should apply for this system. Adjustments to EIL estimates may be necessary depending on changes to the assumptions that were used in developing the original model. For example, if some areas will need two applications of pyriproxifen to suppress *A. ironsidei* crawlers trapped on double sided sticky tape as a correlate of pest density in the present study.

<table>
<thead>
<tr>
<th>Location &amp; Variety</th>
<th>EIL = CN/(Y/P)</th>
<th>EIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kau var 508</td>
<td>(395.2 x 1)/(11,997.0 x 2.2 x 0.00023)</td>
<td>65</td>
</tr>
<tr>
<td>Kau var 344</td>
<td>(395.2 x 1)/(8231.2 x 2.2 x 0.00041)</td>
<td>55</td>
</tr>
<tr>
<td>South Kona var 508</td>
<td>(395.2 x 1)/(9571.2 x 2.2 x 0.0106)</td>
<td>15</td>
</tr>
<tr>
<td>South Kona var 344</td>
<td>(395.2 x 1)/(5090.4 x 2.2 x 0.0002)</td>
<td>246</td>
</tr>
</tbody>
</table>

| A. ironsidei density, Y = yield (kg/ha), P = actual price per unit of yield (US$/kg), and L = % reduction in yield for every unit of pest density. |
current price of macadamia nuts.

Prior to the advent of *A. ironsidei* in Hawaii, macadamia growers avoided spraying foliar application insecticides as far as possible. The cost of managing MFC and the yield reductions caused by a range of infestation levels were previously not quantified. The lack of information about the economic injury level of this pest resulted in arbitrary decision making regarding the application and use of chemical control options. With the high MFC populations that are typical in Hawaii macadamia nut orchards without effective biological control, the EIL will frequently be surpassed. In all our study sites, all infested trees would have reached MFC densities adequate to justify pesticide intervention at least once per season. The EILs determined in this study suggest a need for an effective integrated pest management program for *A. ironsidei* management that will reduce MFC infestations substantially, such as an effective biological control agent (Polaszek et al., 2020), combined with effective orchard management practices (Gutierrez-Coarite et al., 2018). Future MFC research should focus on balancing the use of chemical control options for *A. ironsidei* to minimize potential impacts on biological control agents, though elucidating how effectively a specialist biological control agent such as *M. macadamiae* (Polaszek et al., 2020) suppresses pest populations seasonally. We hypothesize that once released in Hawaii, *M. macadamiae* will reduce *A. ironsidei* infestations to the extent that the EIL is seldom reached.

Credit author statement

Rosemary Gutierrez-coarite: methodology, field data collection, data analysis, writing – original draft; Alyssa Cho: field data collection, data analysis, writing – review and editing; Javier Mollinedo: data collection, data analysis; Ishakh Pulakkatu-Thodi: data collection, data analysis; Mark G Wright: funding acquisition, methodology, investigation, formal analysis, writing – review and editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2020.105378.

Appendix 1

Comparison of mean yields (±SD) in kg per tree from macadamia nut tree cultivars with different initial numbers of macadamia felted coccid (MFC per sample): At commencement of trials: Control = no detectable MFC; Low = mean of 20 MFC; Medium = 80 MFC; High = mean of 350 MFC. ANOVA results: Kau 508: F3,16 = 14.64, P < 0.0001; Kau 344: F3,16 = 13.39, P < 0.0001; Kona 508: F3,16 = 6.40, P = 0.0047; Kona 344: F3,16 = 9.55, P = 0.0007. Means with the same letters not significantly different (Tukey multiple comparisons, P > 0.05). By the conclusion of the trial, mean cumulative MFC numbers per tree (sampled as described in Materials and Methods, Section 2.1) were: Control = 288 MFC; Low = 2,805 MFC; Medium = 7,514 MFC; High = 13,035 MFC. Control infestation was consistently an order of magnitude lower than the Low infestation trees.
References


