Testing the Attractiveness and Efficacy of Baits for the Monitoring and Control of the Thief Ant, *Solenopsis papuana*

Cassandra S. Ogura-Yamada and **Paul D. Krushelnycky**
Department of Plant and Environmental Protection Sciences, University of Hawaii at Manoa, 3050 Maile Way, Gilmore 310, Honolulu, HI 96822. cso@hawaii.edu, pauldk@hawaii.edu.

Abstract. *Solenopsis papuana* is one of the few introduced ant species that have widely infiltrated undisturbed mesic and wet forests in Hawaii. This may be problematic since many endemic Hawaiian insects are limited to mountain forests, and methods for monitoring and controlling *S. papuana* would be useful. Four non-toxic monitoring baits (corn syrup, SPAM®, peanut butter, and tuna/corn syrup blend) and five ant pesticide baits (Advion® Fire Ant Bait™, Amdro® Ant Block®, Extinguish™ Plus, MaxForce® Complete Brand Granular Insect Bait, and Siesta™) were tested for attractiveness to *S. papuana* in choice tests at Lyon Arboretum and Pahole Natural Area Reserve (NAR) on the island of Oahu. Amdro® Ant Block® and Siesta™ were also tested for efficacy against *S. papuana* in field plots at Pahole NAR. SPAM® and peanut butter were the most attractive monitoring baits at both locations. There were few significant differences in attractiveness among the five ant pesticides, but Amdro® Ant Block® attracted the highest or second highest number of ants at both sites, while rankings among the other baits were inconsistent. Amdro® Ant Block® presented in bait stations 2.5 m apart greatly reduced the number of ants at monitoring cards in field plots, by an average of 96% from pre-treatment levels over the course of the 246-day trial. Ant numbers also declined in the Siesta™ plots (by 77%), but more closely mirrored fluctuations in the untreated control plots. These methods were effective for monitoring and suppressing *S. papuana* populations in localized natural areas in the Waianae Mountain Range.

Key words: Hawaii, invasive ants, ant control, bait preference, hydramethylnon, metaflumizone

Invasive species are major drivers of species endangerment and extinction (Clavero and Garcia-Berthou 2005), and islands gain a disproportionately high number of invaders (Mooney and Cleland 2001) compared to continental ecosystems. Invasive ants can cause major ecological changes because of their impacts on native ants and arthropods through predation or competition (Porter and Savignano 1990, Human and Gordon 1997, McNatty et al. 2009). Invasive ants also cause economic damages; Pimentel et al. (2005) estimated that the red imported fire ant (*Solenopsis invicta*) alone costs $1 billion per year in losses, damages, and control expenses in the southern United States. Invasive ants on islands can be detrimental to multiple trophic levels of ecosystems (Wetterer 2007, O'Dowd et al. 2003), and Hawaii is not exempt from the impacts of invasive ants, which have caused conservation (Cole et al. 1992, Gillespie and Reimer 1993, Plentovich et al. 2008), agricultural (Jahn et al. 2003, Souza et al. 2008), and urban problems (Tenorio and Nishida 1995, Leong and Grace 2008). Additional information on the ecology and management of Hawaii's invasive ant species is desirable, as relatively few have been studied in any detail (Reimer 1994, Krushelnycky 2015).

The thief ant, currently known as *Solenopsis papuana* Emery in Hawaii, was first found in the islands in 1966–67 by Huddleston and Fluker (1968), who reported two new, unidentified *Solenopsis* taxa: a dark, more widespread species "a," and a lighter, slightly smaller species "b." Their species "a" was later identified as *S. papuana* (Reimer 1992), and this name has since been used for this taxon in the Hawaiian ant literature (e.g., Gillespie and Reimer 1993, Reimer 1994, Krushelnycky et al. 2005). However, the name *S. papuana*, originally designated for specimens from Papua New Guinea in 1900 (Wilson and Taylor 1967), has subsequently also been applied to specimens across the Pacific, including Samoa, Fiji, Society Islands, Cook Islands, and Pohnpei (Wilson and Taylor 1967, Morrison 1996, 1997, Clouse 2007). Of these latter specimens that we have examined (P. Krushelnycky unpub. data, AntWeb 2016), all differ substantially from those in Hawaii and are unlikely to be conspecific with the Hawaiian species. This conclusion is supported by molecular data, which place Hawaiian specimens in a clade of species described from the Indian Ocean (D. Gotzek pers. comm.). A comprehensive taxonomic revision of small *Solenopsis* species is needed to better understand the species limits, geographic ranges and correct identities of many of the taxa in this group. Until this taxonomy is resolved, we continue to refer to the species in Hawaii as *S. papuana* in the interest of consistency with prior literature in Hawaii, recognizing that nomenclature is likely to change in the future.

In 1966–67, *S. papuana* was found at one site on Oahu and multiple sites across Maui, where it was already observed as a dominant ant species with large nests in some areas (Huddleston and Fluker 1968). Since then it has spread to Kauai, Molokai, Lanai, and Hawaii island (Nishida 2002). It is one of the few ant species that has successfully infiltrated undisturbed mesic and wet upland forests in Hawaii (Reimer 1992, 1994), and field observations suggest that it currently exhibits high population densities across a wide range of natural areas (Plentovich 2010, Ogura-Yamada and Krushelnycky unpub. data). Many endemic Hawaiian insects are now limited to montane habitats (Zimmerman 1948), and can be detrimentally impacted by invasive ants (Cole et al. 1992, Gillespie and Reimer 1993, Krushelnycky and Gillespie 2010).

A broader study investigating the potential impact of *S. papuana* on native arthropod species and food webs required the development of experimental monitoring and control methods for this species. In this paper, we report on these methods, including the relative attractiveness of four non-toxic monitoring baits and five pesticide ant baits, testing a bait station to effectively deliver pesticide baits while minimizing non-target effects, and the efficacy of two of the toxic ant baits against *S. papuana* in field plots. While *S. papuana* is too widespread for eradication to be realistic, the information in this study may be useful for monitoring distribution, relative densities and control in localized areas of high conservation value.

Methods

Study sites. Preference tests for monitoring baits and pesticide baits were conducted in two forested sites on Oahu that supported high densities of *S. papuana*. The first site was located within University of Hawaii's Harold L. Lyon Arboretum, in lowland, non-native wet forest in Manoa valley in the Koolau mountain range (150 m elevation, 3836 mm annual rainfall (Giambelluca et al. 2013)). The second site was located in mixed native and non-native mesic forest in Pahole Natural Area Reserve (NAR) in the Waianae mountain range (480 m elevation, 1375 mm annual rainfall (Giambelluca et al. 2013)). A pesticide bait efficacy test was conducted only at Pahole NAR.

Monitoring bait preference. Four food baits containing varying amounts of sugar, oil and protein were chosen to compare relative attractiveness to *S. papuana*: (1) light corn syrup (Karo®, ACH Food Companies, Cordova, Tennessee), (2) peanut butter (Jif® Creamy, The J.M. Smucker Company®, Orville, Ohio), (3) SPAM® (Hormel Foods, Austin, Minnesota), and (4) a tuna and corn syrup blend (one 5 oz. (142 g) can of tuna (Chicken of the Sea® International, San Diego, California) in water, drained, and blended with 100 g light corn syrup in a food processor). Each of these baits has been used for attracting a variety of ants in bait preference and monitoring studies: corn syrup (Eow and Lee, 2007), peanut butter (Lee, 2002, Causton et al. 2005, Hara et al. 2014), processed meats (Porter and Tschinkel 1987, Peck et al. 2015), and tuna/corn syrup blends (Keeler 1980, Krushelnycky et al. 2011).

Baits (approximately 1.5 cm diameter quantity of corn syrup, tuna/corn syrup blend, and peanut butter, or one cube of SPAM® approximately 1 x 1 x 0.5 cm) were placed in paper cupcake liners (Bake Fresh White Baking Cups, Rockline Industries®, Sheboygan, Wisconsin) and presented next to each other at replicate stations, which were approximately 20 m apart, at each site. The cupcake liners prevented liquid baits from spilling, while allowing ants access to the baits both on the upper surface and underneath as the baits soaked through the paper. Ant numbers on each bait were recorded (top and bottom of wrapper summed) every hour for three hours. The preference test was conducted on 18 June 2015, at Lyon Arboretum, using 25 replicate stations, and on 1 August 2015, at Pahole NAR, using 24 replicate stations. Stations with fewer than 24 ants total across all bait types and hours (i.e., <2 ants/bait/hour on average) were removed from the data set; this left 16 replicate stations at Lyon Arboretum and 19 replicate stations at Pahole NAR. Due to unequal variances among groups, Welch's ANOVA followed by Games-Howell multiple comparison test was used to compare log-transformed numbers of ants among all bait types for each hour at each site. Numbers of ants were subsequently also compared across hours at each site for the two most attractive baits. To compare relative detection rates for the four baits, we compared proportions of stations that attracted any *S. papuana* after one hour at each site, after removing the low ant density stations described above, using a Chi-square contingency table. For the two most attractive baits, we also compared proportions of stations attracting ants at one and two hours at each site, using Fisher's Exact Test.

Pesticide bait preference. Five granular commercial pesticide ant baits were chosen to compare relative attractiveness to *S. papuana*: (1) Advion® Fire Ant Bait (0.045% indoxacarb, EPA# 100-1481, Syngenta Corporation, Greensboro, North Carolina), (2) Amdro® Ant Block® Home Perimeter Ant Bait (0.88% hydramethylnon, EPA# 73342-2, AMBRANDS, Atlanta, Georgia), ((4) MaxForce® Complete Brand Granular Insect Bait (1% hydramethylnon, EPA# 432-1255, Bayer Environmental Science, Research Triangle PK, North Carolina), and (5) Siesta™

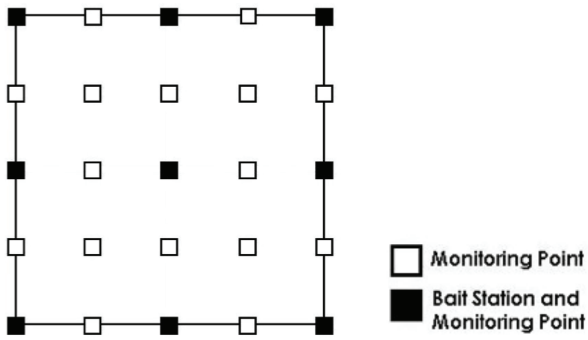

Figure 1. Layout of 5 x 5 m pesticide bait efficacy plots. Each plot contained nine bait stations and 25 monitoring points, whose positions were as indicated except on occasions when bait stations were shifted (see text). Monitoring points were either 0 m, 1.25 m, or 1.8 m from bait stations.

(0.063% metaflumizone, EPA# 7969-232, BASF Corporation, Florham Park, New Jersey). These baits were chosen because they target *Solenopsis* fire ants, or because they have been found to be attractive or effective against other species in the subfamily Myrmicinae (Williams et al. 2001, Oi and Oi 2006, Warner et al. 2008, Hara et al. 2014). Advion® Fire Ant Bait, Amdro® Ant Block®, Extinguish™ Plus, and Siesta™ are all based on a similar bait matrix composed of corn grit saturated with soybean oil. MaxForce® Complete is a mixture of two bait matrix types: a corn grit/soybean oil-based granule and a protein-based granule.

Each bait (2.5 ml (0.5 teaspoon)) was placed into paper cupcake wrappers and presented next to each other at replicate stations at both sites, and ant numbers were recorded every hour for three hours as described for the monitoring bait preference test. The pesticide preference test was conducted on 18 September 2015, at Pahole NAR, using a total of 25 replicate stations, and on 6 November 2015, at Lyon Arboretum, using 25 replicate stations. After excluding stations with fewer than 24 ants total across all bait types and hours, 10 stations at Pahole NAR and 23 stations at Lyon Arboretum remained for analysis. Numbers of ants (log transformed) were compared among bait types at each hour and site as described for the monitoring bait preference test. Since pesticide baits are generally available to ants for longer periods of time, we did not statistically test differences in bait attractiveness across the three monitoring hours.

Pesticide bait efficacy trial. We chose two baits, Amdro® Ant Block® and Siesta™, to test efficacy of continuous treatment over an eight-month period in field plots at Pahole NAR because both exhibited relatively high attractiveness to *S. papuana* at one or both of our bait preference test sites (see Results). Nine 5 x 5 m plots were established on 3 July 2015, and pre-treatment ant densities were determined in each plot: Ants were counted on the tops and bottoms of 25 monitoring cards (one half of a 7.6 x 12.7 cm index card) baited with a smear of peanut butter. Cards were placed on the ground every 1.25 m in a grid pattern (Fig. 1), and collected after 1.5 hours. The nine plots were subsequently randomly assigned to one of three treatments (Amdro® Ant Block®, Siesta™, or untreated control), with the exception that the two lowest-density plots were assigned to the control treatment to ensure that the pesticide baits were tested in plots with high ant densities. Bait stations were used to apply the baits to limit access to non-target arthropods. Stations were constructed of 3.81 cm (1.5 in) long sections of 3.18 cm (1.25 in) diameter PVC tubing, fitted with PVC endcaps on the upper end. The open bottoms were screened with Amber Lumite Screen (530 μm mesh size, Lumite Inc., Alto, Georgia) fastened with PVC cement (Oatey® Co., Cleveland, Ohio). This design allowed access to *S. papuana* workers but excluded most other non-target arthropods. Nine bait stations, separated by 2.5 m in a grid pattern (Fig. 1), were placed in each plot testing the two pesticide baits. Each station was supplied with 2.5 ml (0.5 teaspoon) of Amdro or Siesta ant baits contained within a disposable polypropylene tea bag (Daiso Industries Co., Hiroshima, Japan). This allowed ants to imbibe pesticide-laden oil from the baits while facilitating their periodic replacement. Stations were staked to the ground using 2.05 mm (12 AWG) diameter galvanized wire to ensure that the endcaps shielded the bait from rain, and that contact between the screened opening and the ground was maintained.

Baits were first applied on 3 July 2015 after the pre-treatment monitoring, and replaced every four to seven weeks for a total of five times during the experiment, which ended on 5 March 2016 (total 246 days of treatment). On each date that baits were replaced, ant densities in the plots were assessed using the peanut butter card monitoring methods described above. During the first two bait replacement events, the nine bait stations in each plot were also systematically shifted such that each of the 25 monitoring points received a station by the second event in September, 2015. Bait stations were subsequently returned to their original positions (indicated in Figure 1) for the remainder of the trial, except to target occasional localized surges in ant numbers in plots. Because we had only three replicate plots for each treatment, we present only descriptive statistics for trends in ant densities in the plots. To assess whether the bait station spacing interval (2.5 m grid) was effective in the Amdro and Siesta plots, we compared reductions in numbers of ants at the 25 monitoring points in each plot on the first monitoring event, 28 days after bait station placement, according to the distance of the points from the nearest bait station: 0 m (immediately adjacent to bait station), 1.25 m or 1.8 m (Fig. 1). Because these monitoring points can be considered independent replicates for this test, we used a two factor ANOVA to compare reductions in ant numbers for each bait type, including the factors 'monitoring distance' ($n = 75$) and 'plot number' ($n = 3$) to control for individual plot differences. Statistical analyses were performed using Minitab v. 17.1 (Minitab 2013).

Results

Monitoring bait preference. Among the four foods evaluated as potential monitoring baits, SPAM® and peanut butter generally attracted more *S. papuana* than corn syrup and the tuna/corn syrup blend at most of the time intervals at both sites (Fig. 2). However, these differences were not always statistically significant (see Fig. 2) due to high variation in ant numbers among replicate stations. For SPAM® and peanut butter baits, mean recruitment increased over time, but in most cases these increases were not statistically significant. Specifically, numbers of *S. papuana* at peanut butter baits did not differ among hours at either Lyon Arboretum ($F = 0.34$, $p = 0.716$) or Pahole NAR ($F = 2.08$, $p = 0.140$), nor did they differ among hours at SPAM® baits at Lyon ($F = 1.34$, $p = 0.278$). However, ant numbers at SPAM® baits at Pahole did differ significantly over time

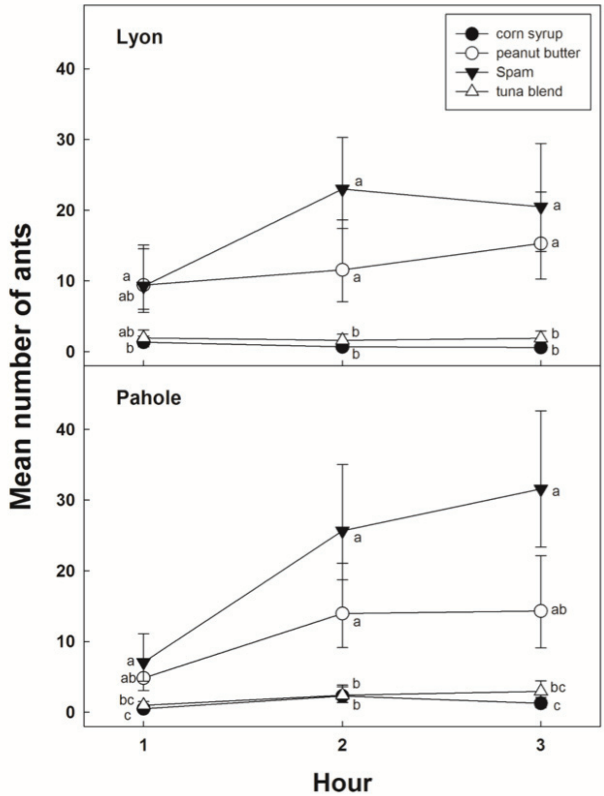

Figure 2. Mean number (±SE) of *S. papuana* attracted to food baits at Lyon (top) and Pahole (bottom) over the course of three hours. Means sharing the same letters within each hour at each site are not significantly different (Welch's ANOVA and Games-Howell posthoc test on log-transformed counts, α=0.05; depicted means and SEs are back-transformed).

(F = 4.12, p = 0.025), with recruitment at hour 3 being significantly higher than at hour 1 (Games-Howell test, p = 0.022). Differences between hours 1 and 2 were marginally significantly different (p = 0.060) and differences between hours 2 and 3 were not statistically significant (p = 0.881) for SPAM® at Pahole.

SPAM® and peanut butter also tended to attract *S. papuana* to a higher percentage of baits offered, relative to the other two baits (Fig. 3). Again, these differences were not always statistically significant. After one hour, an interval commonly used for ant monitoring and distribution mapping (Blachly and Forschler 1996, Lee et al. 2003, Starr et al. 2008), there was a significant association between percentage of baits found and bait type at Pahole NAR (Chi-square = 10.556, p = 0.014), with SPAM® and peanut butter baits exhibiting higher than expected occupancy, and corn syrup and tuna/corn syrup blend exhibiting lower than expected occupancy. At Lyon Arboretum, there was no significant association between percentage of baits

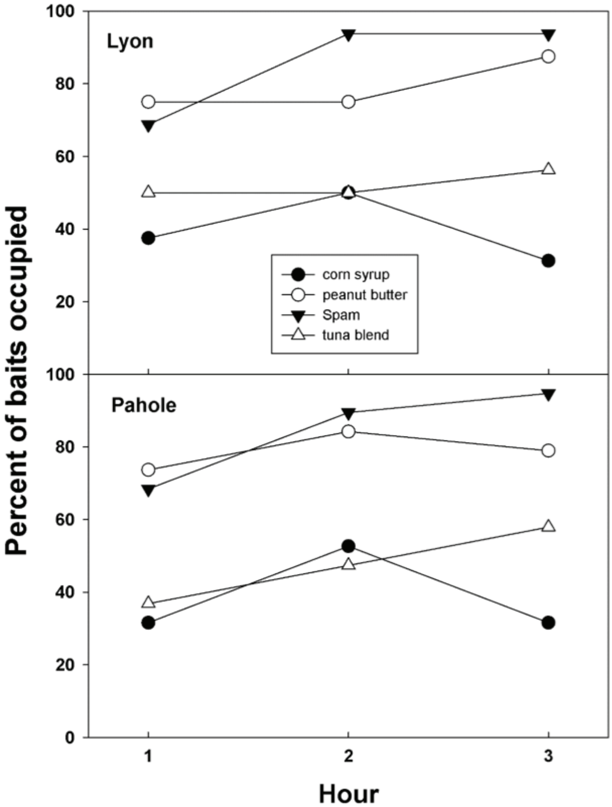

Figure 3. Percent of baits occupied by *S. papuana* at Lyon (top) and Pahole (bottom) over the course of three hours.

found and bait type (Chi-square = 5.830, p = 0.120). For peanut butter baits, there was no significant difference in occupancy rates between hours 1 and 2 at either Lyon (Fisher's Exact Test, p = 1) or Pahole (Fisher's Exact Test, p = 0.693). Similarly, there was no significant difference in occupancy rates between hours 1 and 2 at SPAM® baits at Lyon (Fisher's Exact Test, p = 0.172) or Pahole (Fisher's Exact Test, p = 0.232).

Pesticide bait preference. The relative attractiveness of the five pesticide ant baits to *S. papuana* differed somewhat by location, and large variation among replicate stations resulted in little consistent statistically significant separation between the baits (Fig. 4). Amdro® Ant Block® tended to attract the highest or second highest number of *S. papuana* at both sites, but the relative positions of the other baits varied among sites. In particular, Siesta™ attracted a relatively high number of *S. papuana* at Pahole, but the least number at Lyon.

Pesticide bait efficacy trial. Plots treated with Amdro® Ant Block® generally had a greater reduction in ant densities than those treated with Siesta™ (Fig. 5). Ant counts in the Amdro® Ant Block® plots dropped by 90.4 ± 4.5% from pre-treatment levels by 28 days

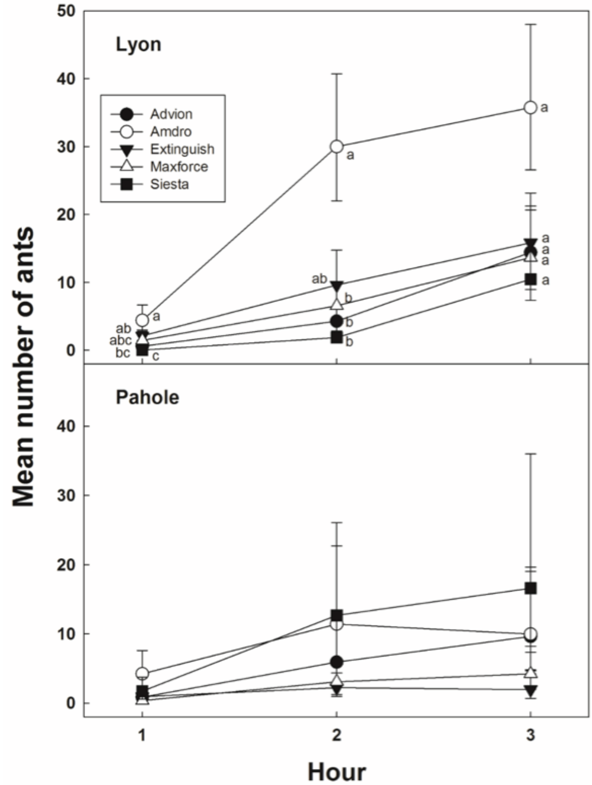

Figure 4. Mean number (±SE) of *S. papuana* attracted to pesticide baits at Lyon (top) and Pahole (bottom) over the course of three hours. Means sharing the same letters within each hour are not significantly different (Welch's ANOVA and Games-Howell posthoc test on log-transformed counts, α=0.05; depicted means and SEs are back-transformed). None of the means were significantly different at any hour at Pahole.

after bait station placement (mean ± SE of the % change in numbers for each of three plots), compared to a 44.8 ± 10.5% and 3.7 ± 23.6% reduction over the same period in the Siesta™ and control plots, respectively. Subsequently, numbers of ants in the Siesta™ plots were very similar to those in the control plots, both of which exhibited a strong reduction from October through December of 2015, followed by a resurgence by February of 2016 (Fig. 5). In contrast, Amdro® Ant Block® plots exhibited only a very small resurgence in the latter period, and averaged 96.2 ± 1.1% reduction from pre-treatment levels over the duration of the eight-month experiment (mean ± SE of % change in numbers for each plot on each date). Ant numbers were reduced on average by 76.8 ± 7.0% and 42.6 ± 24.2% from pre-treatment levels over the entire experiment in the Siesta™ and control plots, respectively.

The magnitude of reduction in ant numbers at monitoring stations 28 days after station placement was not significantly related to distance from the nearest bait station for either Amdro® Ant Block® (F = 1.79, p = 0.174) or Siesta™ (F = 2.30, p

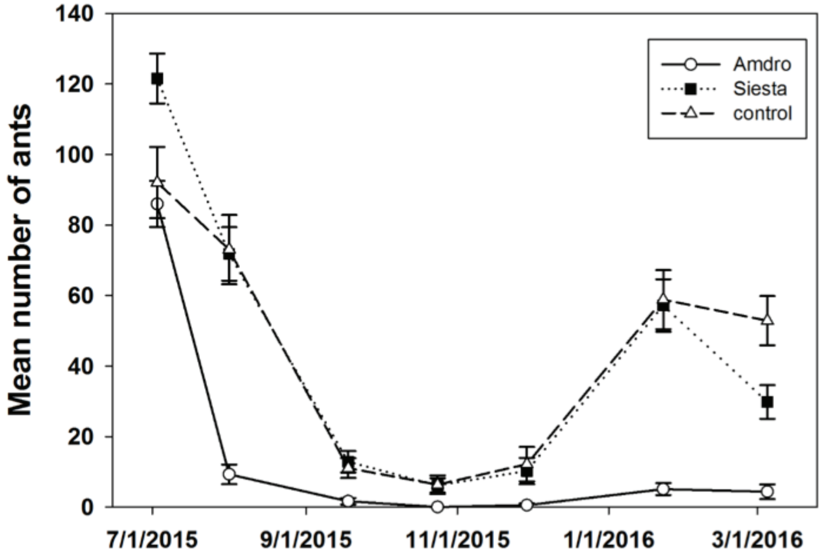

Figure 5. Mean (±SE) number of *S. papuana* in field plots treated with Amdro® Ant Block® and Siesta™ baits, in comparison to untreated control plots. Bait stations were installed in the Amdro® Ant Block® and Siesta™ plots on the first monitoring date (3 July 2015) immediately after monitoring, and baits were replaced on each subsequent monitoring event except the final date (5 March 2016).

= 0.107). In Siesta™ plots, however, there was a non-significant pattern suggesting potentially weaker reduction at greater distances from bait stations, which was absent in Amdro® Ant Block® plots (Fig. 6).

Discussion

Our results indicate that both SPAM® and peanut butter should be effective baits for monitoring relative densities of *S. papuana* and for mapping its distributions. Temporal trends suggested that exposing baits for more than one hour may increase their effectiveness to some degree, both in terms of higher recruitment and higher bait detection, but these trends were relatively weak and usually statistically non-significant. These benefits may therefore not offset the cost of additional monitoring time. Of the two baits, peanut butter is the more practical choice. It is much less expensive than SPAM®, requires no preparation and is easy to use in the field, does not spoil after opening, and adheres to monitoring cards or other monitoring substrates. The high attractiveness and ease of use of peanut butter has made it an effective bait for monitoring a variety of other ant species, particularly those in the myrmicine subfamily, such as *Wasmannia auropunctata*, *Monomorium pharaonis*, *Trichomyrmex destructor*, *Pheidole* spp., *Solenopsis geminata*, and others (Lee 2002, Causton et al. 2005, Starr et al. 2008). Placing monitoring baits on substrates that soak through, like the cupcake liners and index cards used in this study, is likely to be important when monitoring *S. papuana*. This species spends most of its time in the soil and leaf litter, and tends to approach baits from underneath: for both

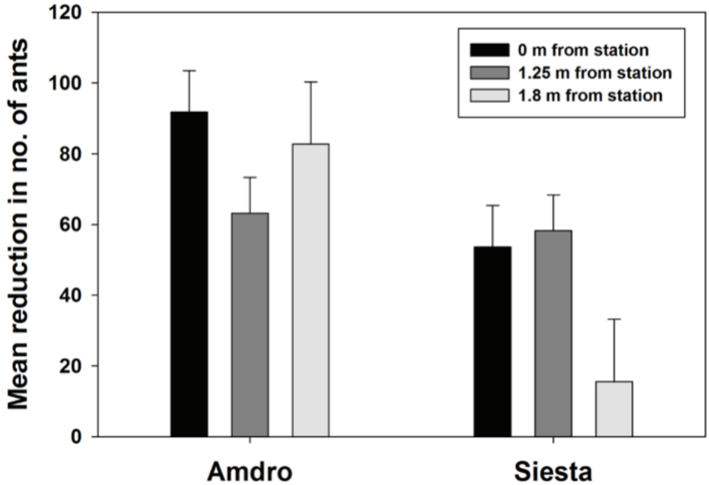

Figure 6. Mean (±SE) reduction in numbers of *S. papuana* 28 days after bait station placement in the field plots, categorized by distance of monitoring points from pesticide bait stations. There was no significant difference (based on ANOVA, α=0.05) in degree of reduction among distances for either ant bait.

SPAM® and peanut butter baits, we often observed equal or greater numbers of ants on the bottom of the bait substrate relative to the top.

We found relatively weak and/or inconsistent differences in attractiveness among the five commercial pesticide baits tested, possibly because they are all based completely or in part on similar corn grit and soybean oil granule matrices. However, each bait may contain additional proprietary ingredients that could influence attractiveness, and some active ingredients may exhibit repellency for certain ant species (Stringer et al. 1964, Reimer and Beardsley 1990, Williams et al. 2001, Montgomery et al. 2015). Of the five baits, Amdro® Ant Block® and Siesta™ tended to attract the greatest number of ants at one or both testing sites.

Amdro® Ant Block® was developed to combat the Red Imported Fire Ant, *S. invicta* (Williams et al. 2001), and has been on the market since 1980. It is a widely-used bait that has been highly effective against *Pheidole megacephala* (Reimer and Beardsley 1990, Hoffmann and O'Connor 2004, Plentovich et al. 2008, Plentovich et al. 2011), *W. auropunctata* in certain situations (Causton et al. 2005), and *S. geminata* to variable degrees (Hoffmann and O'Connor 2004, Plentovich et al. 2008; Plentovich 2011, Hoffmann et al. 2011). Siesta™, a newer product registered in 2007, has demonstrated efficacy against *P. megacephala* (Warner et al. 2008), *S. invicta* (Thompson 2008), and *W. auropunctata* (Hara et al. 2011). When we compared the efficacy of these two baits against *S. papuana* in small field plots, Amdro® Ant Block® yielded greater reductions in ant numbers on average than Siesta™. Strong declines in ant numbers in the control plots from approximately October through December, possibly due to seasonality or other weather events that commonly affect ant populations (e.g. Vanderwoude et al. 1997, Rust et al. 2000, Krushelnycky et al. 2004), made it difficult to differentiate between any of the plots during this period.

Nevertheless, there were substantial differences in trends among treatment groups in the first month post bait application, as well as in the degree of resurgence in ant numbers in the final two months of the trial (Fig. 5). The reason for the lower apparent efficacy of Siesta™ bait is unknown, but in initial tests with a different bait station design that made entry and exit more difficult, we observed many dead *S. papuana* workers after 24 hours inside stations containing Siesta™, but many fewer inside stations containing Amdro® Ant Block®. We therefore suspect that the lower efficacy of Siesta™ may be related to the speed with which metaflumizone kills *S. papuana*, rather than to issues with bait attractiveness.

A preliminary trial suggested that broadcast application of Amdro® Ant Block® was very effective at controlling *S. papuana*, and broadcasting Amdro® Ant Block® could in fact yield faster and perhaps greater control than that obtained with bait stations. However, broadcasted bait granules formulated with hydramethylnon have been found to impact some non-ant arthropod groups, like cockroaches and crickets, in some situations (Plentovich et al. 2010, Plentovich et al. 2011). In our case, the goal was to suppress numbers *S. papuana* while not directly influencing populations of other arthropods, both native and non-native. If minimizing impacts on non-target arthropods is of overriding importance, bait stations can be an effective, if more expensive and laborious, solution. Our bait station design and spacing interval provided good control for *S. papuana* when using Amdro® Ant Block®. The strong reduction in *S. papuana* numbers at monitoring stations suggested that this species was able to easily access the bait. The interior of the stations remained fairly dry provided that the stations were not dislodged by heavy rain or animals, bait replacement was relatively easy, and we observed very few ants or other arthropods trapped inside them. It is possible that a greater spacing interval may remain effective with Amdro® Ant Block® bait, although observations around the peripheries of treated plots suggest that *S. papuana* forages relatively short distances and may not effectively retrieve baits located more than several meters away from the nest.

While the attractiveness of Amdro® Ant Block® was not overwhelmingly stronger than the other baits tested, it was consistently attractive to *S. papuana*, and has other characteristics that make it a good option for controlling *S. papuana* in natural areas. It is widely available, relatively inexpensive, and has the broadest label language regarding allowable uses, including in forested areas. The US EPA (1998) considers hydramethylnon, the active ingredient in Amdro® Ant Block®, to be unlikely to contaminate ground water, of low risk to birds, and to have minimal effects on terrestrial non-target organisms when used for insect control. Hydramethylnon degrades quickly when exposed to light (Vander Meer et al. 1982), so presenting the bait in stations can not only reduce non-target exposure, but also prolong the potency of the active ingredient and protect the granules from adverse weather (Taniguchi et al. 2003). Although not practical over larger areas, we believe the methods discussed in this paper can be an effective tool for land managers to help monitor and control *S. papuana* populations at small scales in sensitive natural areas.

Acknowledgments

We would like to thank the Oahu Army Natural Resources Program for funding and logistical support, the Department of Forestry and Wildlife and the Natural Area Reserve System of the Hawaii Department of Land and Natural Resources for research and access permits, M. Brunthal, E. Coser, B. Doi, P. Gabales, A. Gazarian, T. Kikuta, P. Maher, R. Parker, and M. Pflaum for assistance in the field, and W. Haines, H. Spafford, and anonymous reviewers for their helpful advice and comments on the manuscript.

Literature Cited

AntWeb. 2016. Online database. Available from http://www.antweb.org. (Accessed 26 August 2016).

Blachly, J.S., and **B.T. Forschler.** 1996. Suppression of late-season Argentine ant (Hymenoptera: Formicidae) field populations using a perimeter treatment with containerized baits. J.Econ. Entomol. 89: 1497–1500.

Causton, C.E., C.R. Sevilla, and **S.D. Porter.** 2005. Eradication of the little fire ant, *Wasmannia auropunctata* (Hymenoptera: Formicidae), from Marchena Island, Galapagos: On the edge of success? Fla. Entomol. 88: 159–168.

Clavero, M., and **E. Garcia-Berthou.** 2005. Invasive species are a leading cause of animal extinctions. TRENDS Ecol. Evol. 20: 110.

Clouse, R.M. 2007. The ants of Micronesia (Hymenoptera: Formicidae). Micronesica 39: 171-295.

Cole, F.R., A.C. Medeiros, L.L. Loope, and **W.W. Zuehlke.** 1992. Effects of the Argentine ant on arthropod fauna of Hawaiian high-elevation shrubland. Ecology 73: 1313–1322.

Eow, A.G.H. and **Y.C. Lee.** 2007. Comparative nutritional preferences of tropical pest ants. *Monomorium pharaonis*, *Monomorium floricola* and *Monomorium destructor* (Hymenoptera: Formicidae). Sociobiology 49: 165–186.

Giambelluca, T.W., Q. Chen, A.G. Frazier, J.P. Price, Y.-L. Chen, P.-S. Chu, J.K. Eischeid, and **D.M. Delparte**, 2013. Online Rainfall Atlas of Hawai‘i. Bull. Amer. Meteor. Soc. 94, 313-316, doi: 10.1175/BAMS-D-11-00228.1.

Gillespie, R.G. and **N. Reimer. 1993.** The effect of alien predatory ants (Hymenoptera: Formicidae) on Hawaiian endemic spiders (Araneae: Tetragnathidae). Pac. Sci. 47: 21–33.

Hara, A.H., S.K. Cabral, R.Y. Niino-Duponte, C.M. Jacobsen, and **K. Onuma.** 2011. Bait Insecticides and Hot Water Drenches Against the Little Fire Ant, *Wasmannia auropunctata* (Hymenoptera: Formicidae), Infesting Containerized Nursery Plants. Fla. Entomol. 93: 517–526

Hara, A.H., K.L. Aoki, S.K. Cabral, and **R.Y. Niino-DuPonte.** 2014. Attractiveness of gel, granular, paste, and solid formulations of ant bait insecticides to the little fire ant, *Wasmannia auropunctata* (Roger) (Hymenoptera: Formicidae). Proc. Hawaiian Entomol. Soc.: 46:45–54.

Hoffmann B.D. and **S. O'Connor.** 2004. Eradication of two exotic ants from Kakadu National Park. Ecological Management and Restoration 5: 98–105.

Hoffmann, B., P. Davis, K. Gott, C. Jennings, S. Joe, P. Krushelnycky, R. Miller, G. Webb, and **M. Widmer.** 2011. Improving ant eradications: details of more successes, a global synthesis and recommendations. Aliens 31: 16–23.

Huddleston, E.W. and **S.S Fluker.** 1968. Distribution of ant species of Hawaii. Proc. Hawaiian Entomol. Soc. 20: 45–69.

Human, K.G. and **D.M Gordon.** 1997. Effects of Argentine ants on invertebrate biodiversity in Northern California. Conserv. Biol. 11: 1242–1248.

Jahn, G.C., J.W. Beardsley, and **H. Gonzalez-Hernandez.** 2003. A review of the association of ants with mealybug wilt disease of pineapple. Proc. Hawaiian Entomol. Soc. 36:9–28.

Keeler, K.H. 1980. Distribution of plants with extrafloral nectaries in temperate communities. Am. Midl. Nat. 104: 274–280.

Krushelnycky, P.D. 2015. Ecology of some lesser-studied introduced ant species in Hawaiian forests. J. Insect Conserv. 19:659–667.

Krushelnycky, P.D., and **R.G. Gillespie**. 2010. Correlates of vulnerability among arthropod species threatened by invasive ants. Biodiversity and Conservation 19: 1971–1988.

Krushelnycky, P.D., L.L. Loope, and S.M. Joe. 2004. Limiting spread of a unicolonial invasive insect and characterization of seasonal patterns of range expansion. Biol. Invasions 6: 47–57.

Krushelnycky, P.D., L.L. Loope, and **N.J.**

Reimer. 2005. The ecology, policy, and management of ants in Hawaii. Proc. Hawaiian Entomol. Soc. 37:1–25.

Krushelnycky, P.D., W. Haines, L. Loope and E. Van Gelder. 2011. The Haleakala Argentine ant project: a synthesis of past research and prospects for the future. Pacific Cooperative Studies Unit Technical Report 173. University of Hawai‘i at Mānoa, Department of Botany. Honolulu, HI. 127 pp.

Lee, C.Y. 2002. Tropical household ants: Pest status, species diversity, foraging behavior, and baiting studies. *In* S.C. Jones, J. Zhai, and W.H. Robinson (eds.), Proceedings of the Fourth International Congress on Urban Pests. pp 3–18. Virginia: Pocahontas Press.

Lee, C.Y., L.C. Lee, J.P. Na, P.Y. Loke, K.T. Lim, and **E.H.H. Teo, E.** 2003. Evaluation of methoprene granular baits against foraging pharaoh ants, *Monomorium pharaonis* (Hymenoptra: Formicidae). Sociobiology 41: 717–723.

Leong M.K.H., and **J.K. Grace.** 2008. Occurrence and distribution of ants (Hymenoptera: Formicidae), cockroaches (Blattodea), centipedes (Chilopoda), and wasps (Hymenoptera: Vespidae) of public health importance on the island of Oahu. Proc. Hawaiian Entomol. Soc. 40:33–49.

McNatty, A., K.L. Abbott, and **P.J. Lester.** 2009. Invasive ants compete with and modify the trophic ecology of hermit crabs on tropical islands. Oecologia 160: 187–194.

Minitab. 2013. Version 17.1 Minitab, Inc. State College, PA.

Montgomery, M.P., C. Vanderwoude, and **A.J.J. Lynch.** 2015. Palatability of baits containing (S)-methoprene to *Wasmannia auropunctata* (Hymenoptera: Formicidae). Fla. Entomol. 98(2):451–455.

Mooney, H.A., and **E.E. Cleland.** 2001. The evolutionary impact of invasive species. P. Natl. Acad. Sci. USA. 98(10): 5446–5451.

Morrison, L.W. 1996. The ants (Hymenoptera: Formicidae) of Polynesia revisited: species numbers and the importance of sampling intensity: Ecography 19: 73–84.

Morrison, L.W. 1997. Polynesian ant (Hymenoptera: Formicidae) species richness and distribution: a regional survey. Acta Oecologica 18: 685–695.

Nishida, G.M. 2002. Hawaiian terrestrial arthropod checklist. Fourth edition. Bishop Museum Technical Report No. 22. Hawai‘i Biological Survey Bishop Museum. Honolulu, HI. 313 pp.

O'Dowd, D.J., P.T. Green, and **P.S. Lake.** 2003. Invasional 'meltdown' on an oceanic island. Ecol. Lett. 6:812–817.

Oi, D.H., and **F.M. Oi.** 2006. Speed of efficacy and delayed toxicity characteristics of fast-acting fire ant (Hymenoptera: Formicidae) baits. J. Econ. Entomol. 99: 1973–1748.

Peck, R.W., P.C. Banko, D. Donmoyer, S. Kropidlowski, and **A. Pollock.** 2015. Efforts to eradicate yellow crazy ants on Johnston Atoll: Results from crazy ant strike team IX, December 2014-June2015. Hawaii Cooperative Studies Unit Technical Report 67. University of Hawaii at Hilo. Hilo, HI. 20 pp.

Pimentel, D., R. Zuniga, D. Morrison. 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol. Econ. 52: 273–268.

Plentovich, S. 2010. Survey of invasive ant species within Makua and Oahu Implementation plan management units, Oahu, Hawaii 2004–2009. 2010 Makua and Oahu Implementation Plan Status Report. Honolulu, HI. 16 pp.

Plentovich, S., C. Swenson, N. Reimer, M. Richardson, and **N. Garon.** 2010. The effects of hydramethylnon on the tropical fire ant, *Solenopsis geminata* (Hymenoptera: Formicidae), and non-target arthropods on Spit Island, Midway Atoll, Hawaii. J. Insect Conserv. 14: 459–465.

Plentovich, S., A. Hebshi, and **S. Conan.** 2008. Detrimental effects of two widespread invasive ant species on weight and survival of colonial nesting seabirds. Biol. Invasions 11:289–298.

Plentovich. S., J. Eijzenga, H. Eijzenga, and **D. Smith.** 2011. Indirect effects of ant eradication efforts on offshore islets in the Hawaiian Archipelago. Biol. Invasions 13: 545–557.

Porter, S.D., and **W.R. Tschinkel.** 1987. Foraging in *Solenopsis invicta* (Hymenoptera: Formicidae): Effects of weather and season. Environ. Entomol.16: 802–808.

Porter, S.D, and **D.A. Savignano.** 1990. Invasion of polygyne fire ants decimates native ants and disrupts arthropod community.

Ecology. 71: 2095–2106.

Reimer, N.J. 1992. Notes and exhibitions. Proc. Hawaiian Entomol. Soc. 31:23.

Reimer, N.J. 1994. Distributional and Impact of Alien Ants in Vulnerable Hawaiian Ecosystems. *In* D.F. Williamns (ed.), Exotic Ants Biology, Impact, and Control of Introduced Species. pp 11–22. Colorado: Westview Press.

Reimer, N.J., and **J.W. Beardsley Jr.** 1990. Effectiveness of hydramethylnon and fenoxycarb for control of bigheaded ant (Hymenoptera: Formicidae), an ant associated with mealybug wilt of pineapple in Hawaii. J. Econ. Entomol. 83:74–80.

Rust, M.K., D.A. Reierson, E. Paine, and L.J. Blum. 2000. Seasonal activity and bait preferences of the Argentine ant (Hymenoptera: Formicidae). J. Agric. Urban Entomol. 17: 201–212.

Souza, E., P.A. Follett, D.K. Price, and **E.A. Stacy.** 2008. Field suppression of the invasive ant *Wasmannia auropunctata* (Hymenoptera: Formicidae) in a tropical fruit orchard in Hawaii. J. Econ. Entomol. 101:1068–1074.

Starr, F., K. Starr, and **L.L. Loope.** 2008. Survey for ants on the island of Maui, Hawaii, with emphasis on the little fire ant (Wasmannia auropunctata). Pacific Cooperative Studies Unit Technical Report 156. University of Hawai‘i at Mānoa, Department of Botany. Honolulu, HI. 47 pp.

Stringer, C.E., C.S. Lofgren Jr., and **F.J. Bartlett.** 1964. Imported fire ant toxic bait studies: Evaluation of toxicants. J. Econ. Entomol. 57: 941–945.

Taniguchi, G.Y., A.K. Ota, M.K. Kawate, K.G. Rohrbach, and **G.K. Uchida.** 2003. Preliminary field tests on the suitability of Amdro and Distance in ant bait container for control of the big-headed ant, Pheidole megacephala (Hymenoptera:Formicidae. Proc. Hawaiian Entomol. Soc. 36:129–133.

Tenorio, J.M., and **G.M. Nishida.** 1995. What’s Bugging Me?: Identifying and controlling household pests in Hawaii.Univ. Hawaii Press, Honolulu. 184 pp.

Thompson, A.N. 2008. Field evaluation of aerial applications of hydramethylnon and metaflumizone to control the red imported fire ant, *Solenopsis invica* (Buren), and related ant species (Hymenoptera:Formicidae). (Master’s Thesis, Texas A&M University).

US EPA. 1998. EPA R.E.D. Facts. Hydramethylnon. Prevention, Pesticides and Toxic Substances; www3.epa.gov/pesticides/chem_search/reg_actions/reregistrations/fs_PC-118401_1-Sep-98.pdf (accessed Aug. 25, 2016).

Vander Meer, R.K., D.F. Williams, and **C.S. Lofgren.** 1982. Degradation of the toxicant AC 217300 in Amdro imported fire ant bait under field conditions. J. Agr. Food Chem. 30: 1045–1048.

Vanderwoude, C., A.N. Andersen, and **A.P.N. House.** 1997. Community organization, biogeography and seasonality of ants in an open forest of south-eastern Queensland. Australian J. Zoology 45: 523–527.

Warner, J., R. Yang, and **R.H. Scheffrhan. 2008.** Efficacy of selected bait and residual toxicants for control of bigheaded ants, *Pheidole megacephala* (Hymenoptera: Formicidae), in large field plots. Fla. Entomol. 91: 277–282.

Wetterer, J.K. 2007. Biology and impacts of Pacific Island invasive species. 3. The African big-headed ant, *Pheidole megacephala* (Hymenoptera: Formicidae). Pac. Sci. 61:437–456.

Williams, D.F., H.L. Collins, and **D.H. Oi. 2001.** The red imported fire ant (Hymenoptera: Formicidae): An historical perspective of treatment programs and the development of chemical baits for control. American Entomologist: 47: 146–159.

Wilson, E.O., and **R.W. Taylor.** 1967. The ants of Polynesia. Pacific Insects Monographs 14.

Zimmerman, E.C. 1948. Insects of Hawaii. Volume 1. Introduction. Univ. of Hawaii Press, Honolulu. 206 pp.