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DEVELOPING TOOLS TO ERADICATE ECOLOGICALLY DESTRUCTIVE ANTS ON ROSE ATOLL: EFFECTIVENESS AND ATTRACTIVENESS OF FORMICIDAL BAITS

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ABSTRACT

A key factor contributing to the decline in the population of *Pisonia grandis* on Rose Atoll is an infestation of the non-native scale, *Pulvinaria urbicola* (Homoptera: Coccidae). Ants, in facultative relationships with scale insects, may facilitate scale population growth and increase their effect on plant hosts. Three ant species found on Rose Atoll, *Tetramorium bicarinatum*, *T. simillimum*, and *Pheidole oceanica*, are capable of tending *Pulvinaria* on *Pisonia* and may have contributed to the demise of the trees on the atoll. Replicated trials conducted on Rose Atoll during 17–21 March 2013 tested the effectiveness and relative attractiveness of five formicidal baits potentially to be used to eradicate these ants on the atoll. Three baits contained toxins (hydramethylnon in Amdro® and Maxforce®, indoxacarb in Provaunt®) and two baits contained an insect growth regulator (IGR; pyriproxyfen in Distance® and s-methoprene in Tango®). Amdro, Distance, and Maxforce are granular baits while Provaunt and Tango were mixed with adjuvants to form a gel-like matrix. Results varied among ant species and baits, but Provaunt was highly effective against workers of both *Tetramorium* species while Amdro and Maxforce were highly effective against *T. simillimum* and *P. oceanica*. Limited time on the island prevented the evaluation of the effectiveness of the IGR baits. The relative attractiveness of the baits generally mirrored their ability to kill worker ants. *Tetramorium simillimum* was attracted to all five baits; *T. bicarinatum* was attracted to Provaunt, Distance, and Tango; and *P. oceanica* was attracted to the three granular baits. These results and the small area of Rose Atoll suggest that island-wide application of formicidal baits may result in eradication of these ants, but an application strategy targeting all three species would more likely succeed with the use of multiple baits.

INTRODUCTION

Rose Atoll National Wildlife Refuge, containing Rose Island, the easternmost island of the Samoan Archipelago, provides significant nesting and roosting habitat for 17 species of federally protected seabirds and shorebirds, as well as the threatened green turtle (*Chelonia mydas*). On Rose Island, overall productivity of bird and turtle populations was greatly enhanced with the eradication of the non-native Polynesian rat (*Rattus exulans*) in 1993. Rose Atoll also supports a relatively rich terrestrial arthropod fauna of more than 30 species from 13 orders documented in a recent survey (U.S. Geological Survey unpublished data). While the status is still undetermined for several arthropod species, some are thought to be native to the atoll while others are likely to have become established following human contact. Geographic isolation and restricted entry onto Rose Island currently provide protection for this important ecosystem.

Rose Island has experienced a dramatic reduction in its once extensive stand of the canopy-forming tree, *Pisonia grandis.* As of April 2013, the population of *Pisonia* was reduced to only four individuals measuring >3 m in height and a few smaller saplings. The decline of *Pisonia* is not unique to Rose Atoll but is a phenomenon that has occurred widely in the Pacific and Indian Oceans (Hill *et al.* 2003, Handler *et al.* 2007, Greenslade 2010). The decline on Rose Atoll is probably due to several factors, including hurricanes, establishment of new plant species following rat removal, and stress caused by the invasive scale insect, *Pulvinaria urbicola* (Homoptera: Coccidae; Figure 1). The sap-feeding *Pulvinaria* primarily weakens or kills trees by removing essential plant nutrients from leaf tissues and may indirectly reduce photosynthetic efficiency by facilitating the growth of sooty mold which grows on the carbohydrate-rich "honeydew" secreted by the scales. Honeydew is also a highly attractive food source for ants,

Figure 1. One of the four remaining mature *Pisonia grandis* on Rose Atoll (left) and a *Pisonia* leaf infested with the invasive *Pulvinaria urbicola* scale responsible for the *Pisonia* decline (right).

which may support or enhance scale populations by providing protection from natural enemies such as predatory and parasitic insects or by assisting scale dispersal within, or possibly among, *Pisonia* (Bach 1991, Reimer *et al.* 1993, Gaigher *et al.* 2011).

Recent observations on Rose Atoll have identified two species of alien ants, *Tetramorium bicarinatum* and *T. simillimum*, tending *Pulvinaria* on *Pisonia* (U.S. Geological Survey unpublished data). A third species found on Rose Atoll, *Pheidole oceanica*, has not been observed on *Pisonia*, although it has been observed tending *Pulvinaria* on Swains Atoll (Mark Schmaedick, American Samoa Community College, personal communication), and is likely capable of tending the scales on Rose Atoll as well. *Pheidole oceanica* is considered native to the Indo-Pacific region, including the Samoan Archipelago (Wetterer and Vargo 2003), and may occur naturally on Rose Atoll.

Pisonia provides important nesting and roosting habitat for birds on Rose Atoll; therefore, protecting these trees is a high priority for refuge managers. In November 2012, a systemic insecticide (IMA-jet® containing imidacloprid) was injected into all four large *Pisonia* trees to reduce the infestation of *Pulvinaria* and prevent the imminent death of the trees. Although observations during April 2013 indicate that the treatment seemed to have at least temporarily reduced scale numbers, long-term suppression of *Pulvinaria* may require an integrated strategy that depends upon controlling ants (Smith *et al.* 2004, Lester 2008, Gaigher *et al.* 2013). Our objective was to develop methods to eliminate scale-tending ants as an important first step toward restoring the health and integrity of *Pisonia* on Rose Atoll.

This report summarizes work conducted during 17–21 March 2013 to evaluate the effectiveness and relative attractiveness of a suite of formicidal baits (hereafter referred to as "bait") that could potentially be used to eradicate *T. bicarinatum*, *T. simillimum*, and *P. oceanica* from Rose Atoll. Six additional alien species of ants have been detected on the atoll (*Cardiocondyla kagutsuchi*, *Hypoponera punctatissima*, *Monomorium pharaonis*, *Nylanderia minutula*, *Ponera swezyi*, and *Strumigenys rogeri*; U.S. Geological Survey unpublished data), but these three species were targeted because they were observed and considered capable of tending *Pulvinaria*.

METHODS

Study Area

Rose Atoll National Wildlife Refuge, located approximately 278 km (150 nautical miles) east of Pago Pago, American Samoa, consists of two islands, Rose and Sand, each approximately 6.6 and 1.3 ha, respectively (Figure 2). The vegetation of Rose Island is presently dominated by *Tournefortia argentea* but also includes *Cordia subcordata*, *Hibiscus tiliaceus*, *Cocos nucifera*, and *Pisonia grandis* as well as several understory plant species. Rose Island was dominated by *Pisonia* as recently as 1970. Sand Island is currently devoid of vegetation. Access to the atoll is by boat. There is no source of fresh water on the atoll.

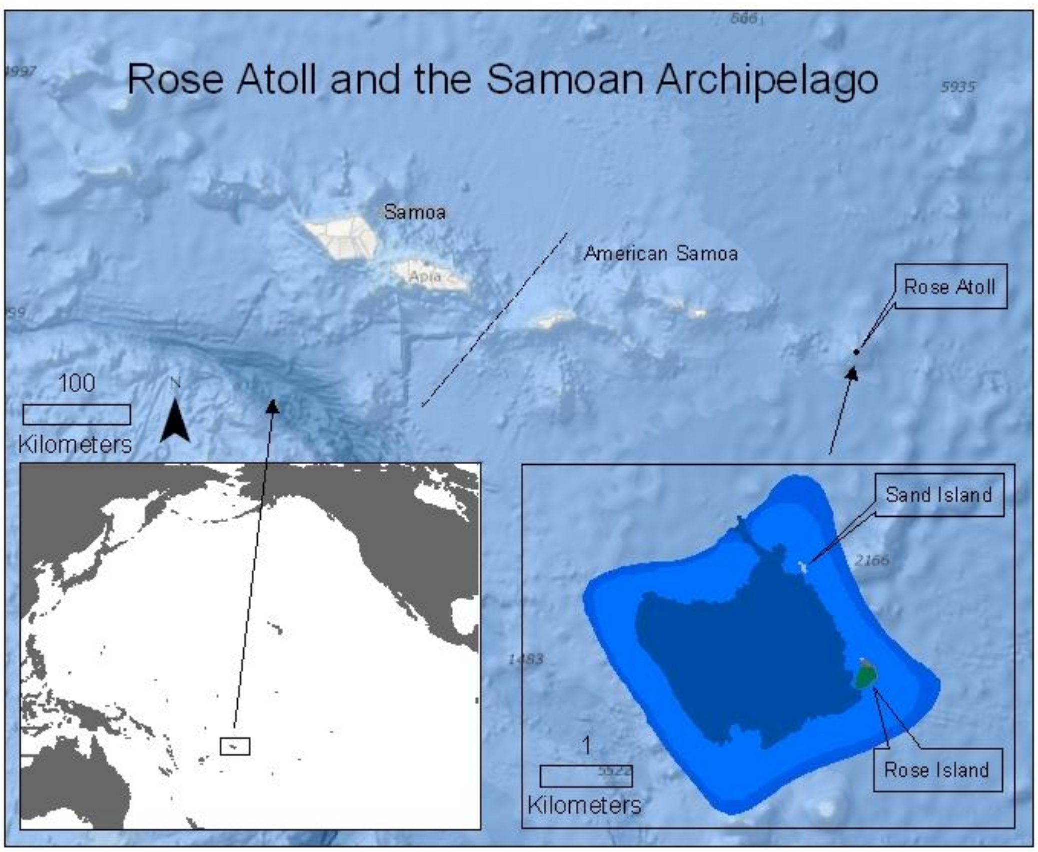

Figure 2. Location of Rose Atoll and the Samoan Archipelago.

Schedule of Bait Trials
We conducted the bait trials over five days during 17–21 March 2013. On day 1, we located populations of the three ant species and demarcated the treatment plots. On day 2, we conducted pre-treatment abundance surveys in the morning and began distributing baits in the afternoon. On the morning of day 3 we completed distributing baits. On day 5 we assessed the effectiveness of the baits. Bait attractiveness trials were conducted on days 3–5.

Effectiveness of Baits
Five baits were tested against *P. oceanica*, *T. bicarinatum*, and *T. simillimum*: Amdro®, Maxforce®, Distance®, Provaunt®, and Tango® (Table 1). Amdro, Maxforce, and Provaunt utilize toxins that can quickly kill ants that ingest the bait while Distance and Tango incorporate insect growth regulators (IGRs) that inhibit queen ants from producing eggs and prevent brood from maturing into adults. Amdro, Maxforce, and Distance are granular baits and were applied directly in the form supplied from the manufacturer. Both Tango and Provaunt are sold in a concentrated form and are meant to be mixed with adjuvants attractive to the ants being targeted. Tango is sold in a liquid form and Provaunt is available as water soluble pellets. Tango and Provaunt were mixed into a matrix consisting of water, vegetable oil, peanut butter, and xanthum gum in proportions recommended by Cas Vanderwoude at the Hawaiʻi Ant Lab, Hawaii Department of Agriculture, Hilo, Hawaiʻi. This matrix has been shown to be attractive to oil-loving ants, particularly the little fire ant (*Wasmannia auropunctata*), but it had not previously been tested against *P. oceanica*, *T. bicarinatum*, or *T. simillimum*. Baits were applied at the maximum rate allowed on the labels.

Table 1. Formicidal baits tested against *Pheidole oceanica*, *Tetramorium bicarinatum*, and *T. simillimum* on Rose Atoll, 18–22 March 2013. (IGR = insect growth regulator)

Registered name	Active ingredient (conc.)	Mode of action	Form	Application rate
Amdro ant bait	hydramethylnon (0.73%)	toxin	granule	2 lb/ac
Distance fire ant bait	pyriproxyfen (0.5%)	IGR	granule	1.5 lb/ac
Maxforce Complete ant bait	hydramethylnon (1.0%)	toxin	granule	1.5 lb/ac
Provaunt insecticide	indoxacarb (30%)[a]	toxin	gel	17.6 lb[b]/ac
Tango insecticide	s-methoprene (0.25%)[a]	IGR	gel	17.6 lb[b]/ac

[a] undiluted concentration
[b] weight of final mixture

The five baits were tested against each ant species in 100 m^2 treatment plots. Plot placement was determined by identifying locations of each ant species using a dollop of canned tuna (mixed in oil) placed on 3 x 5 cm paper cards. Once ants were identified at a location, plots were centered on the card yielding the ants. Plot centers were located >25 m apart. Initially, plots were 50 m^2 in size (approximately 7 x 7 m), but about 24 hours after treatment, additional bait was applied around plot perimeters to expand the area of treatment to 100 m^2 (approximately 10 x 10 m). The smaller, initial plot size was necessary to conserve bait in case rain necessitated retreatment of the plots. Two replicate plots were established for each ant species and bait type for a total of 30 plots. Baits were applied between approximately 3:00 and 6:30 pm on 18 March and 7:15 and 8:15 am on 19 March.

The effectiveness of the baits within each plot was evaluated by comparing mean abundances of ants at cards containing tuna before and after application of bait. Pre-treatment measurements were made using two cards located about 0.5 m on either side of the plot center between about 8:00 and 10:00 am on 18 March. On several occasions, the ant species identified at cards during pre-treatment assessment did not match that detected when plots were initially established, resulting in unbalanced numbers (i.e., other than two) of treated plots for some species.

To increase the probability of detecting reduced numbers of ants, post-treatment measurements of ant abundance were made using three cards with tuna placed in each plot in an approximately equidistant array about 1.0 m from the plot center between 10:00 am and 2:00 pm on 21 March. During both pre- and post-treatment measurements, the numbers of ants on cards were counted 30 and 60 minutes after distributing the tuna cards. At 60 minutes, ants were also counted on the bottoms of cards and added to counts on the tops because ants often were found lapping tuna oil that had penetrated the cards. Although numbers of ants on tops of the cards were generally similar after 30 and 60 minutes, only counts at 60 minutes are reported.

Attractiveness of Baits

Concurrent with the bait effectiveness trials, we assessed the relative attractiveness of the baits to the ants. We distributed 5 ml of each bait type in areas occupied by one of each of the three ant species. Bait samples were placed on 3 x 5 cm cards that were spaced about 10 cm apart. Bait cards were either placed randomly in clusters >1 m from the nearest tree or randomly in an arc around the base of a *Pisonia* or *Tournefortia* (Figure 3). We counted the number of ants at each bait card after 30 and 60 minutes. Two to twelve replicates were performed for each ant species.

Figure 3. Cards containing the five bait types placed in a cluster (left) or around the base of a tree (*Tournefortia*; right) where ants of a particular species were present. The number of ants at each card after 60 minutes indicated the relative attractiveness of each bait type to the three species of ants.

RESULTS

Effectiveness of Baits

The number of plots treated with each bait varied among ant species, ranging from 1 to 4, due to 1) differences in the species of ants detected on plots during plot establishment and during pre-treatment measurements of abundance and 2) the presence of two ant species in a few plots (Table 2). Ant species that were detected during plot establishment but not during pre-treatment measurements were likely present but overlooked during the pre-treatment survey.

Table 2. Number of plots treated with each of the five baits against *Pheidole oceanica*, *Tetramorium bicarinatum*, and *T. simillimum*. Amdro, Maxforce, and Distance are granular baits while Provaunt and Tango are gel baits. (IGR = insect growth regulator)

	Toxin			IGR		
Ant species	Amdro	Maxforce	Provaunt	Distance	Tango	Total
Pheidole oceanica	3	1	2	1	2	9
Tetramorium bicarinatum	4	3	4	2	1	14
Tetramorium simillimum	2	3	2	1	3	11
Total	9	7	8	4	6	34

Mean abundances of worker ants at tuna cards prior to treatment were 32.0 ± 4.2 (range = 23.0–44.5) in *P. oceanica* plots, 51.3 ± 8.5 (range = 36.1–61.7) in *T. bicarinatum* plots, and 51.4 ± 13.6 (range = 28.3 – 92.0) in *T. simillimum* plots (Table 3).

Table 3. Mean (± SEM) abundance of *Pheidole oceanica*, *Tetramorium bicarinatum*, and *T. simillimum* at tuna cards in plots prior to and following treatment of formicidal baits. Pre-treatment values represent numbers of ants on all treatment plots combined for each ant species. Amdro, Maxforce, and Distance are granular baits while Provaunt and Tango are gel baits. (IGR = insect growth regulator)

		Toxin			IGR	
Ant species	Pre-treatment	Amdro	Maxforce	Provaunt	Distance	Tango
Pheidole oceanica	32.0 (4.2)	0.1 (0.1)	0.0	22.8 (2.5)	12.7	5.3 (1.3)
Tetramorium bicarinatum	51.3 (8.5)	10.9 (6.8)	4.2 (2.6)	0.1 (0.1)	104.0 (24.0)	16.7
Tetramorium simillimum	51.4 (13.6)	0.2 (0.2)	0.0 (0.0)	0.0 (0.0)	32.0	8.8 (3.9)

Abundances of *P. oceanica* declined sharply in plots treated with Amdro (one ant on one tuna card) and Maxforce (no ants; Table 3). In contrast, 22.8 ± 2.5 ants/card/plot were found on the two plots treated with Provaunt. Ants were detected in Distance and Tango plots but at 39.7% and 16.6% of pre-treatment levels, respectively.

The abundance of *T. bicarinatum* declined most dramatically on Provaunt plots, as only a single ant was found in the four plots treated with that bait (Table 3). Maxforce was the second most effective bait followed by Amdro. The plots treated with Distance contained about twice the number of ants recorded in the pre-treatment plots while the single Tango plot contained about one-third the number of ants as in the pre-treatment plots.

Tetramorium simillimum abundance was reduced to nearly zero in all three toxic bait plots; only one ant was detected in each of the two plots treated with Amdro (Table 3). Mean *T. simillimum* abundance in the Tango and Distance plots ranged from 8.8 to 32.0.

Attractiveness of Baits
Difficulty finding populations of *P. oceanica* that were not influenced by bait treatments (i.e., adjacent to treated plots) resulted in only two bait attractiveness trials being conducted for that species. In contrast, 10 trials were conducted for *T. bicarinatum* and 12 were conducted for *T. simillimum*.

Although differences were not significant, *P. oceanica* were recorded more often at Distance baits (5.0 ± 3.0 ants/card) compared to Maxforce (3.0 ± 1.0) and Amdro (1.5 ± 1.5; Figure 4), but they were rare (0.5 ± 0.5 ants/card) on cards containing the gel baits Provaunt and Tango. Although ant numbers at cards containing the three granular baits were low compared to those found at tuna monitoring cards, overall activity was often high as ants were often observed carrying granular bait to their nests via well-developed trails. We did not quantify the rate of bait removal.

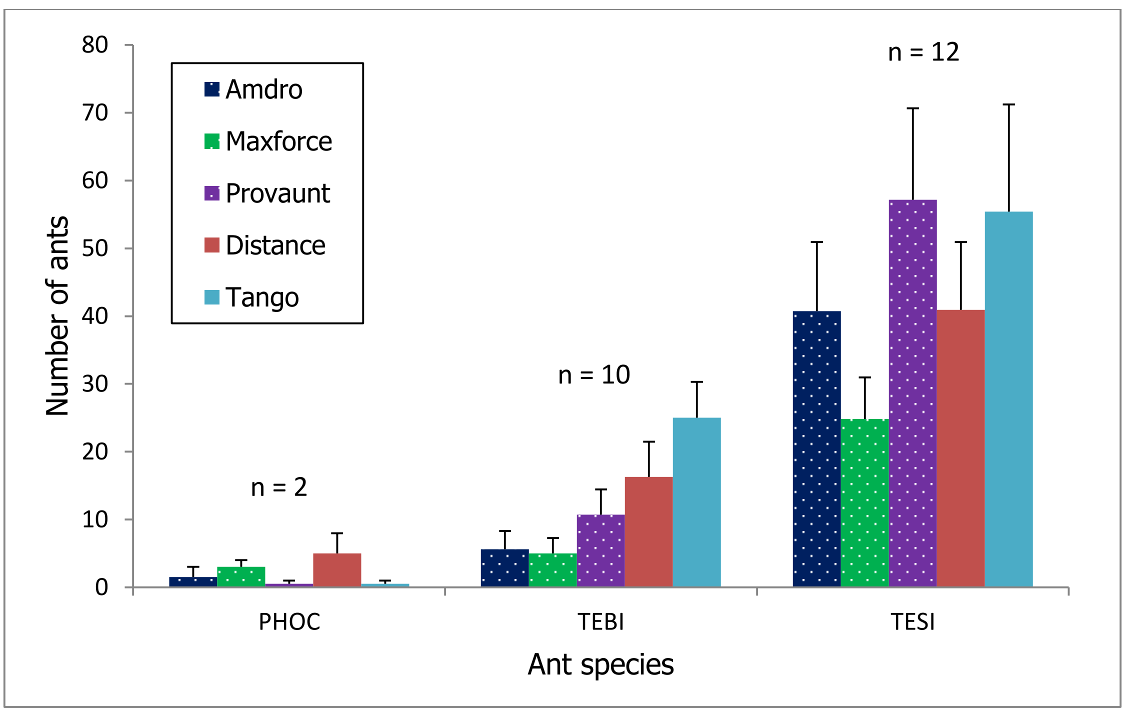

Figure 4. Mean (± SEM) abundance of *Pheidole oceanica* (PHOC), *Tetramorium bicarinatum* (TEBI), and *T. simillimum* (TESI) after 60 minutes at the five different baits. The number of trials performed for each species is shown above each set of five bars. Stippled bars represent toxic baits and solid bars indicate IGR (insect growth regulator) baits. Amdro, Maxforce, and Distance are granular baits, while Provaunt and Tango are gel baits.

Tetramorium bicarinatum was found in greatest abundance at cards containing Tango (25.0 ± 5.3 ants/card), followed by Distance (16.3 ± 5.2), Provaunt (10.7 ± 3.8), Amdro (5.6 ± 2.7), and Maxforce (5.0 ± 2.3; Figure 4). An overall significant difference was found among baits (One-way ANOVA: F = 4.26, df = 4, *P* = 0.005) with post-hoc pairwise differences found between Tango and Amdro (*P* = 0.014) and Tango and Maxforce (*P* = 0.011).

Differences in the abundance of *T. simillimum* among bait types were not significant (One-way ANOVA: F = 1.29, df = 4, *P* = 0.29), but we recorded more ants at Provaunt and Tango (57.2 ± 13.5 and 55.4 ± 15.8 ants/card, respectively) than we recorded at Amdro and Distance (40.8 ± 10.2 and 40.9 ± 10.0 ants/card, respectively) or Maxforce (24.8 ± 6.1; Figure 4).

Discussion

Our results indicate that the formicidal baits tested were highly effective at killing workers of *P. oceanica*, *T. bicarinatum*, and *T. simillimum* on Rose Atoll. While elimination, or near elimination, of worker ants on experimental plots indicates that the bait was consumed by most or all foraging workers, it does not show that egg-producing queens within the nest were also killed by the bait. Although there was insufficient time to excavate nests to evaluate the effect of the baits on queens, high worker mortality suggests that some baits were shared among ants within the nest, probably also including queens.

No single bait was effective against all three ant species targeted in this study. Amdro and Maxforce were highly effective at reducing numbers of *P. oceanica* workers within the plots. These results are consistent with other studies that have shown hydramethylnon, particularly in the Amdro matrix, to be effective at eradicating the closely related *P. megacephala* (Hoffmann and O'Connor 2004, Plentovich *et al.* 2009). Although it is not known whether *P. oceanica* would respond similarly to *P. megacephala*, both species share the behavior of recruiting quickly to oil-based granular baits and aggressively dominating them over other species, behaviors that likely contribute to bait effectiveness. In contrast, the gel-based Provaunt was ineffective against *P. oceanica*, perhaps due to the gel matrix being difficult to carry to the nest. The low efficacy of Provaunt was corroborated by our observations of low numbers of *P. oceanica* at either of the gel baits during the attractiveness trials. It is possible that Provaunt would be more attractive to *P. oceanica* if incorporated into a more desirable food or into a matrix that was easier for the ants to carry.

Provaunt was highly effective in reducing numbers of both *Tetramorium* species; there were no *T. simillimum* on two treatment plots and only one *T. bicarinatum* on four treatment plots. The gel matrix (including Tango) was highly attractive to both *Tetramorium* species in the choice trials, which likely contributed to its effectiveness. Amdro and Maxforce also resulted in near or complete elimination of *T. simillimum* on the treatment plots, indicating a high level of efficacy for all three toxin-based baits against this species. The inconsistent efficacy and low attractiveness of Amdro and Maxforce to *T. bicarinatum* indicate that these ants do not aggressively consume or distribute these baits among themselves, at least under the conditions we encountered.

While our results suggest that toxic baits are highly effective at reducing numbers of workers of both species of *Tetramorium* on treatment plots, it is unclear whether a single application of bait would be sufficient to eradicate either species from Rose Atoll. Compared to other aggressive ant species such as the big-headed ant (*P. megacephala*), Argentine ant

(*Linepithema humile*), and the tropical fire ant (*Solenopsis geminata*), little effort has gone into controlling *Tetramorium* ants in natural settings, and, to our knowledge, no work has directly targeted *Tetramorium* in an eradication effort. However, efforts targeting other ant species in habitat also occupied by *Tetramorium* suggest that relatively long-lasting suppression, or perhaps eradication, can be attained. For example, on 6.07–ha Spit Island, Midway Atoll, neither *T. bicarinatum* nor *T. simillimum* was detected on ten bait cards one month following the island-wide application of Maxforce targeting the tropical fire ant (Plentovich *et al.* 2010). However, *T. simillimum* was relatively quick to rebound, being detected at approximately pre-treatment rates four months after treatment. In contrast, *T. bicarinatum* was not detected on bait cards until six years (73 months) following treatment. Although a greater sampling effort might have detected *T. bicarinatum* earlier, it is also possible that it was eradicated from the island but recolonized from one of two neighboring islands that were not treated.

Differences in foraging behaviors among ant species likely influenced their relative abundance at bait cards as well as the effectiveness of the baits. For example, *P. oceanica* recruited relatively quickly to bait on cards and carried the bait away, presumably to one or more nests. Such dominant foraging behavior is common for *Pheidole* and allows the colony to monopolize ephemeral food resources (U.S. Geological Survey unpublished data). In our study, this dominant foraging often resulted in ants removing bait from cards so quickly that few individuals were counted on the cards. In several instances, we observed well-developed trails consisting of many ants carrying bait away from cards. Once all the bait had been removed from the cards, *P. oceanica* showed little interest in the oily residue that remained. In contrast, *T. simillimum* and *T. bicarinatum* tended more to feed on bait *in situ*, imbibing oil from the bait rather than carrying it to the nest (Figure 5). As a result of their preference for *in situ* feeding, we often observed large numbers of *T. simillimum* and *T. bicarinatum* on the undersides of bait cards, imbibing oil that had penetrated the paper, even after *P. oceanica* had removed all the bait. The tendency of *P. oceanica* to quickly remove granular bait might interfere with a multi-species eradication effort, which has implications for developing a treatment strategy.

Figure 5. *Tetramorium simillimum* feeding at Tango (left) and Amdro (right) during bait attractiveness trials.

For example, an eradication strategy targeting *Tetramorium* with granular bait might involve multiple treatments with the idea that *P. oceanica* would need to be reduced by the first treatment before *Tetramorium* could be affected by subsequent treatments. An alternative strategy would be to target *P. oceanica* with granular bait and *T. simillimum* and *T. bicarinatum* with the gel-based Provaunt.

We could not assess the efficacy of either IGR baits, although we did determine that Distance was highly attractive to *P. oceanica* and both Distance and Tango were attractive to *T. simillimum* and *T. bicarinatum*. Because IGRs work at the scale of weeks, rather than days, their ability to eradicate ants should be evaluated where nests can be monitored over an adequate period of time. We were unable to collect queen ants from plots following treatment to evaluate the effect of bait on egg development. *Tetramorium* nests were located underground along roots or in dead pith tissue within live *Tournefortia* stems, making them difficult to access in the short time frame available without damaging live plants. Nevertheless, the highly attractive IGR baits could be effective management tools on Rose Atoll.

The toxic baits we tested were entirely removed by worker ants within 48–60 hours, which reduced bait exposure to sun and rain. Hydramethylnon, in particular, is rapidly degraded by exposure to sunlight and has been found to be ineffective against red imported fire ants (*Solenopsis invicta*) after 12–30 hours of exposure (Vander Meer *et al.* 1982). Rain, which can be expected at nearly any time on Rose Atoll, can greatly reduce the effectiveness of the baits through disintegration of the granules or development of mold that would render the bait unattractive to the ants (Krushelnycky and Reimer 1998).

On Rose Atoll, only *T. bicarinatum* and *T. simillimum* were observed tending *Pulvinaria* scales on *Pisonia*. During April 2012, we observed that *T. simillimum* was considerably more common than *T. bicarinatum* on *Pisonia*, but in March 2013 only *T. bicarinatum* was observed tending scales. This raises the question of whether the shift of dominance in scale-tending was affected by the reduction of scales following the application of imidacloprid insecticide into *Pisonia* during November 2012 by the U.S. Fish and Wildlife Service. Moreover, we expect that *P. oceanica* might tend scales on Rose Atoll in the absence of either *Tetramorium* species or under different environmental conditions. And in the absence of these three species, it is unclear whether any of the other ants found on the atoll would tend the scales, but species of *Nylanderia* and *Monomorium* have been observed tending honeydew-producing insects elsewhere (Wetterer 2009, Sharma *et al.* 2013).

Formicidal baits applied at the landscape level may have negative impacts on non-target arthropods. We did not test the baits on other arthropods found on Rose Island, but based on taxon-specific food preferences and foraging behaviors, the baits should pose relatively little risk to most non-ant species. Since the active ingredient used in bait must be ingested to affect the consuming organism, they potentially impact only arthropods that scavenge for food. On Rose Atoll, the scavenging guild primarily includes cockroaches (two species), crickets (two species), isopods (three species), hermit crabs (two+ species) and coconut crabs (one species; U.S. Geological Survey unpublished data). Knowledge of non-target impacts of formicidal baits is generally poor, but Plentovich *et al.* (2010) found significantly fewer cockroaches and crickets 30 days following application of Maxforce on Midway Atoll. A similar result was found during ant eradication attempts using Amdro on offshore islets of O'ahu, Hawai'i, where Plentovich *et al.* (2011) found a significant reduction in cockroach abundance on treated islets compared to untreated islets two to four weeks after application of the formicidal bait. During our study, hermit crabs were rarely observed consuming ant bait, although on one occasion we did see several hermit crabs (*Coenobita perlatus*) taking both gel and granular bait off cards in the late afternoon. Although hermit crabs on Rose Atoll probably feed to some extent on interior parts of the island, mark-recapture data suggest that they primarily feed in the intertidal zone at night (U.S. Geological Survey and U.S. Fish and Wildlife Service unpublished data). It is unclear whether coconut crabs (*Birgus latro*) would consume ant bait, but this species has been found to be susceptible to granular bait containing fipronil on Christmas Island in the Indian Ocean (Boland *et al.* 2011). Collecting and sheltering hermit crabs and coconut crabs prior to bait application would greatly reduce non-target risk to a large proportion of their populations.

Dynamic interactions among *Pisonia*, the invasive *Pulvinaria* scale that attacks it, and the ants that tend the scales present complex challenges to managing the remote ecosystem of Rose Atoll. For example, eradication of the targeted species may lead to changes in the relative abundance of the remaining ant community, or result in less resilience against other, more aggressive ant species that may threaten the atoll in the future (Plentovich *et al.* 2011). Furthermore, eradication of *P. oceanica* would be considered removal of a species that is likely native to the Samoan Archipelago (Wetterer and Vargo 2003), a potentially controversial, but likely useful action to control scales. Although we investigated methods for controlling ants, research on other management options, including biological control of the scale through the introduction of natural predators, could facilitate a comprehensive and long-term solution.

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LITERATURE CITED

Bach, C. E. 1991. Direct and indirect interactions between ants (*Pheidole megacephala*), scales (*Coccus viridis*) and plants (*Luchea indica*). Oecologia 87:233–239.

Boland, C. J. R., M. J. Smith, D. Maple, B. Tiernan, R. Barr, R. Reeves, and F. Napier. 2011. Heli-baiting using low concentration fipronil to control invasive yellow crazy ant supercolonies on Christmas Island, Indian Ocean. Pp. 152–156 *in* C. R. Veitch, M. N. Clout, and D. R. Towns (editors). Island invasives: eradication and management. IUCN, Gland, Switzerland.

Gaigher, R. M., M. J. Samways, J. Henwood, and K. Jolliffe. 2011. Impact of a mutualism between an invasive ant and honeydew-producing insects on a functionally important tree on a tropical island. Biological Invasions 13:1717–1721.

Gaigher, R., M. J. Samways, and S. Van Noort. 2013. Saving a tropical ecosystem from a destructive ant-scale (*Pheidole megacephala*, *Pulvinaria urbicola*) mutualism with support from a diverse natural enemy assemblage. Biological Invasions (published online 12 March 2013).

Greenslade, P. 2010. Did alien ants initiate a population explosion of a coccoid plant pest on an islet in the Coral Sea? Journal of Insect Conservation 14:419–421.

Handler, A. T., D. S. Gruner, W. P. Haines, M. W. Lange, and K. Y. Kaneshiro. 2007. Arthropod surveys on Palmyra Atoll, Line Islands, and insights into the decline of the native tree *Pisonia grandis* (Nyctaginaceae). Pacific Science 61:485–502.

Hill, M., K. Holm, T. Vel, N. J. Shah, and P. Matyot. 2003. Impact of the introduced yellow crazy ant *Anoplolepis gracilipes* on Bird Island, Seychelles. Biodiversity and Conservation 12:1969–1984.

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

Krushelnycky, P. D., and N. J. Reimer. 1998. Efficacy of Maxforce bait for control of the Argentine ant (Hymenoptera: Formicidae) in Haleakala National Park, Maui, Hawaii. Environmental Entomology 27:1473–1481.

Lester, P. J. 2008. Integrated pest management: an under-utilized tool for conservation and the management of invasive ants and their mutualistic Hemiptera in the Pacific. Pacific Conservation Biology 14:246–247.

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

Plentovich, S., A. Hebshi, and S. Conant. 2009. Detrimental effects of two widespread invasive ant species on weight and survival of colonial nesting seabirds in the Hawaiian Islands. Biological Invasions 11:289–298.

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. Journal of Insect Conservation 14:459–465.

Reimer, N. J., M. -L. Cope, and G. Yasuda. 1993. Interference of *Pheidole megacephala* (Hymenoptera: Formicidae) with biological control of *Coccus viridis* (Homoptera: Coccidae) in coffee. Environmental Entomology 22:483–488.

Sharma, S., D. H. Oi, and E. A. Buss. 2013. Honeydew-producing hemipterans in Florida associated with *Nylanderia fulva* (Hymenoptera: Formicidae), an invasive crazy ant. Florida Entomologist 96:538–547.

Smith, D., D. Papacek, M. Hallam, and J. Smith. 2004. Biological control of *Pulvinaria urbicola* (Cockerell) (Homoptera: Coccidae) in a *Pisonia grandis* forest on North East Herald Cay in the Coral Sea. General and Applied Entomology 33:61–68.

Vander Meer, R. K., D. F. Williams, and C. S. Lofgren. 1982. Degradation of the toxicant AC217,300 in Amdro imported fire ant bait under field conditions. Journal of Agricultural and Food Chemicals 30:1045–1048.

Wetterer, J. K. 2009. Worldwide spread of the destroyer ant, *Monomorium destructor* (Hymenoptera: Formicidae). Myrmecological News 12:97–108.

Wetterer, J. K., and D. L. Vargo. 2003. Ants (Hymenoptera: Formicidae) of Samoa. Pacific Science 57:409–419.