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Precision control of an invasive ant on an ecologically sensitive tropical island: a principle with wide applicability

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Abstract. Effective management of invasive ants is an important priority for many conservation programs but can be difficult to achieve, especially within ecologically sensitive habitats. This study assesses the efficacy and nontarget risk of a precision ant baiting method aiming to reduce a population of the invasive big-headed ant *Pheidole megacephala* on a tropical island of great conservation value. Area-wide application of a formicidal bait, delivered in bait stations, resulted in the rapid decline of 8 ha of *P. megacephala*. Effective suppression remained throughout the succeeding 11-month monitoring period. We detected no negative effects of baiting on nontarget arthropods. Indeed, species richness of nontarget ants and abundance of other soil-surface arthropods increased significantly after *P. megacephala* suppression. This bait station method minimized bait exposure to nontarget organisms and was cost effective and adaptable to target species density. However, it was only effective over short distances and required thorough bait placement. This method would therefore be most appropriate for localized *P. megacephala* infestations where the prevention of nontarget impacts is essential. The methodology used here would be applicable to other sensitive tropical environments.

Key words: big-headed ant; Cousine Island, Seychelles; formicide Siege; hydramethylnon; invasive species; nontarget effects; pesticide; Pheidole megacephala; *protected area.*

Introduction

Management of invasive species is essential for the conservation of ecosystems (Zavaleta et al. 2001) but can be extremely challenging (Myers et al. 2000). Social invasive insects, such as ants, are among the species causing the most widespread ecological damage (Holway et al. 2002, New 2008), but are especially difficult to control (Holway et al. 2002, Gentz 2009). The development of management strategies for well-established invasive ants can be time-consuming and costly (Williams et al. 2001), and control programs for some species have had limited success (Silverman and Brightwell 2008). Management is further complicated in sensitive habitats where environmental repercussions of management practices have to be taken into account (Gentz 2009). The possibility of nontarget impacts and accumulation of toxins in the environment is a considerable risk in fragile or protected habitats, and ecosystem-wide effects can be unpredictable (Plentovich et al. 2010*a*, *b*).

The development of highly selective insecticides, with precise mechanisms of action and greatly reduced environmental risk, provides an opportunity to manage invasive ants in areas of high conservation value (Gentz 2009). Several studies have demonstrated that selective formicidal bait can be used to locally eradicate invasive ants, with most successes reported for smaller, isolated infestations (Abedrabbo 1994, Hoffmann and O'Connor 2004, Causton et al. 2005, Plentovich et al. 2009, Hoffmann 2011). Formicidal bait has also been used to reduce population levels (Cook 2003) and to limit range expansion of invasive ants (Krushelnycky et al. 2004). Different methodologies were used according to local conditions and the species involved. Results of the treatments have been varied, with recovery of native species in some cases (Cook 2003, Hoffmann 2010). However, in other cases nontarget and indirect effects (Plentovich et al. 2010*a*, *b*) or posttreatment recovery of the target species occurred (Plentovich et al. 2009). Clearly we need more information on the efficacy, costs/benefits, and risks of different strategies to refine and

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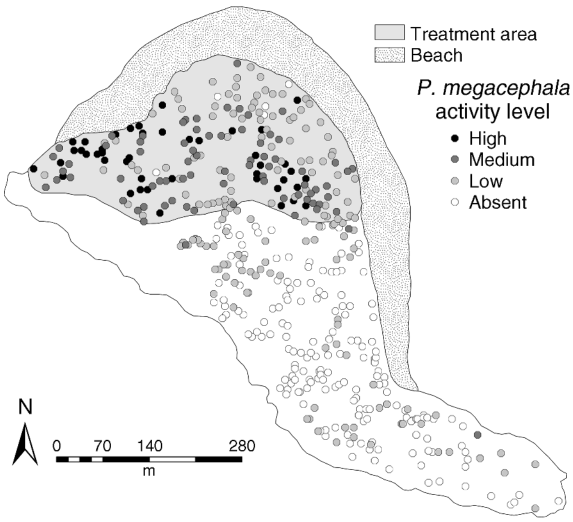

FIG. 1. Distribution and activity levels of the invasive big-headed ant *Pheidole megacephala* on Cousine Island, Seychelles in June 2010. These activity levels were before application of formicidal bait aimed at selectively decreasing *P. megacephala* abundance. Activity levels were categorized based on the number of ants in 4 cm per 30-s observation: absent (no ants), low (1–25 ants), medium (26–50 ants), or high (>50 ants).

develop control methodologies (Simberloff 2009, Hoffmann et al. 2010, Hoffmann 2011).

Cousine Island, Seychelles, is of major conservation significance to the archipelago, as it sustains populations of many endemic and threatened species (Samways et al. 2010*a*). Unfortunately, also present is the highly invasive big-headed ant *Pheidole megacephala*, which is notorious for impacting native ecosystems (Hoffmann et al. 1999, Holway et al. 2002, Wetterer 2007, Krushelnycky and Gillespie 2008). In recent years, this ant has significantly impacted parts of this island ecosystem (Gaigher et al. 2011), thereby posing a major threat to some significant biota (see Plate 1). Effective control of the species has since become a priority for island management (Samways et al. 2010*a*), with the greatest challenge being minimizing nontarget impacts on the large number of endemic species within this small and ecologically sensitive environment. Here we present an evaluation of the efficacy and nontarget impacts of a precision baiting method recently used to control *P. megacephala* on Cousine Island.

METHODS

Delineation of treatment area

Cousine Island is a 27-ha granitic island in the Seychelles, 4°20′41″ S, 55°38′44″ E. A pretreatment survey of *Pheidole megacephala* population levels was conducted in May–June 2010 to demarcate the treatment area. Ant activity, defined as the number of ants moving in one direction across a 4-cm horizontal section of a trunk foraging trail in 30 s, was recorded across the island on haphazardly selected trees and mapped using a GPS. We sampled 494 trees, which provided sufficient detail to detect fine-scale variation in population levels. Activity levels were categorized as absent (no ants per 4 cm per 30 s), low (1–25 ants), medium (26–50 ants), or high (>50 ants). High and medium ant densities on Cousine were associated with direct impacts on other fauna (R. Gaigher, K. G. Jolliffe, and S. Jolliffe, *personal observation*) and indirect impacts on the native forest (Gaigher et al. 2011), but no impacts were obvious at low densities. Because the treatment aimed not for eradication, but for the suppression of the overall population to low activity levels that result in no observable ecological impact, the treatment area was a single 8-ha area with medium and high ant activity (Fig. 1).

Treatment

Treatment was conducted between 15 June and 23 July 2010 using the commercial formicidal bait Siege (also known as Amdro; BASF, Midrand, Gauteng, South Africa). Siege granules consist of maize grits, soybean oil, and the active ingredient hydramethylnon, a slow-acting metabolic inhibitor, which is dispersed among workers within colonies by communal feeding (Bacey 2000, Gentz 2009). Siege is highly effective at controlling *P. megacephala* in agricultural (Samways 1986, Zerhusen and Rashid 1992, Taniguchi et al. 2005, Arakaki et al. 2009) and natural systems (Hoffmann and O'Connor 2004, Plentovich et al. 2010*a*). Siege is also of low toxicity thereby presenting minimal risk to most nontarget terrestrial organisms, except for scavenging arthropods that may ingest the bait (Stanley 2004). Risk of environmental contamination is minimal, as hydramethylnon degrades rapidly in sunlight and water (Apperson et al. 1982, Vander Meer et al. 1982).

The bait was distributed inside bait stations (Grout 2008) to provide the best likelihood of avoiding nontarget impacts, as well as to prolong bait efficacy by limiting bait exposure to sunlight and water. These stations allowed ant access, but excluded most nontarget species. The stations were 200 mm long pieces of plastic irrigation tubing, 15 mm diameter, sealed at the ends, with two 7-mm holes drilled into the sides for ant access. Each station held 10 g of bait and stations were placed at the base of trees with *P. megacephala* activity. Station density was adapted to *P. megacephala* density, with overall bait coverage of 4 kg/ha. We used a higher dosage than the recommended 2.5 kg/ha, because of the exceptionally high densities of ants throughout the area. Stations were collected after one week, while simultaneously inspecting for persisting colonies that were subsequently baited.

Data collection

To document the short-term *P. megacephala* response to the treatment, we recorded ant activity in 10 locations in the treated area on four days in the week before treatment, daily after treatment until the ants were suppressed to low activity levels, and once a week for five weeks after suppression.

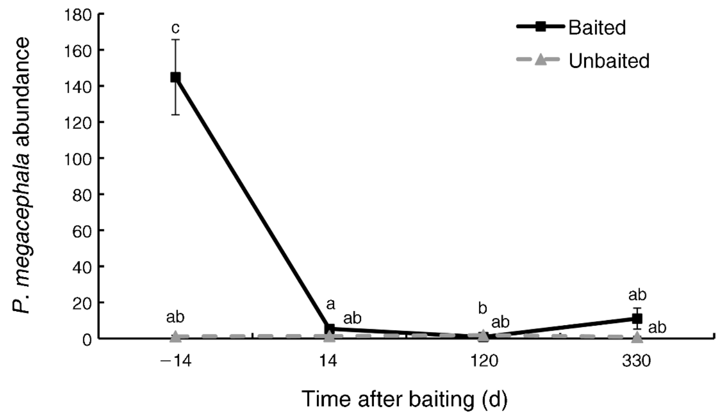

FIG. 2. *P. megacephala* abundance (mean ± SE) in baited and unbaited plots before and after baiting. Means with lowercase letters in common are not significantly different at $P < 0.05$. Note the nonlinear *x*-axis scale.

To test for longer-term effects of baiting on *P. megacephala* and nontarget arthropods, pairs of pitfall traps were placed in 40 random locations (20 within and 20 outside the treated area). Traps within each pair were 1 m apart and each location was separated by at least 10 m. Each pitfall trap was a 50-mL test tube with a 2.5 cm diameter, half filled with water and a drop of detergent. Traps were left open for two days during each survey, which was undertaken two weeks before baiting, two weeks after baiting, four months after baiting, and 11 months after baiting. Abundance data of soil-surface arthropods were recorded. Ants were identified to species level and other arthropods to order, and sorted into morphospecies. Voucher specimens are in the Stellenbosch University Entomological Museum.

To detect localized *P. megacephala* resurgence outside the permanent sampling locations, we conducted island-wide surveys four and 11 months after treatment (in October 2010 and May 2011, respectively), when activity levels were recorded, categorized, and mapped as in the pretreatment survey. The purpose of the October 2010 survey was to detect resurgence mainly within the treated area and included 149 trees in the treated and adjacent areas. In May 2011, we aimed to resurvey the entire island and sampled 290 trees across the island. Sampling intensity was lower than in the initial survey as we determined that a lower sampling effort would be sufficient to detect resurgence, based on initial survey results.

Statistical analysis

To determine the short-term response of *P. megacephala* to treatment, one-way analysis of variance (ANOVA) was performed with Bonferroni-corrected post hoc pairwise comparisons. As data did not satisfy parametric assumptions, they were square root transformed prior to analysis, but means reported are based on untransformed data (Townend 2002). To test for longer-term effects of baiting on *P. megacephala* and nontarget arthropods, repeated-measures ANOVA with "treatment" as the main factor and "time" as the repeated-measures factor were performed on *P. megacephala* abundance, as well as abundance and species richness of other ants and non-ant arthropods (Townend 2002). Bonferroni-corrected post hoc tests were performed to detect pairwise differences, and where data did not satisfy parametric assumptions, bootstrap multiple comparisons were performed. Analyses were done in Statistica 10 (Statsoft 2003).

RESULTS

Short-term P. megacephala *response to baiting*

P. megacephala activity was significantly reduced within a week after treatment from 62 ± 11 ants to 1 ± 1 ant (mean ± SE; $F_{13,126} = 42.19$, $P < 0.0001$). Activity remained suppressed below four ants per 4 cm per 30 s in these plots for the duration of the five-week survey.

Longer-term effects of baiting on P. megacephala *and nontarget arthropods*

Baiting caused a significant longer-term decline in *P. megacephala* abundance from 145 ± 21 ants per plot to fewer than 12 ants per plot for the rest of the 11-month study period ($F_{3,114} = 40.13$, $P < 0.0001$; Fig. 2, Table 1), while *P. megacephala* abundance in unbaited plots remained unchanged ($P > 0.05$; Fig. 2).

We detected no negative effect of baiting on any of the nontarget arthropods, but instead a positive effect of *P. megacephala* removal. Abundance of other ants in baited plots increased from 1 ± 1 ant before baiting, which was significantly lower than in control plots ($P < 0.05$), to 12 ± 3 ants after 11 months, which was comparable to control plot abundances ($P > 0.05$). Abundance in unbaited plots also increased over time, although less so than in baited plots, resulting in a statistically nonsignificant baiting × time interaction ($F_{3,114} = 0.39$, $P = 0.76$; Fig. 3A, Table 1). Baiting significantly influenced species richness of other ants ($F_{3,114} = 3.58$, $P < 0.05$; Fig. 3B, Table 1). Ant species richness in baited plots increased from 0.1 ± 0.1 species per plot to 2.1 ± 0.3 species per plot, whereas ant species richness in unbaited plots remained unchanged ($P > 0.05$; Fig. 3B). The composition of the ant assemblage in

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TABLE 1. Effect of baiting on abundance of the invasive ant *Pheidole megacephala*, and abundance and species richness of other ants and non-ant arthropods.

Response variables	df	*F*	*P*
P. megacephala abundance			
Treatment	1	56.12	<0.0001
Time	3	39.89	<0.0001
Time × treatment	3	40.13	<0.0001
Other ant abundance			
Treatment	1	12.60	<0.005
Time	3	13.50	<0.0001
Time × treatment	3	0.39	0.76
Ant species richness (excluding *P. megacephala*)			
Treatment	1	25.64	<0.0001
Time	3	19.30	<0.0001
Time × treatment	3	3.58	<0.05
Non-ant arthropod abundance			
Treatment	1	78.85	<0.0001
Time	3	23.58	<0.0001
Time × treatment	3	22.41	<0.0001
Non-ant arthropod species richness			
Treatment	1	119.74	<0.0001
Time	3	10.04	<0.0001
Time × treatment	3	1.77	0.16

Note: Statistics are derived from repeated-measures ANOVA.

baited plots also changed after baiting. Before baiting, the ant assemblage was dominated by *P. megacephala* (99.6%), with only *Brachymyrmex cordemoyi* sympatric (Table 2). Assemblages in unbaited plots throughout the study period consisted of a greater diversity of species including other introduced species and the Seychelles endemic *Pheidole flavens farquharensis* (Table 2). The diversity of ants in baited plots steadily increased after baiting (Table 2), and 11 months after treatment, assemblages in baited plots consisted of the tramp ants *P. megacephala* (47.0%), *B. cordemoyi* (7.0%), *T. simillimum* (1.1%), *P. longicornis* (2.5%), *P. bourbonica* (8.1%), *Tapinoma melanocephalum* (1.3%), *Plagiolepis alluaudi* (0.4%), *Cardiocondyla emeryi* (6.2%), *Camponotus maculatus* (0.9%), and the endemic *P. flavens farquharensis* (25.5%) (Table 2).

Non-ant arthropods in pitfall traps included cockroaches, isopods, mites, spiders, springtails, beetles, centipedes, millipedes, true bugs, and pseudoscorpions, with 94% of the total number of arthropods trapped being represented by one species of alien cockroach *Pycnoscelus indicus* and two species of unidentified isopods. Non-ant arthropod abundance was significantly influenced by baiting ($F_{3,114} = 22.41$, $P < 0.0001$; Fig. 4A, Table 1), increasing from 47 ± 9 individuals to 219 ± 35 individuals after 11 months, corresponding with no change in unbaited plots ($P > 0.05$; Fig. 4A). The effect of baiting on non-ant arthropod species richness was nonsignificant ($F_{3,114} = 1.77$, $P = 0.16$; Fig. 4B, Table 1).

Island-wide P. megacephala *activity surveys*

Four months after baiting, we recorded 79% *P. megacephala* absences, 19% low activity, 2% medium activity, and 0% high activity in the treated area (n = 107). Untreated areas had 51% *P. megacephala* absences, 46% low activity, 2% medium activity, and 0% high activity observations (n = 42) (Fig. 5A). Eleven months after baiting, treated areas had 67% *P. megacephala* absences, 31% low activity, 2.5% medium activity, and 0% high activity observations (n = 134) (Fig. 5B). Untreated areas had 49% absences, 37% low activity, 15% medium activity, and 0% high activity observations (n = 156).

Hours worked and costs of the treatment

A total of 322 hours were worked during the treatment of the 8-ha area. This included construction of the bait stations (82 hours), filling stations with bait (49 hours), deploying them in the field (83 hours), collecting empty bait stations (60 hours), and all pre- and posttreatment surveys (48 hours). A total of U.S. $2616.40 was spent on materials used during treatment of the 8-ha area and included the cost of Siege used in treatment ($1922.73), shipping costs ($450.79), and materials for bait stations ($242.87).

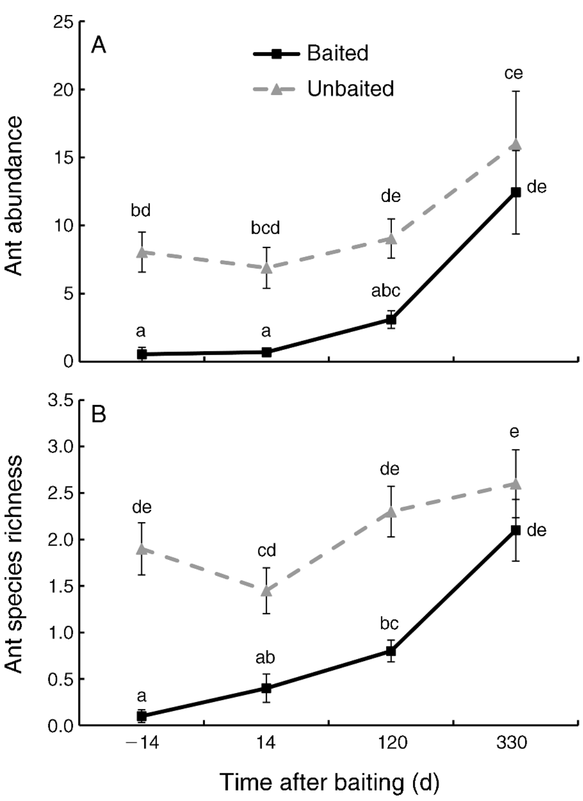

FIG. 3. (A) Abundance and (B) species richness of ants in baited and unbaited plots before and after baiting (excluding *P. megacephala*); all values are shown as mean ± SE. Means with lowercase letters in common are not significantly different at $P < 0.05$. Note the nonlinear x-axis scale.

Table 2. Total abundance of each ant species sampled in baited and unbaited control plots before and after baiting.

Species	Baited plots: 14 d before baiting	Baited plots: 14 d after baiting	Baited plots: 120 d after baiting	Baited plots: 330 d after baiting	Control plots: 14 d before baiting	Control plots: 14 d after baiting	Control plots: 120 d after baiting	Control plots: 330 d after baiting
Brachymyrmex cordemoyi	11	10	42	33	8	6	11	10
Camponotus maculatus	0	0	0	4	0	0	1	0
Cardiocondyla emeryi	0	0	20	29	0	0	0	1
Monomorium floricola	0	0	0	0	7	1	8	0
Monomorium seychellense	0	0	0	0	0	0	3	1
Odontomachus simillimus	0	0	0	0	113	116	69	110
Paratrechina bourbonica	0	0	0	38	1	0	2	12
Paratrechina longicornis	0	0	0	12	4	0	3	33
Pheidole flavens farquharensis	0	0	0	120	7	1	14	2
Pheidole megacephala	2897	107	17	221	24	27	37	17
Plagiolepis allaudi	0	0	0	2	0	2	0	1
Strumigenys emmae	0	2	0	0	0	1	1	0
Tapinoma melanocephalum	0	2	0	6	0	0	0	75
Technomyrmex albipes	0	0	0	0	0	0	0	3
Tetramorium simillimum	0	0	0	5	21	11	69	72

Note: Pheidole flavens farquharensis is native; all other species are exotic.

Discussion

Efficacy of the treatment

The treatment was effective at reaching our conservation goal of suppressing the 8-ha *P. megacephala* infestation to innocuous levels. Area-wide application of Siege in bait stations resulted in rapid decline of *P. megacephala* density, with effective suppression after one week. This decline in ant density is significant, as the population levels of the ant on the island had been continuously high over many preceding years (Samways et al. 2010*a*, *b*). Suppression lasted for the duration of the 11-month posttreatment monitoring period. Population levels were still low throughout the treated area at the end of the study and only very localized spot treatments have since been required where isolated nests recovered to maintain suppression.

The biology of *P. megacephala* most likely contributed to the efficacy of the treatment. Silverman and Brightwell (2008) emphasize three traits of most invasive ants that make them well-suited for management attempts: (1) dispersal through budding, which results in clear colony boundaries, (2) flexible diet to ensure acceptance of the bait, and (3) rapid recruitment to, and monopolizing of, food resources, which ensures spread of the toxicant through the colony. For all of these factors, *P. megacephala* fits the description (Holway et al. 2002, Wetterer 2007), making it susceptible to control measures and an ideal candidate species for management (Hoffmann and O'Connor 2004, Hoffmann 2010).

As in other effective *P. megacephala* management programs (Hoffmann and O'Connor 2004, Plentovich et al. 2010*a*, Hoffmann 2011), effective suppression was aided by the small dimensions of the infestation. The small area allowed focused treatment in locations of high ant density, which increased the possibility of achieving complete coverage in these areas. The isolation of the island also ruled out the possibility of reintroduction, which has caused resurgence after treatment in other studies (Apperson et al. 1982, Samways 1986, Cook 2003).

Effect of baiting on nontarget arthropods

To fully evaluate the outcomes of control methods, information on nontarget effects is essential, especially in

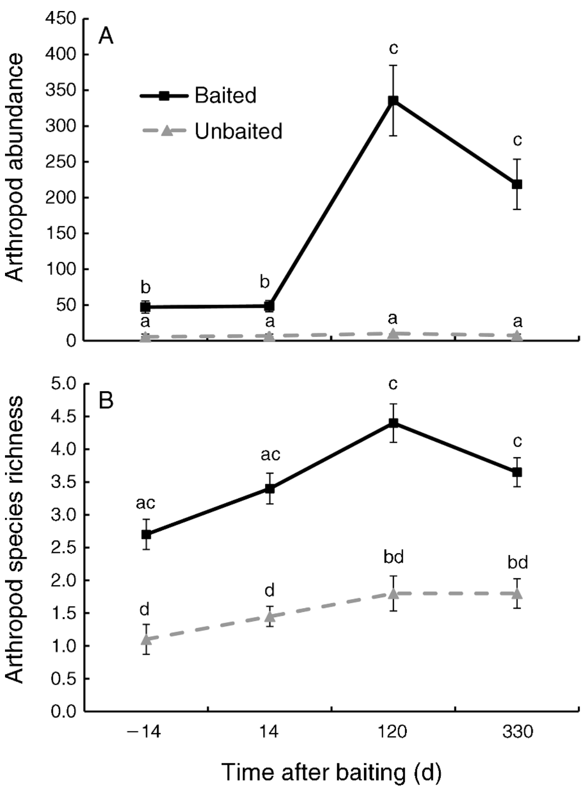

Fig. 4. (A) Abundance and (B) species richness of non-ant arthropods in baited and unbaited plots before and after baiting; all values are shown as mean ± SE. Means with lowercase letters in common are not significantly different at $P < 0.05$. Note the nonlinear x-axis scale.

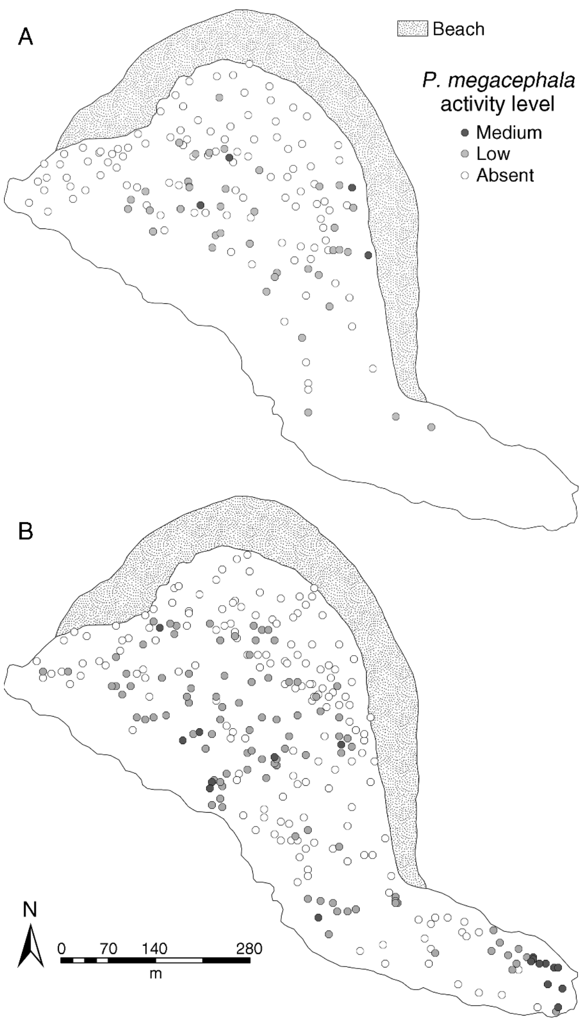

FIG. 5. *Pheidole megacephala* distribution and activity levels on Cousine Island, Seychelles in (A) October 2010, four months after ant bait application and (B) May 2011, 11 months after ant bait application.

natural habitats. Although hydramethylnon-based baits are reported to be highly specific (Bacey 2000, Stanley 2004), there have been reports of impacts of broadcasting on nontarget arthropods (Plentovich et al. 2010*a*, *b*). Cousine is home to a rich endemic litter fauna (Kelly and Samways 2003) and a threatened keystone detritivore, the Seychelles giant millipede (*Seychelleptus seychellarum*; Lawrence and Samways 2003). Smaller organisms such as these may have been vulnerable to baiting despite their physical exclusion by bait stations. The lack of nontarget effects observed here suggests that the ecological costs of treatment are insignificant, and lends support for the use of this treatment method in sensitive habitats.

The significant increase in nontarget ants and other soil-surface arthropods following *P. megacephala* control indicates that there is potential for the arthropod community to recover following *P. megacephala* management. Consequences of *P. megacephala* control in other tropical ecosystems have been varied. In northern Australia, *P. megacephala* eradication resulted in recovery of the native ant assemblage (Hoffmann 2010). However, its eradication in Hawaii resulted in subsequent invasion by *A. gracilipes*, the impact of which was considered to be worse than that of *P. megacephala* (Plentovich et al. 2010*a*). In our study, both native and exotic species benefitted from *P. megacephala* control, but none of the exotics are considered to be aggressive invaders (Dorow 1996, Samways et al. 2010*b*) and some such as *P. indicus* are functionally important naturalized components of the ecosystem (Samways et al. 2010*b*). Overall, the system appears to have benefitted substantially from *P. megacephala* suppression.

Benefits and disadvantages of the bait station method

Bait stations have been used to control ants in agricultural systems (Taniguchi et al. 2003, 2005, Arakaki et al. 2009) and to selectively exclude ants from tropical forest canopies (Klimes et al. 2011). But they have never been used for invasive ant management in natural habitats. For this environment, it proved to be a very effective application method.

The main advantage of this precision baiting method is the reduced opportunity for bait uptake by nontarget organisms. We have observed cockroach mortality during previous small-scale broadcasting trials on Cousine, as well as ingestion of exposed bait by endemic taxa. Due to the risk of nontarget effects of broadcasting, we considered it essential to avoid exposure of these species to the bait, and bait stations provided the opportunity to do so.

In areas with variable *P. megacephala* levels, the bait stations were ideal, as they allowed focused bait placement and control over small-scale application rates, which is less achievable with broadcasting. A drawback of the localized influence of the stations is that they were only effective over short distances (up to 5 m), making thorough bait placement necessary. This was in contrast to the 15-m influence of bait stations used by Taniguchi et al. (2003) in pineapple fields and the ability of *P. megacephala* to detect bait stations from 12 m away in orchards (Grout 2008). The complex vegetation and terrain of the island, compared to these agricultural systems may have influenced the distance over which the bait stations were effective. Additionally, it is likely that the island with its large proportion of suitable nesting habitat was able to support a higher ant nest density compared to agricultural land. This would have influenced the rate of bait uptake and increased the need for higher station density on the island.

Approximately U.S. \$350 was spent per hectare on materials used in the treatment and 41 hours were worked per hectare. These estimates include only material and personnel costs for the treatment phase in the field and do not include time spent preparing for field trips, laboratory work, or overhead costs, which

PLATE 1. A White-tailed Tropicbird (*Phaeton lepturus*), a native ground-nesting seabird, being harassed by *Pheidole megacephala* workers. Photo credit: K. G. Jolliffe.

may contribute significantly to the overall costs. The total cost of eradicating a 21-ha infestation of *W. auropunctata* from Marchena Island was \$13 680 per hectare (Causton et al. 2005). The cost of the program on Cousine was more comparable to that of the eradication of *P. megacephala* (30 ha) and *S. geminata* (3 ha) from Kakadu National Park at ~\$900 per hectare, which was considered to be very cost effective (Hoffmann and O'Connor 2004).

CONCLUSION

The precision bait station method was suitable for use on a small tropical island, as it effectively controlled high *P. megacephala* densities with no observed nontarget effects. The method used in this study is surely applicable within other sensitive tropical environments threatened by this species, particularly undisturbed habitats and protected areas. This study demonstrates that the innovative use of low-tech, low-cost methods can be effective in achieving invasive ant management goals and we hope that it will stimulate further research on selective low-impact control methods.

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