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ORIGINAL PAPER

The effects of hydramethylnon on the tropical fire ant, *Solenopsis geminata* (Hymenoptera: Formicidae), and non-target arthropods on Spit Island, Midway Atoll, Hawaii

Sheldon Plentovich · Chris Swenson · Neil Reimer · Mike Richardson · Norman Garon

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Abstract Invasive ants can cause major disruptions in native ecosystems. Ant eradication methods without significant non-target effects are needed to stop incipient invasions and to aid in ecosystem restoration. Successful ant eradications are rare and there is very little understanding of the effects of ant eradication methods, such as the use of formicides, on non-target species. Here we attempted to control and possibly eradicate the invasive tropical fire ant, *Solenopsis geminata*, from a small islet using the formicide Maxforce® (active ingredient: hydramethylnon), and to quantify the non-target effects on an almost exclusively alien ground-dwelling arthropod community. *S. geminata* abundance was reduced and the species was not detected on bait cards for 12 months post-treatment. The abundance of another non-target invasive ant that was primarily detected in pitfall traps, *Tetramoruim bicarinatum*, declined in pitfall traps following treatment, but seemed to be excluded from bait cards by *S. geminata*. Total ant abundance did not return to original levels until more than 12 months post-treatment. Populations of alien cockroaches (Order Blattaria) and crickets (Orthoptera: Gryllidae) were negatively affected by the treatment. We conclude that Maxforce® can be used to control small infestations of *S. geminata* and *T. bicarinatum* effectively; however we recommend it be used cautiously due to the potential ecological cost to non-target species. Use in areas where infestations are small and isolated will maximize the likelihood of success while minimizing non-target effects.

Keywords Ant eradication · Ecological cost · Formicidae · Maxforce · Non-target effects

Introduction

Invasive ants cause widespread economic and ecological effects (Christian 2001; Holway et al. 2002; Hill et al. 2003; O'Dowd et al. 2003; Tschinkel 2006; Davis et al. 2008) and are capable of decimating native arthropod fauna (Perkins 1913; Risch and Carroll 1982; Cole et al. 1992; LaPolla et al. 2000; Gillespie and Reimer 1993; Hoffmann 2009; Hill et al. 2003; O'Dowd et al. 2003), directly and indirectly harming vertebrates (Meek 2000; Holway et al. 2002; Davis et al. 2008; Plentovich et al. 2009) and altering plant communities (Bach 1991; Green et al. 1997; Christian 2001; Hill et al. 2003; O'Dowd et al. 2003). These effects can be devastating on oceanic islands, such as the Hawaiian Islands, that lack ants, but have high levels of endemism in the native fauna (Perkins 1913, Howarth 1985; Wilson 1996; Gillespie and Reimer 1993; LaPolla et al. 2000; Krushelnycky and Gillespie 2008; Plentovich et al. 2009). The presence of hundreds of invasive ant species with expanding ranges dictates a necessity to further our understanding of how to interdict, manage, and

S. Plentovich (✉)
Department of Zoology, University of Hawaii, Edmondson Hall 152, 2538 McCarthy Mall, Honolulu, HI 96822-2279, USA
e-mail: plentovi@hawaii.edu

C. Swenson · M. Richardson
U. S. Fish and Wildlife Service, 300 Ala Moana Blvd., Honolulu, HI, USA

N. Reimer
U. S. Department of Agriculture, 1428 S. King St., Honolulu, HI, USA

N. Garon
92-1059 Makakilo Dr., Kapolei, HI, USA

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possibly eradicate ants while minimizing ecological cost (McGlynn 1999; Holway et al. 2002).

For decades land managers have tried to eradicate invasive ants and this task has proven to be exceptionally difficult (Williams 1994; Holway et al. 2002; Tschinkel 2006; Green and O'Dowd 2009). However, over the last 20 years a limited number of eradications have been documented throughout the world. *Wasmannia auropunctata* (little fire ant) was eradicated from 3 ha on Santa Fe Island (Abedrabbo 1994) and 21 ha on Marchena Island (Causton et al. 2005) in the Galapagos archipelago. *Pheidole megacephala* (big-headed ant) was eradicated from treated pineapple plantations in Hawaii (Reimer and Beardsley 1990) and on 3.85-ha Mokuauia, an islet offshore of Oahu, Hawaii (Plentovich 2010). In addition, *P. megacephala* and *Solenopsis geminata* (tropical fire ant) were eradicated from ~30 ha and 3 ha respectively around human settlements in Kakado National Park, Australia (Hoffmann and O'Connor 2004). In some of these cases, the eradication of one species was followed by invasion by another species that was more harmful and more difficult to eradicate (Hoffmann et al. 2010; Plentovich 2010).

Solenopsis geminata is native to northern South America, Central America and the southern United States, but has invaded tropical and warm temperate regions around the world (Taber 2000; Holway et al. 2002; Tschinkel 2006). It is capable of causing widespread ecological damage to invaded areas (Risch and Carroll 1982; Plentovich et al. 2009). Experiments involving removal of *S. geminata* from an agroecosystem in southern Mexico documented increases in species richness and total numbers of arthropods (especially herbivores and predators) and decreases in aphids (Homoptera) in treated plots (Risch and Carroll 1982). Control of *S. geminata* on an offshore islet in the Hawaiian Archipelago resulted in increased fledging success and reduced injuries to colonial nesting seabirds relative to seabirds on the untreated islet (Plentovich et al. 2009).

Like most other invasive ants, this species is especially difficult to eradicate. Hoffmann and O'Connor's (2004) successful eradication of this species required substantial effort, and the species was still present after 10+ applications of Amdro®. Eradication was finally achieved with the combination of baiting with Amdro® followed by nest-drenching with Diazinon. On offshore islets in the main Hawaiian Islands, two island-wide broadcasts of Amdro® along with more localized treatments were used to temporarily reduce *S. geminata* numbers, but the population rebounded in the absence of continued application (Plentovich et al. 2009).

The non-target effects of ant control techniques involving toxicants such as hydramethylnon (i.e., the active ingredient in formicides such as Amdro® and Maxforce®) to control fire ants (*Solenopsis* spp., Williams et al. 2001; Tschinkel 2006) are not well studied. Of the work that has been conducted, in longleaf pine (*Pinus palustris*) forests in the southeastern United States, non-target effects on ground-dwelling arthropods were not detected following broadcast of hydramethylnon (Colby 2002). On offshore islets in the main Hawaiian Islands the broadcast of hydramethylnon resulted in declines in alien cockroaches (Order: Blattodea, Plentovich 2010). The use of another toxicant, fipronil, on Christmas Island, Indian Ocean to control the yellow crazy ant (*Anoplolepis gracilipes*) reduced abundance of land crabs, but did not appear to affect other non-target arthropods (Marr et al. 2003). Additional information on the ecological cost of control and eradication efforts is necessary to protect native ecosystems in our efforts to manage invasive species. This is especially salient in areas with high numbers of endemic species where eradication programs are being considered. Without information on non-target effects, good intentioned eradication programs have the potential to cause more harm than the invader itself (Bergstrom et al. 2009).

Small, isolated island and atolls offer opportunities to study the ecological cost of ant eradication attempts. Ants are not native to many Pacific Islands such as Midway Atoll in the Northwestern Hawaiian Islands, so there is no risk of killing non-target native ant species (Wilson 1996). Midway Atoll is comprised of three islets. We chose 6-ha Spit Island, the smallest of the three, to the study the cost versus the benefits of using ant control methodology. Spit Islet was an ideal location for this work due its small size and low numbers of native arthropods (Nishida and Beardsley 2002). We focused on the control of *S. geminata*. Our specific objectives were to (1) control and possibly eradicate the tropical fire ant, *S. geminata*, using the formicide Maxforce®; (2) monitor the groups of ground dwelling arthropods for non-target effects as proxies for native species; (3) document the time it takes for ant numbers to recover; and 4) monitor changes in species composition.

Study site and methods

Study site

Spit Island (Long: 177°4′20″ Lat: 28°5′31″) is the smallest of the three islets that comprise Midway Atoll. It is 6.07 ha and is located 190 m west of 148-ha Eastern Island and 850 m east of 452-ha Sand Island (Fig. 1). The island is flat (maximum height above sea level: 4 m) with dense vegetation dominated by *Scaevola sericea*, *Sesuvium portulacastrum*, and *Fimbristrylis cymosa* as well as introduced species including *Conyza bonariensis* and *Tournefortia*

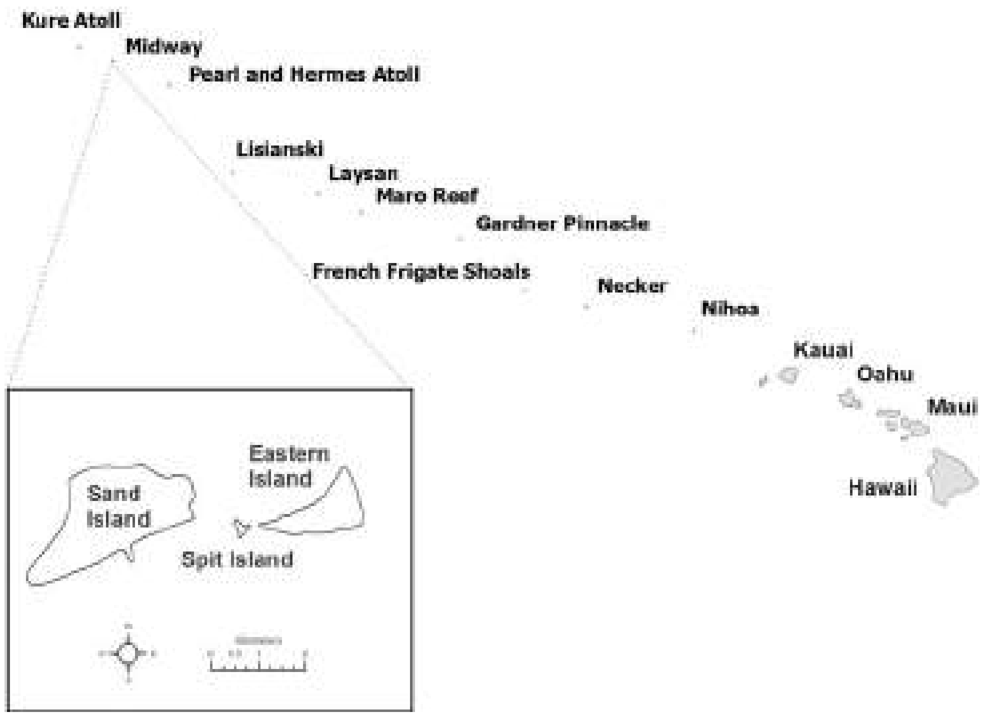

Fig. 1 Location of Midway Atoll where Spit Island (Long: 177°4′20″ Lat: 28°5′31″) was used to study the effects of the broadcast of MaxForce® (active ingredient: hydramethylnon) on tropical fire ant (*Solenopsis geminata*) populations

argentea. Arthropod surveys on the three islets comprising the atoll recorded a total of 546 species of which 455 (83%) were adventive or purposely introduced (Nishida and Beardsley 2002). Midway Atoll is a National Wildlife Refuge belonging to the United States Fish and Wildlife Service. Since the refuge's primary objective is to conserve wildlife, invasive species are of particular concern, and a considerable amount of time and resources are allotted to their management. A total of fifteen invasive ant species have been recorded from the three islets comprising the atoll.

Treatment protocol

The islet was treated with MaxForce® (active ingredient: hydramethylnon) twice, on 24, 25 August 2001 and 12, 13 September 2001. Prior to application, transects were established at 3-m intervals across the islet and marked with surveyor flagging. It was relatively easy to move around the islet, however transects bisecting dense thickets of *S. sericea* were cleared with a machete. Three people applied bait along transects using hand-held "Whirley-bird" spreaders and treated areas were marked with additional flagging. The formicide was applied at 1.7 kg/ha (1.5 lb/acre).

Arthropod sampling

We measured the relative abundance of ant species using 7.6 cm × 12.7 cm index cards with peanut butter, honey and SPAM® placed centrally on the card as attractants. We placed ten cards every 50 m along a 450 m transect bisecting the islet, once before and nine times during the 12 month period following the initial broadcast of Maxforce®. Bait cards were placed two additional times, 65 and 73 months following the initial broadcast. Cards were collected after a minimum of 1 h and placed in zip lock bags. Ants were then counted and identified in the lab. Between 23 March–30 August 2002 two additional cards were placed approximately 50 m on either side of the ten standard stations along the transect. To standardize these different collection methods, we only used data from cards placed along the transect in our analyses. However, additional data gathered from cards not directly on the transect were used to denote presence/absence of species.

We monitored abundance of ground-dwelling arthropods using pitfall traps (diameter: 7.5 cm, depth: 7 cm). Each pitfall trap was ¾ filled with water and a few drops of surfactant. Pitfall traps were set in pairs at the same 10 transect points used for bait card sampling. Pairs were placed on either end of a 30.5 cm (12 inch) plastic drift fence designed to direct arthropods into the traps. Traps were operated for 24 h and collected on 21 August 2001, 21 September 2001, and 25 September 2002. N. Reimer, M. Richardson and S. Plentovich identified ants (Hymenoptera: Formicidae). Entomologists at Bishop Museum identified non-ant arthropods collected in pitfall traps. Voucher specimens of all species were deposited in the entomology collection at the Bishop Museum.

Table 1 Mean abundance ± standard error of common (i.e., those occurring in at least 30% of the sampling points) orders of non-target arthropods collected in pairs of pitfall traps set at ten points 1 day before and 30 days after application of MaxForce® on Spit Island, Midway Atoll

Order	Before ($n = 10$)	After ($n = 10$)	Occurrence in traps	Significance
Acari	0.3 ± 0.15	1.5 ± 0.73	7	
Araneae	0.1 ± 0.1	2.2 ± 0.68	8	
Blattaria	8.4 ± 2.3	0	8	*$U = 18.0$, $df = 9$, $P = 0.008$
Coleoptera	0.4 ± 0.22	0.5 ± 0.22	7	
Hymenoptera	49.4 ± 7.5	1.4 ± 0.42	17	**$U = 22.5$, $df = 9$, $P = 0.004$
Hemiptera	0.5 ± 0.22	5.2 ± 2.26	13	
Orthoptera	11.6 ± 3.12	0.60 ± 0.499	12	**$U = 27.5$, $df = 9$, $P = 0.002$

Solenopsis geminata was excluded from Hymenoptera due to the focus on non-target effects

* Marginally significant, but potentially biologically meaningful results. Statistical significance required a *P*-value of <0.007 following Bonferroni's adjustment

** The null hypothesis of no mean difference between the two sampling periods was tested using a Wilcoxon signed-rank test. We corrected for multiple comparisons using Bonferroni's adjustment

Statistical analysis

Data from bait cards were used to determine the effectiveness of Maxforce® in reducing both the relative abundance of all ant species and of *S. geminata*. Standard least squares mixed-model ANOVAs were used with point and presence or absence of Maxforce® application as main effects and relative abundance as the response variable. We considered differences to be significant at an alpha of <0.05. To assess the effects of Maxforce® on non-target arthropods we used data from pitfall traps set on 21 August 2001 and 21 September 2001. Data from pairs of pitfall traps were pooled at each point. To maximize statistical power and biological relevance, only the most common orders were tested [i.e., those occurring in >30% ($n = 6$) of traps, Table 1]. A Wilcoxon Signed-rank Test was used to test the null hypothesis that there was no difference between the mean abundance of arthropods collected in pitfall traps on 21 August 2001 and 21 September 2001. *P*-values were adjusted for multiple comparisons using Bonferroni's adjustment (Miller 1981). Average values are given as mean ± standard error. We considered differences to be significant at an alpha of less than 0.007 for these tests. All tests were performed using JMP version 8 (SAS Institute Inc.).

Results

Ant control

The application of MaxForce® resulted in declines in the total abundance of ants present on Spit Island according to data collected from bait cards (Standard least-squared mixed-model ANOVA: F-ratio $= 17.8$, $df = 1$, $P < 0.0001$, Fig. 2) and pitfall traps (Wilcoxan signed-rank test, $U = 27.5$, $P = 0.002$, Fig. 3). Total abundance remained suppressed for more than 12 months (Fig. 2). Abundance of the target ant species, *S. geminata*, declined following the application of MaxForce® on bait cards throughout the 73-month sampling period (Standard least-squared mixed-model ANOVA: F-ratio $= 27.0$, $df = 1$, $P < 0.0001$, Fig. 2). A total of 760 individuals were recorded on 3 of the 10 bait cards prior to application. The species was not recorded again until 20 August 2002 when it was found in small numbers outside of the standardized sampling area. *S. geminata* was numerically dominant on all bait cards

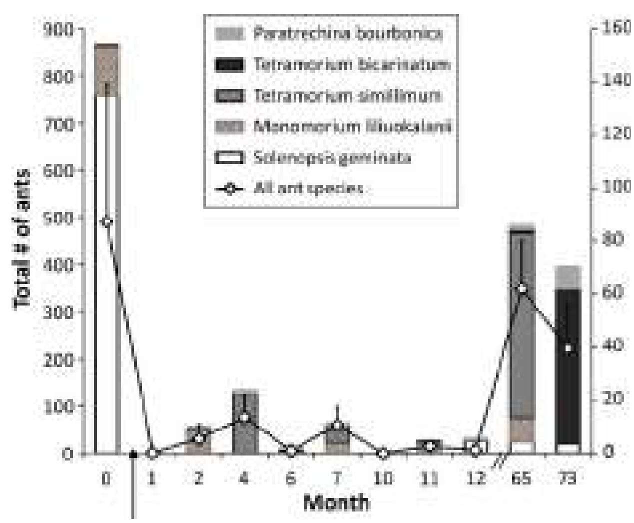

Fig. 2 Comparison of total number of each ant species (1st *vertical axis*) and average number of ants + standard error (2nd *vertical axis*) collected at ten bait cards before (Month = 0) and after (Month = 1–73) application of MaxForce® on Spit Island, Midway Atoll. MaxForce® was broadcast on 24, 25 August 2001 and again on 12, 13 September 2001 (see *arrow*)

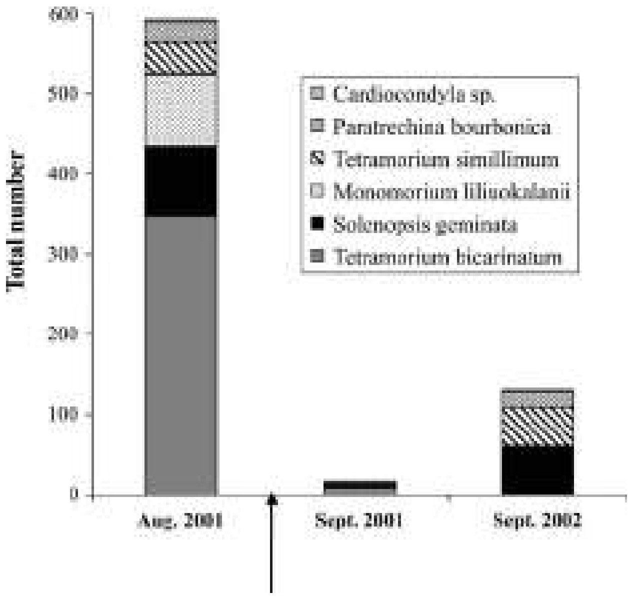

Fig. 3 Total number of ants by species present in pitfall traps ($n = 10$) before (August 2001) and after (September 2001 and 2002) two applications of MaxForce®. MaxForce® was broadcast on 24, 25 August 2001 and again on 12, 13 September 2001 (see *arrow*). Pitfall traps were operated for 24 h and collected on 21 August 2001, 21 September 2001, and 25 September 2002

where it was present, however, it was not common in pitfall traps. For example, only 87 individuals were recorded in three traps prior to treatment and three individuals were recorded in one trap 1 month after treatment (Fig. 3). Using these data, we did not detect a significant decrease in abundance (Wilcoxon Signed-rank Test: $U = 3$, $df = 1$, $P = 0.12$).

Non-target effects

Including Hymenoptera, non-target effects were quantified for seven of the most commonly represented arthropod orders (Table 1). When the target species, *S. geminata* was removed from the Hymenoptera data set, the total abundance of non-target ants declined following the application of MaxForce® (Wilcoxan signed-rank test, $U = 22.5$, $df = 9$, $P = 0.004$) in pitfall traps (Table 1), but not bait cards. The decline in pitfall traps was likely driven by significant declines in *T. bicarinatum* (Wilcoxan signed-rank tests, $U = 26.5$, $df = 9$, $P = 0.004$), which was the most common ant recorded in pitfall traps (present in 9 of 10 traps). Unlike *S. geminata*, this species was uncommon on bait cards until May 2007. A total of three individuals were recorded on one bait card prior to treatment. The species was then absent from bait cards until 2007 when seven were recorded on two bait cards in May and a total of 340 individuals were recorded on four bait cards in September (Fig. 2).

We also observed significant declines in Orthoptera, which was represented solely by crickets (Family: Gryllidae, Wilcoxon Signed-rank Test: $U = 27.5$, $df = 9$, $P = 0.002$). We observed marginally significant declines in Blattaria (Wilcoxon Signed-rank Test: $U = 18.0$, $df = 9$, $P = 0.008$). Although cockroaches (*Blattella* spp.) were collected in eight of ten traps prior to application, no cockroaches were collected in 21 September 2001, 1 month after application (Table 1). Four individuals of another cockroach species (i.e., *Simploce pallens*) were collected in two traps on 25 September 2002, 1 year after application. The tropical house cricket, *Gryllodes sigillatus*, was the sole representative of the order Orthoptera. Although this species was negatively affected by the broadcast of MaxForce®, there was no difference in pre-treatment abundance when compared to data from pitfall traps collected in September 2002, a year after the broadcast (Wilcoxon Signed-rank Test: $U = 13.5$, $df = 9$, $P = 0.19$).

Discussion

Ant control

The absence of *S. geminata* from bait cards set on Spit Island over an ~12 month period following the application of MaxForce® and the absence of *T. bicarinatum* for more than 65 months suggests that MaxForce® may be an effective way to control these two species. As observed in other studies, the application of hydramethylnon reduced target ant abundances within 1 month of application (Su et al. 1980; Taber 2000; Plentovich 2010). Although an initial reduction in ant abundance is commonly observed following application of hydramethylnon (the active ingredient in both MaxForce® and AMDRO®), most species of invasive ants are notoriously difficult to eradicate with the exception of *Pheidole megacephala* (Holway et al. 2002; Hoffmann and O'Connor 2004; Plentovich 2010). In other studies, AMDRO® has been used to temporarily reduce abundance of *S. geminata*, however the use of this bait alone has yet to achieve an eradication of this species (Hoffmann and O'Connor 2004; Plentovich 2010). In the absence of more thorough sampling on our study site, we can only conclude that application of MaxForce® can reduce abundances and could potentially eradicate small, isolated populations of these species.

Ant populations can fluctuate dramatically in response to changes in weather patterns, vegetation, and colonization by certain species that facilitate increases in ant abundance (e.g., scales and aphids; Greenslade 1971; Bach 1991; O'Dowd et al. 2003). Dramatic changes in ant abundance have also been observed following direct management actions such as the eradication of rats (*Rattus* spp., Feare 1999) and other invasive ants (Plentovich 2010). We observed pronounced changes in ant community composition on Spit Island prior to and in response to our ant control effort. *S. geminata* was not detected on the islet in 2000 (Swenson, per. obs.), however it was numerically dominant on bait cards prior to the first application in August 2001 (Fig. 2). Following treatment, *T. similimum* was consistently present until 69 months post treatment when its population increases dramatically. At 73 months post treatment *T. bicarinatum* was the most abundant species (Fig. 2).

Interestingly, *T. bicarinatum* was numerically dominant in pitfall traps prior to application in August 2001 when compared to *S. geminata* (347 vs. 87 individuals respectively). This pattern was reversed on bait cards set during the same sampling period. On bait cards, *S. geminata* was numerically dominant compared to *T. bicarinatum* (3 vs. 760 respectively). Lab experiments demonstrate high degrees of agonism among some ant species that result in one species suppressing or excluding others from resources (Kirschenbaum and Grace 2008). Numerical dominance of *S. geminata* on bait cards may be the result of its superior ability to monopolize resources compared to *T. bicarinatum*.

Non-target effects

Our data indicate that MaxForce® may negatively affect cockroaches (Order Blattaria) and crickets (Orthoptera: Gryllidae) in addition to other ant species such as *T. bicarinatum*. Although common in pitfall traps prior to treatment, cockroaches in the genus *Blattella* were not detected in pitfall traps set in September 2001 or a year later in 2002. Conversely, cricket abundance appeared to recover within 1 year of application. In a study from islets offshore of the main Hawaiian Islands, the application of AMDRO® reduced densities of cockroaches, but not crickets on treatment versus control sites (Plentovich 2010). Hydramethylnon, which is known to negatively affect cockroaches (Order Blattaria, Milio et al. 1986), is the active ingredient in both AMDRO® and MaxForce® (Stanley 2004). The two products differ in the primary nutrient of the bait carrier (lipid vs. protein) and the concentration of hydramethylnon (0.73 vs. 1%, Stanley and Robinson 2007). Negative effects on crickets may be associated with a preference for the bait carrier used in MaxForce® versus AMDRO®. These results could also be due to a number of different context-dependent issues. For example, food scarcity or arthropod densities could enable crickets to monopolize bait on Spit Island compared to offshore islets around Oahu. It is also possible that crickets are secondarily ingesting the bait via dead arthropods. Regardless, how much bait is available to different groups and which groups find the bait attractive may vary from site to site.

Although we did not detect non-target effects on other members of the arthropod community, there is a possibility for species-level effects that were masked by our coarser, order-level analyses. The lack of significant numbers of native arthropod species on Spit Island was advantageous in that we could test the effects of MaxForce® on an almost purely alien community; however it is also a disadvantage in that we do not know specifically how the toxicant affects native species. Thus, based on our findings, we can only hypothesize that native coastal crickets, such as those in the genus *Cacnomobius* (Orthoptera: Gryllidae) and potentially other native detrivitores may be negatively affected by the broadcast of hydramethylnon.

Until we have a better understanding of how the eradication of invasive ants can be achieved and how it affects ecosystems, it is difficult to predict the outcome of such actions (Bergstrom et al. 2009; Plentovich 2010). Future invasive ant management efforts must involve careful consideration of the ecological cost versus the benefit of broadcast of formicides in the context of ecosystem management and restoration. Prudent management will involve intensive monitoring of species and abundances in sensitive areas and aggressive, organized eradication campaigns at the onset of isolated invasions.

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