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Technical Report 109

Efforts at Control of the Argentine Ant in Haleakala National Park, Maui, Hawaii

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ABSTRACT

The Argentine ant, *Linepithema humile* (Mayr), has proven to be a threat to native arthropod species in Haleakala National Park, and is also a potential threat to the park's native flora. As it continues to expand its range, an effort has been undertaken to eradicate it, or at the least, control its spread. During a year-long bait preference test implemented at each of the ant's two infestation sites, the commercially available Maxforce granular ant bait from the Clorox Corporation was found to be the most attractive and feasible bait for large scale control. Subsequently Maxforce, which is formulated with 0.9% hydramethylnon, was used in test plots to determine the efficacy of the bait in the field. Initially, Maxforce was tested at two application rates: broadcast at 2lbs/acre and 4lbs/acre. Later, the following treatments were also tested: a Maxforce and honey granule mix, Maxforce with 0.5% hydramethylnon, Maxforce with a different solvent, Maxforce distributed in exposed piles, and Maxforce distributed in covered piles. While there were significant differences in the magnitude of ant reduction among the various treatments, all yielded the same general result. Foraging ant numbers at monitoring bait stations declined an average maximum of 97.0% in the test plots, with no plots achieving 100% reduction. At two months post treatment the average number of foraging ants was still reduced by 92.1%. Nest survival in the plots was impacted to a lesser degree, and was difficult to measure accurately due to the occurrence of nest movement. Nevertheless, data showed no significant differences in the rates of nest survival between the treatments after two months. A second identical application in plots treated with Maxforce at 2 and 4lbs/acre did not result in eradication. Bait attractiveness and a small window of foraging opportunity were judged to be the main obstacles in achieving total eradication. The next step in Argentine ant investigations at Haleakala should test the effectiveness of treating range margins with Maxforce for preventing or slowing range expansion.

INTRODUCTION

Ants in Hawaii

The Hawaiian Islands is one of only a few areas in the world which possesses no native species of ants (Wilson and Taylor 1967). They make up the most isolated island chain in the world, located over 3000 km from the nearest continent, and apparently ants were never able to successfully cross this formidable barrier. The extreme isolation of the islands insured that very few colonizers made it (Loope and Mueller-Dombois 1989), resulting in a very co-evolved biota that is highly adapted for the particular conditions and array of species that survived. Arthropod predators have been limited mainly to birds, spiders and other arthropods with relatively low voraciousness. In short, nothing with the predatory capability of ants helped shape native arthropod defense mechanisms.

Today, over 40 species of ants have been collected in the Hawaiian Islands, and a large percentage of these have become naturalized (Huddleston and Fluker 1968; Reimer et al. 1990). The vulnerability of native arthropods to ant predation has been well documented (Cole et al. 1992; Gillespie and Reimer 1993), and as early as 1913 the naturalist Perkins remarked on the dramatic effects of ants on the arthropod fauna: "As with the birds, destruction of forest has, doubtless, caused the disappearance of many local insects, but even of greater importance has been the introduction of foreign carnivorous species, especially of the dominant ant, *Pheidole megacephala*...This native fauna, especially of beetles, appears as if by magic, the moment the limit of range of *Pheidole* is reached" (Illingworth 1917).

While many of these introduced ants have proven to be low-impact cryptic species, a handful have become serious problems. Undoubtedly the most destructive species from an environmental perspective are the big-headed ant, *Pheidole megacephala* (Fabricius), the long-legged ant, *Anoplolepis longipes* (Jerdon), and the Argentine ant, *Linepithema humile* (Mayr) (Reimer et al. 1990). Typically, the effects of alien ants have been limited to sea level and lowland areas of the islands (Fellers and Fellers 1982). The big-headed and the long-legged ants fit this category. The long-legged ant seems to thrive in low-elevation areas, both wet riparian zones and drier habitats, while the big-headed ant appears to prefer drier habitats, although it too can be rather ubiquitous below 1200 m elevation (Reimer et al. 1990). Both species are prevalent in disturbed or non-native systems, as almost all of Hawaii's lowland areas have either been developed or are dominated by introduced species (Moulton and Pimm 1986).

The Argentine ant, however, differs in the fact that it has become established at higher elevations, and therefore has invaded largely intact natural areas (Cole et al. 1992). It has reached all the main islands, but apparently has been extirpated from the relatively low-elevation island of Oahu by the big-headed ant (Reimer pers. comm.). On the island of Hawaii, though largely unmonitored, *L. humile* has been recorded up to elevations of 2520 m (Wetterer et al. in press). On Maui, the Argentine ant reaches 2830 m in Haleakala National Park (Cole et al. 1992). Not only do these higher elevation populations put *L.humile* into undisturbed native habitat, but they also take it out of the range of other dominant alien ants. While Haleakala National Park has two introduced species of ants in addition to the Argentine ant, *Cardiocondyla venustula* (Wheeler) and *Hypoponera opaciceps* (Mayr), these are both low-impact, low-density species that are not observed interacting with *L. humile* (Krushelnycky and Reimer pers. obs.; Fellers and Fellers 1982). Therefore, the Argentine ant on Maui not only has found a home inhabited by arthropods unadapted and vulnerable to ant predation, but in Haleakala National Park it is also effectively free from competition from other species of ants.

The Argentine Ant

Formerly known as *Iridomyrmex humilis* (Mayr), the Argentine ant has been renamed *Linepithema humile* by Shattuck (1992) in his revision of the genus *Iridomyrmex*. Characterized as an aggressive, polygynous tramp species native to South America, the Argentine ant has proven to be a pest in various areas of the world, including the Caribbean, western Australia, Bermuda, South Africa, the Mediterranean, Hawaii and California (Holldobler and Wilson 1990). As such, much work has been done in these places to determine the biology, habits, and ecology of the ant. Little, however, has been done in its native range. From studies in southern France, California and Louisiana, it has been learned that *L. humile* is both polygynous (having multiple queens per nest) and polydomous (having multiple interconnected nests per colony) (Markin 1968; Keller 1988; Newell 1909). It displays little or no intraspecific aggression, resulting in the formation of large, continuous unicolonies (Markin 1968). Because it is polydomous, it can be difficult to define individual nests or colonies, with nests often interconnected and workers moving freely among them. Each nest contains multiple queens, with an entire population possessing thousands of queens (Krushelnycky pers. obs.).

As queens of the Argentine ant do not participate in nuptial flights, dispersal is achieved through colony budding (Newell 1909). Gynes mate with one alate male in their nest, lose their wings shortly thereafter, and remain in the nest (Keller and Passera 1992). This results in the polygynous nest structure. Males may or may not fly out of their nest to pursue a virgin queen, apparently depending on the number of available unmated queens in their own nest (Passera and Keller 1994). While gynes may mate with nestmate males, inbreeding is avoided by the practice of virgin queens preferentially mating with non-sibling males (Keller and Passera 1993). Genetic studies have shown that the level of relatedness within the Argentine ant nest is low (Kaufman et al. 1992), unlike monogynous colonies. Genetic heterogeneity and the presence of multiple queens per nest are believed to be the main factors permitting *L. humile* to form large uni-colonies devoid of intraspecific aggression.

Unlike some polygynous species, all queens in the Argentine ant nest are fertile and actively produce eggs (Keller 1988). At times, a queen may leave its nest and, with a retinue of workers, form a new nest. This budding and expansion process is apparently dependent on several factors, including nest density, resource status, and abiotic conditions. Argentine ants are constantly moving nests. Colonies expand into new areas or fuse to form larger nests, taking advantage of and reacting to ever-changing conditions (Markin 1968). The workers that tend to the queen and brood are monomorphic and are also responsible for nest defense and resource allocation (Newell 1909). While trail-forming and homopteran-tending appear to be infrequent behavioral practices in the Haleakala populations, in other locations foraging workers often form dense trails to food sources, and are often reported tending aphids and other homopterans (Markin 1968). Economically, much attention has been directed at this homopteran-tending behavior. Aphids and scale insects are often agricultural pests, and the tending of them by ants for the honeydew produced prevents effective biocontrol of the homopterans (Markin 1968). In addition, homeowners in California and elsewhere consider this ant a pest (Knight and Rust 1991; Forschler and Evans 1994), driving another sector of the insecticide and pest control industry.

Ecologists have also concentrated on the impacts of the Argentine ant. In virtually every area where it has become established, *L. humile* has displaced the native ant fauna. In South Africa, Bond and Slingsby (1984) have shown that this results in the disruption of a native ant-plant mutualism, and severely decreases seed dispersal and establishment in the fynbos. In Hawaii, Cole et al. (1992) have demonstrated the effects of the ant's presence and predation on the native arthropod fauna, and have predicted that this could have a significant impact on native plant reproduction, as some of the affected insects are major pollinators of native plants.

The Argentine Ant in Haleakala National Park

The spread of the Argentine ant in Haleakala National Park has been loosely monitored since its first record in 1967 (Huddleson and Fluker 1968), and has been studied more intensively over the past decade (Beardsley 1980). At the time of its discovery in the park, a relatively small infestation was limited to the areas adjacent to the Park Headquarters buildings. Fellers and Fellers (1982) speculated that the Argentine ant required these buildings for shelter during Haleakala's harsh winters, and that the population's range was knocked back in the winter months. This, however, has not proven to be the case, and by the mid 80's, two distinct populations had become established at two different elevations on Haleakala's upper western slopes (Medeiros et al. 1986, Cole et al. 1992). The lower population, at an elevation of 2070-2260 m, was a direct expansion of the original infestation around park headquarters, and had grown to an approximate area of 292 hectares. Meanwhile, a second smaller population of approximately 26 hectares became established at 2740-2830 m (derived from Cole et al. 1992). This is believed to be the result of human activity, as the upper elevation population is centered around a visitor overlook and parking lot.

At the site of the lower ant population on Haleakala volcano, the terrain is characterized by mixed cinder and soil, with an abundance of interspersed volcanic rock, rock ridges and flows. The vegetation consists of dense shrubs and small trees, with a ground cover of grasses, sedges, ferns and exotic herbs (Appendix 1). The native shrubs mamane (*Sophora chrysophylla*)[1] and kupaoa (*Dubautia menziesii*) both produce yellow showy flowers, as do the introduced weedy herbs evening primrose (*Oenothera stricta*) and hairy cat's ear (*Hypochoeris radicata*). All of these appear to be major nectar sources for the Argentine ant (Krushelnycky per. obs.). The site of the higher elevation ant population has a terrain with poorly developed soil and is dominated by cinder, volcanic rock and rocky cliffs. Vegetation is considerably more sparse and stunted. Four natives make up the shrub composition, dominated by pukiawe (*Styphelia tamieameiae*) and

[1] Nomenclature for vascular plants follows Wagner et al. (1990) and Wagner and Wagner (unpubl.)

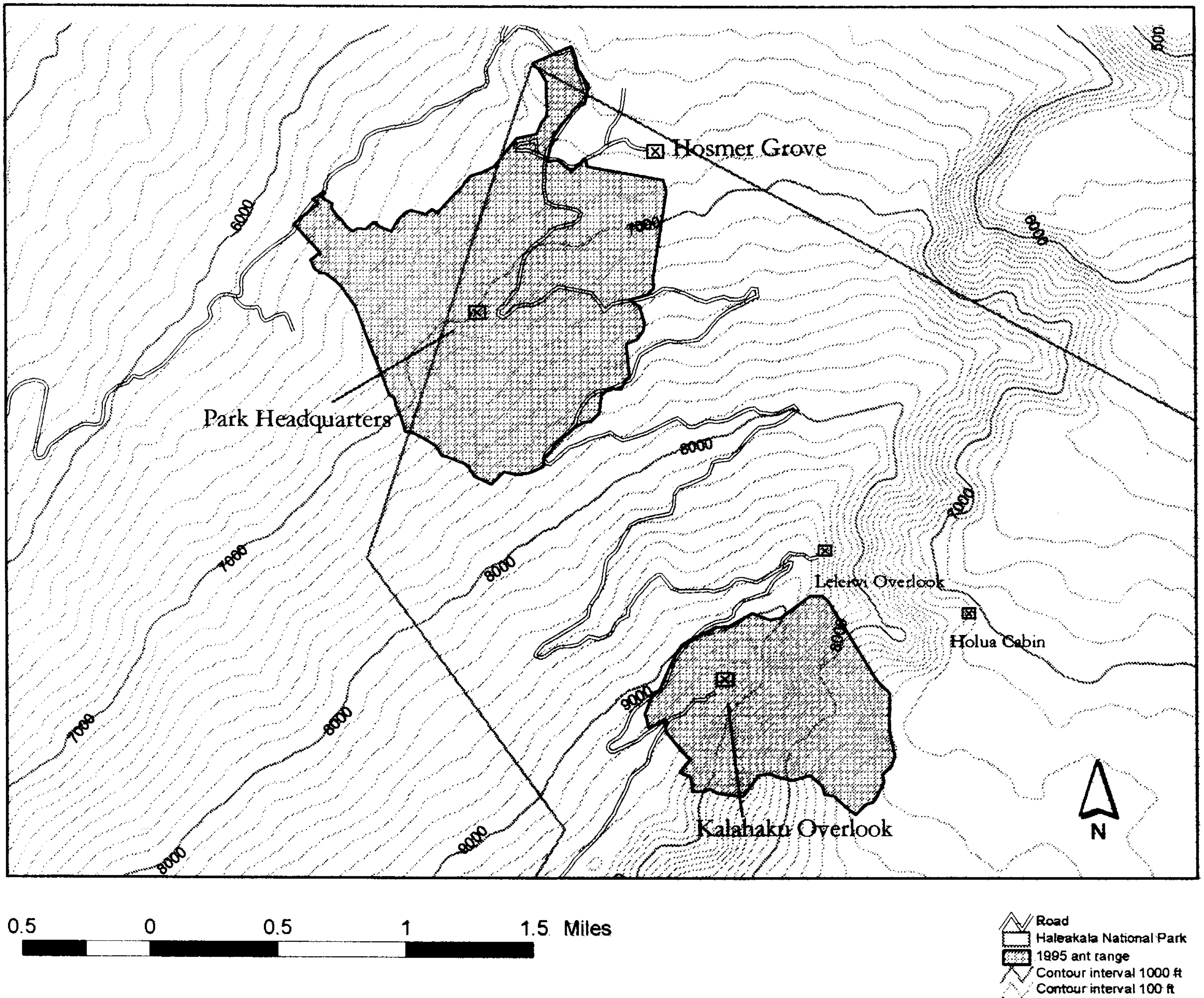

Figure 1 - The two populations of *L. humile* in Haleakala National Park

kupaoa (*D. menziesii*), and herbs, grasses, sedges and ferns make up most of the remaining scattered vegetation (Appendix 2). Some areas, however, are dominated by relatively dense bunchgrass fields (*Deschampsia nubigena*).

Climatic conditions on Haleakala can be rather extreme, particularly at the higher elevations. Mean monthly air temperatures at 2100 m elevation and 3000 m elevation are shown in Table 1. Temperatures can fluctuate greatly, varying from day to day or from hour to hour. A change of 15° C in a given day is not unusual, and during winter months, frost and ice overnight are not uncommon. Occasionally, winter snow storms blanket the mountain in areas above 2700 m. Alternately, the intense sun can produce hot and dry conditions on any day of the year. At high elevation, this can cause the exposed soil surface temperature to soar. While the relative humidity near the summit can be very low (often between 10 and 20%), low clouds and mist are common. This provides moisture to the otherwise dry habitat, and only during heavy rains is running water existent. Winds on Haleakala can also fluctuate greatly. While steady trade winds usually create at least a slight breeze, wind speeds can often reach 30-35 km/h, and occasionally attain speeds of 100-150 km/h. Despite these extreme, quickly changing conditions, the Argentine ants have been able to persist, reproduce, and expand.

Table 1 - Mean monthly air temperatures on Haleakala (°C)

Elevation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2100m	11.1	10.6	10.6	11.3	12.0	13.7	13.8	14.3	13.6	12.7	12.7	12.3
3000m	7.5	6.3	6.8	8.6	9.2	10.6	10.2	10.6	9.8	9.8	8.5	8.8

Cole et al. (1992) used pitfall trapping and under-rock surveying to assess the impact of the Argentine ant on the arthropod fauna in the two ant populated areas of upper Haleakala in 1985-1986. While studies elsewhere have suggested that the ant is most attracted to sugar sources such as honeydew (Baker et al. 1985, Markin 1970a), the results of this study show that in areas infested with ants, numbers of native as well as non-native arthropods are significantly reduced. Adult flightless forms and larval stages of flighted insects seem to be most vulnerable. As the native plants of upper Haleakala are predominantly insect pollinated, this has obvious implications on native plant reproduction as well. Two plants potentially affected are the federally threatened Haleakala silversword (*Argyroxiphium sandwicense macrocephalum*), and kupaoa (*D. menziesii*). These closely related members of the aster family (Asteraceae) have been found to require cross-pollination for seed set (Carr et al. 1986). The larval stages of the native ground-nesting solitary bee (*Hylaeus*) and noctuid moths, some of the major pollinators of these and other plants, appear to be heavily impacted by the Argentine ant (Cole et al. 1992).

Fluctuations in the area and density of the populations have occurred over the past decade. Through the mid to late eighties, both populations remained vigorous. However in 1988-89, a rather dramatic decrease occurred in the lower population, while the upper elevation remained relatively constant. Since then, both populations have been expanding their territory. In 1995-6, another survey was carried out to determine more accurate boundaries of both populations (Figure 1). Analysis of this survey indicates that since 1984, the lower population has increased in area from about 292 hectares to 312 hectares, and the upper elevation population spread from about 26 hectares to 141 hectares. The expansion of the upper population carried the ants over the crater rim, down the crater walls, and to the crater floor for the first time. Based on current observations of habitat already occupied by the Argentine ant, much of the crater would seem to be suitable for the ants' survival and colonization (A. C. Medeiros pers. comm.; Fellers and Fellers 1982).

The Project

Due to the persistent advance of the Argentine ant in Haleakala National Park, the Research Division (now a unit of the National Biological Service) began investigating a control strategy for the pest. As biological control is not considered feasible, the program has studied toxicants as a possible method for control. Trophallaxis, the passing of regurgitated food among colony members, is a frequent behavioral practice of the Argentine ant and would allow an attractive bait to be shared with all nest members, both adult and larval stages (Markin 1970). The key therefore, is to formulate a highly attractive bait with a slow acting toxicant.

Because of the previously mentioned economic impact of the Argentine ant on the agricultural industry, much effort and research has gone into developing effective toxicants for its control in agricultural as well as domestic situations. Early work centered around chemicals applied with broadcast or spray treatments, such as DDT, chlordane and dieldrin (Jenkins and Forte 1973). These chemicals, however, were eventually outlawed due to environmental and health concerns, as were later toxicants such as diazanon, heptachlor, lorsban and Mirex (Haney 1984, Jenkins and Forte 1973).

In the wake of these unsuccessful or unsafe pesticides, the toxicant Amdro with the active ingredient hydramethylnon was developed by the American Cyanamid Corporation. This chemical was found to be effective against the red imported fire ant (*Solenopsis invicta* Buren) in pasture areas (Apperson et al. 1984) and the big-headed ant in pineapple fields in Hawaii (Su et al. 1980). Early tests of the efficacy of Amdro against the Argentine ant in California citrus groves by Gaston and Baker (1984) used the toxicant suspended in a 25% sugar water solution and found a 40-fold reduction in ant numbers on tree trunks. The toxicant was subsequently improved and formulated with several baits, one of which was a high protein silkworm-based granule found to be attractive to the Argentine ant. This bait, containing the active ingredient hydramethylnon, is marketed under the name Maxforce. It has been purchased by the Clorox Corporation and has full EPA approval for certain domestic uses.

While early topical sprays were often concerned with reduction in foraging ant numbers (Jenkins and Forte 1973, Haney 1984), true control or eradication requires complete extermination of nests. Because the primary goal of the Argentine ant project at Haleakala National Park is at least localized eradication of the ant, complete elimination of nests is necessary. Maxforce bait is therefore an obvious choice, because the purported delayed toxicity of hydramethylnon allows the bait to be brought back and presented to the entire nest, including queens and brood. Additionally, Maxforce is an attractive option because of its low toxicity levels and short life span, making it a much safer pesticide than previous chemicals.

Previously, control of the introduced ant *Wasmannia auropunctata* (Roger) was achieved on Santa Fe island in the Galapagos using the bait Amdro, a corn-grit granular bait with hydramethylnon as the active ingredient (Abedrabbo 1994). While this control effort also took place in a natural area, the size of the infestation, estimated at 2 to 3 hectares, was considerably smaller than the one at Haleakala. Bait preference tests have been conducted for the Argentine ant in the lab and in citrus groves in California, and it has often been found to prefer sugar water over all other baits (Baker et al. 1985, Gaston and Baker 1984). Additionally, Forschler and Evans (1994) found that the commercially formulated Maxforce, hydramethylnon in a silkworm high-protein bait, was attractive to and effective against the Argentine ant in urban situations in Georgia. Because the sites of infestation in Haleakala National Park consist largely of undisturbed natural areas, however, regular food sources are much more unpredictable. For this reason it was deemed necessary to carry out an on-site bait preference test specific to the ants of Haleakala National Park.

The first part of the control effort, therefore, was a year-long bait preference test. This test was carried out in the field at each of the park's two Argentine ant populations to determine what types of baits are most attractive to the ants and how this preference changes seasonally. The best bait would then be formulated with 0.9% hydramethylnon for field testing and actual control. To accomplish this, the help of the Clorox Technical Center in Pleasanton, California was enlisted. As the manufacturer of Maxforce and other ant control products, they were able to provide us with the various baits to be tested, as well as with invaluable advice and financial support.

Critical to the program was the condition that the baits to be tested would be practical in a large scale broadcast control method. For instance, while sugar water has been found to be very attractive to the Argentine ant, this medium would not be the most practical for treating large and often fairly inaccessible areas. The resulting six baits represented both high protein and high sugar food sources, and were formulated in either a granular or doughy form. They were also tested against sugar water and water in order to compare their relative attractiveness in the field at Haleakala.

The second part of the control effort tested the efficacy of the best bait, chosen from the bait preference test according to attractiveness and feasibility in a large scale treatment program. The efficacy test investigated the effectiveness of the chosen bait with 0.9% hydramethylnon toxicant in eradicating ants in field test plots. This technical report presents the results of the bait preference test and the ensuing efficacy test at Haleakala National Park.

METHODS AND MATERIALS

Bait Preference Test

The bait preference test was carried out from June 1994 to June 1995. Eight baits were tested, all formulated without the active ingredient hydramethylnon. The eight baits were: Maxforce, the regular commercially available granular protein-based bait; honey granules, a high sugar granular bait; insect protein granules, a granular bait produced from silkworm pupae and without the additional ingredients making up Maxforce; honey doughy bait, a high sugar bait with a doughy constitution; high protein doughy bait; fish protein bait, a doughy bait produced from fish; sugar water, a 25% sugar water solution; and water (Table 2).

Two test sites were chosen, one in each of the two ant populations. The test site for the upper elevation population was located at 2835m in the Kalahaku area, while the test site for the lower elevation population was located at 2165m near park headquarters (Figure 1). At each site, five replicates of each of the eight baits were put out for a period of 24 hours during each bait test. Each of the five replicates consisted of eight small plastic petri dishes containing the bait, placed on the ground and covered with an inverted pie pan to protect the baits from direct rain, wind and rodents. Pieces of felt were attached to the inside of the pie pans to prevent moisture from collecting on the aluminum surface and dripping onto the baits. The sugar water and water baits were injected into small cotton balls to prevent spilling during transport and placement, yet were still readily available to foraging ants. Uneven ground surface allowed access to the inverted pans and the baits inside.

Each of the two test sites also had a corresponding control site, located just outside the range of each ant population. The purpose of the controls was to measure the effects of weather conditions on the weight of the baits over the 24 hour test period. Control sites were chosen to represent the microhabitat of the test sites as closely as possible, and had identical set ups, with five replicates of each of the eight baits. Each bait test therefore had four sites (two test and two control) and 20 replicates (five at each site) of each of the eight baits, for a total of 160 individual petri dishes per test.

Table 2 - Dates of bait preference tests and baits used

Bait Test #	Date	Baits Used
1	June 18, 1994	Maxforce
2	July 9, 1994	Honey granules
3	July 23, 1994	Insect protein granules
4	August 11, 1994	Honey doughy bait
5	August 24, 1994	High protein doughy bait
6	September 14, 1994	Fish protein bait
7	October 6, 1994	Sugar water
8	October 18, 1994	Water
9	November 18, 1994	
10	December 13, 1994	
11	January 18, 1995	
12	February 16, 1995	
13	March 17, 1995	
14	April 21, 1995	
15	May 16, 1995	
16	June 15, 1995	

Baits were weighed prior to placement on an Ohaus electronic balance, placed in the field in the morning, collected 24 hours later and weighed again. This process was repeated every two to four weeks over a period of one year, for a total of 16 bait preference tests (Table 2). Changes in weight of test baits were corrected with changes in weight of control baits to account for weather effects, resulting in the weight of bait taken by ants for each bait. Bait test data were normalized with the square root transformation and compared using an F-test to check for homogeneity of variances. Means of baits with similar variances were then compared with a two-tailed t-test for matched pairs.

Efficacy Test

A. Initial test

Following the year-long bait preference test, an efficacy test with Maxforce bait was begun in July of 1995. Maxforce bait with 0.9% active ingredient was first tested at two application rates: two pounds per acre and four pounds per acre. Each rate was tested with three replicate test plots in a high density ant area near the park headquarters. Three replicate control plots were also established, which received no treatment (Table 3). Test plots were 25m by 25m in size and were placed so as to represent the typical subalpine shrubland of the entire lower infested area.

Table 3 - Test plot treatment and survey information

Treatment #	Treatment	# of Replicate Plots	Treatment Dates	Nest Survey Dates
1	Regular Maxforce broadcast at 4lbs/acre	3	7/16/95 8/19/95	8/1/95 8/31/95 9/21/95 10/20/95
2	Regular Maxforce broadcast at 2lbs/acre	3	7/16/95 8/19/95	n/a
3	1:1 Mix of regular Maxforce and honey granules, broadcast at 4lbs/acre	1	8/24/95	9/12/95 9/25/95 10/24/95
4	Maxforce formulated with 0.5% hydramethylnon, broadcast at 4lbs/acre	1	8/24/95	9/8/95 9/25/95 10/24/95
5	Maxforce with 0.5% hydramethylnon and a different solvent, broadcast at 4lbs/acre	1	8/24/95	9/11/95 9/25/95 10/24/95
6	Regular Maxforce distributed in uncovered piles, 4lbs/acre	1	9/12/95	n/a
7	Regular Maxforce distributed in covered piles, 4lbs/acre	1	9/14/95	n/a
Control	No treatment	3	n/a	n/a

Pretreatment ant counts were conducted in all nine plots to establish baseline ant numbers. Five bait stations were placed in the center of each plot, separated by approximately two meters. Bait stations consisted of a fermented fish paste ("siganid") placed on one half of a 3" by 5" index card. Total number of ants on the card was counted roughly 45 minutes after placement. Test plots were first treated on July 16, 1995 by walking through the plots and broadcasting the granular bait with a standard Ortho "whirlybird" hand spreader. Plots were treated at dusk to minimize the bait's exposure to sunlight, as the active ingredient hydramethylnon degrades in UV radiation. Post-treatment ant counts were conducted every two days for approximately a week and a half and at less regular intervals subsequently.

Inspection of test plots about two weeks post-treatment yielded an unexpected finding. Bait was found molding in nests under rocks, making it clearly visible. Otherwise, the small granules are impossible to distinguish from the soil and cinder. Taking advantage of this fortuitous development, the three test plots treated at 4lbs/acre were surveyed for bait distribution by the ants. Fifty nests were located in two of the plots, and 43 in the third, that either had molding bait or were still active (defined as having either brood or a queen present) or both. Nests that only had workers visible and no bait were not counted, because it was impossible to determine whether the nest was dying from the treatment or whether it had moved the brood, queens and the majority of the workers prior to treatment. These same nests were surveyed again after the second treatment, one month after the second treatment and two months after the second treatment (Table 3). For each nest, information was recorded regarding the relative amount of visible bait, as well as whether the nest was active or inactive (defined as having no brood and no queens).

B. Subsequent tests

Maxforce test plots were treated a second time on August 19, 1995, at the original application rates. Ant counts at bait stations continued to be used as a means to measure ant numbers in the plots. Additionally, five new plots were set up to test the following new treatments: a mix of one half Maxforce granules and one half honey granules; Maxforce granules formulated with 0.5% hydramethylnon; Maxforce granules formulated with 0.5% hydramethylnon and a different solvent; Maxforce granules distributed in 25 piles, uncovered; and Maxforce granules distributed in 25 piles, covered (Table 3). In the two plots treated with piles of Maxforce, the piles were evenly spaced five meters apart in a grid. The plots were treated on the dates shown in Table 3.

Ant counts using bait stations were implemented to monitor ant numbers in the five new plots, and for the three plots utilizing broadcast treatment (not piles) nest surveys to detect bait distribution were conducted as described above. The first such survey was conducted roughly two to two and a half weeks post treatment, with the follow-up surveys one month and two months post treatment (Table 3). Casual checks of ant nests in all plots previously monitored in this fashion were conducted approximately four and five months post treatment. Ant count data were normalized by $\log_{10}(x+1)$ transformation and analyzed using an F-test to check for homogeneity of variances. Treatments with similar variances were then tested with either a one-way or two-way ANOVA, depending on whether the treatments had replicate plots. Means were subsequently compared with a Tukey Test for equal sample sizes or a Tukey-Kramer Test for unequal sample sizes (Sokal and Rohlf 1981). Nest observation data were analyzed using a chi-square contingency table.

RESULTS

I Bait Preference Test

Ants from both the lower (park headquarters) and the upper (Kalahaku) elevation populations took more Maxforce bait than any of the other baits (Table 4). Comparison of the amounts of bait taken by ants at the lower elevation using an F-test showed that the variance of the Maxforce data was different (at $P=0.05$) from those of all other baits except sugar water and the honey granular bait. Further comparison of the mean amount of Maxforce taken with the mean amount of sugar water taken indicated that this difference was not significant ($t=0.06$, $P>0.05$). In contrast, the mean amount of Maxforce taken was highly significantly greater than the mean amount of honey granular bait taken ($t=7.41$, $P<0.001$).

An F-test showed that for the upper elevation population data, the variance of the Maxforce data was different (at $P=0.05$) from those of all other baits except sugar water. Further analysis indicated that the difference between the mean amount of Maxforce bait taken and the mean amount of sugar water taken was not significant ($t=0.20$, $P>0.05$). Thus, at both the upper and lower elevation, the amount of Maxforce bait taken by ants was significantly greater than all other baits except sugar water.

Table 4 - Average amounts of bait taken by ants during the bait preference tests

	Lower Elevation		Upper Elevation	
Bait	Ave. Bait Taken (g)	Standard Error	Ave. Bait Taken (g)	Standard Error
Maxforce	0.74	±0.06	0.31	±0.04
Honey granules	0.26	±0.04	0.06	±0.01
Insect protein granules	0.16	±0.02	0.11	±0.02
Honey doughy bait	0.08	±0.01	0.01	±0.00
High protein doughy bait	0.14	±0.02	0.06	±0.01
Fish protein bait	0.19	±0.02	0.09	±0.01
Sugar water	0.70	±0.06	0.18	±0.03
Water	0.19	±0.03	0.06	±0.01

Most of the attractiveness of the baits was seasonal in nature. At the lower elevation, Maxforce was most attractive from mid-March to October, and at the upper elevation from mid-March to late August (Figure 2). The sugar baits had a similarly seasonal attractiveness. Sugar water remained attractive until mid-November at the lower elevation (Figure 2), but only until August at the higher elevation (Figure 4). The honey granular bait was much more attractive overall at the lower elevation (Figure 2), competing well with the Maxforce bait during the summer of 1994. Both populations showed a small increase in interest in the honey granules in November of 1994, somewhat later than Maxforce's period of attractiveness (Figures 2 and 4).

II Efficacy Test

A. Ant Counts

The average numbers of ants per bait station post treatment in the test plots were very low, regardless of treatment (Table 5). However, an F-test on the $\log_{10}(x+1)$ transformed data indicated that the ant count data for treatments 1, 2 and the control were different (at P=0.05) from the count data for treatments 3-7. These two groups of treatments were therefore analyzed separately.

Table 5 - Average number of ants per bait station after treatment

Trtmnt #	Treatment	Ave. # of Ants/Station	Standard Error
1	Maxforce at 4lbs/acre	2.59	±0.18
2	Maxforce at 2lbs/acre	2.07	±0.16
3	Maxforce/honey granule mix	1.85	±0.22
4	Maxforce w/0.5% hydrameth.	2.50	±0.24
5	Maxforce w/0.5% hydrameth. and a different solvent	1.25	±0.18
6	Maxforce in uncovered piles	1.60	±0.22
7	Maxforce in covered piles	2.64	±0.42
Control	No treatment	8.80	±0.48

A two-way ANOVA showed that for treatments 1, 2 (Maxforce at 4lbs/acre and Maxforce at 2lbs/acre) and control, there was no significant difference among the three replicates of each ($F_{2,801}$ =2.91, P>0.05). However, the differences between the two treatments and the control was highly significant ($F_{2,801}$ =205.68, P<0.001). Subsequent separation of means with a Tukey Test revealed that there was a small significant difference between the mean ant counts of the two treatments (Tcritical=0.064, difference between means=0.179), while there was a large significant difference between the 4lbs/acre treatment and the control (Tcritical=0.064, difference between means=1.343) and between the 2lbs/acre treatment and the control (Tcritical=0.064, difference between means=1.522).

Comparison of treatments 3-7 using a one-way ANOVA showed that the difference between the means of these treatments was highly significant ($F_{4,165}$ =5.84, P<0.001). Separation of means with a Tukey Test for equal sample sizes and a Tukey-Kramer Test for unequal sample sizes revealed that treatment 5 (mix of Maxforce and honey granules) was different from both treatment 4 (Maxforce with 0.5% hydramethylnon) and treatment 7 (Maxforce distributed in covered piles). All other treatments were not significantly different from each other.

All treatments exhibited the same general pattern: relatively high ant levels prior to treatment and a dramatic crash within several days post treatment (Figures 6-8). This crash can be quantified as an average of a 95.9% reduction in average number of ants per bait station in all plots two days after treatment. The maximum average reduction in number of ants in all plots reached 97.0%. In plots treated with Maxforce at 2 and 4lbs/acre, ant levels inched slowly back up to a 70.0% reduction until they were treated again, 34 days after the first treatment (Figure 6). All plots treated with scattered granular bait (not in piles) averaged a retention of 92.1% reduction two months after the latest treatment (Figure 6,7). Control plots had an average reduction of 48.3% in the average number of ants per station over the length of the study (Figures 6-8).

B. Nest Surveys

Approximately two weeks post treatment 49.6%, 75.6%, 44.0% and 44.0% of all surveyed nests were still active in plots treated with Maxforce at 4lbs/acre, Maxforce and honey granule mix, Maxforce with 0.5% hydramethylnon, and Maxforce with a different solvent, respectively (Figures 9-12). As a consequence of the bait molding, it was possible to determine that 72.0%, 26.8%, 64.0% and 60.0% of all nests surveyed had visible signs of bait retrieval in plots treated with the previously mentioned four treatments, respectively (Figure 14). However, not all nests that retrieved the baits became inactive. As shown in Figure 14, 43.7%, 3.2%, 18.2% and 9.1% of all active nests displayed visible signs of bait in plots treated with Maxforce at 4lbs/acre, Maxforce and honey granule mix, Maxforce with 0.5% hydramethylnon, and Maxforce with a different solvent, respectively.

After the plots originally treated with Maxforce at 4lbs/acre were treated a second time with an identical treatment, 23.1% of all the surveyed nests remained active (Figure 9). These active nests constituted 46.5% of the originally active nests in the plots. While 43.7% of all active nests had visible signs of bait retrieval after the first treatment (Figure 14), only 6.1% of all active nests had visible signs of bait after the second treatment.

One month post treatment (post second treatment for plots treated twice), the percentage of all nests surveyed that were still active decreased in all plots and for all treatments (Figures 9-12). However, they did not all have the same rates of nest survival (proportion of active to inactive nests), and it was determined that the differences in nest survival corresponding to the different treatments were highly significant at one month post treatment ($X^2_3 = 12.36$, $P<0.01$). Specifically, nest survival was higher in the plot treated with the Maxforce/honey granule mix, and was lower in the plot treated with Maxforce with 0.5% hydramethylnon (Figures 9-12).

Two months after treatment, the percentage of all nests surveyed that were found to be active decreased again in most of the plots (Figures 9-12). At this point, however, the differences in nest survival were not as great and were found to be not statistically significant ($X^2_3 = 1.78$, $P>0.05$).

Analysis of the patterns of nest survival in the plots revealed a rather consistent rate of nest mortality or movement during the time interval between surveys (Figure 13). Nests that were active on one check and inactive upon the next check were assumed to have either died or moved to a new site. At the same time, surveyed nests that were at one time inactive but were found to be active at a later date were assumed to have been recolonized by a live nest. As can be seen from Figure 13, there was often a considerable percentage of "newly active" nests (active nests that were previously inactive), indicating a fair amount of nest movement within the plots.

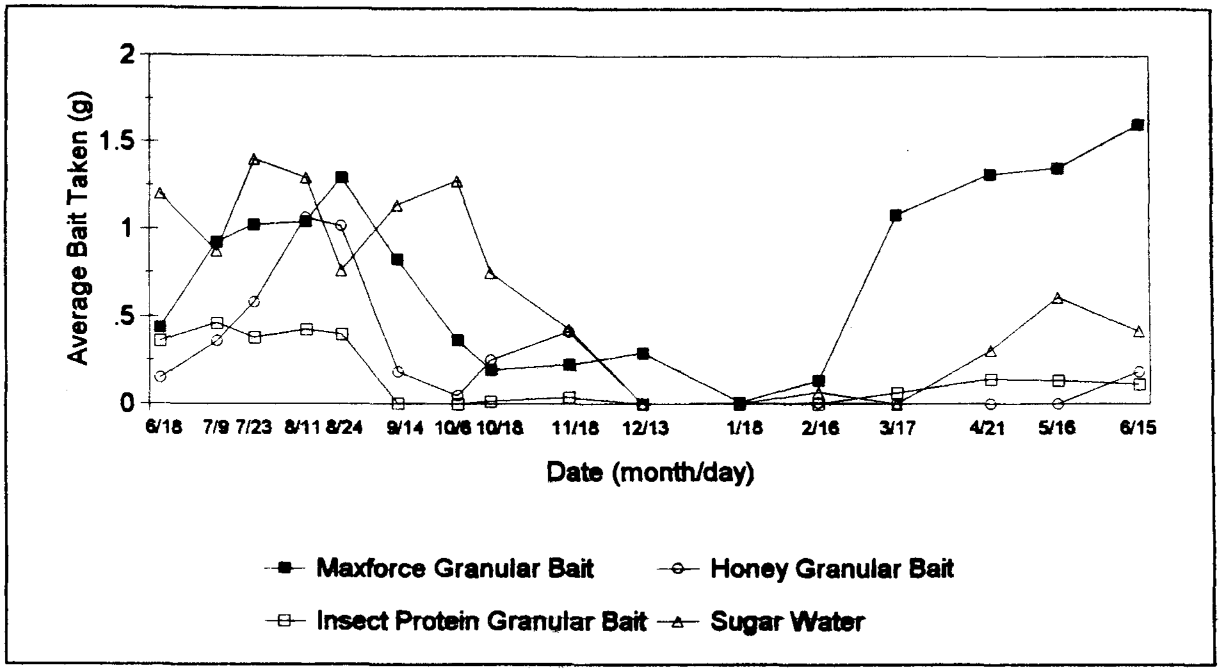

Figure 2 - Average amounts of the four most popular baits taken during each bait preference test at the lower elevation

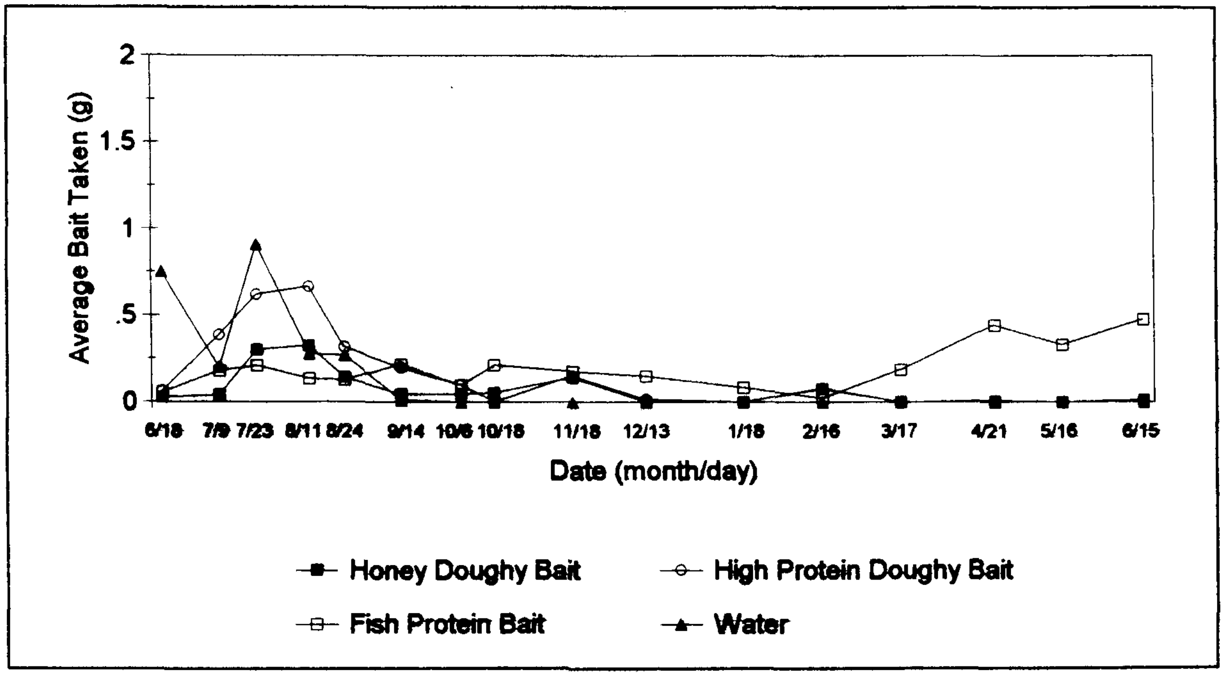

Figure 3 - Average amounts of the four least popular baits taken during each bait preference test at the lower elevation

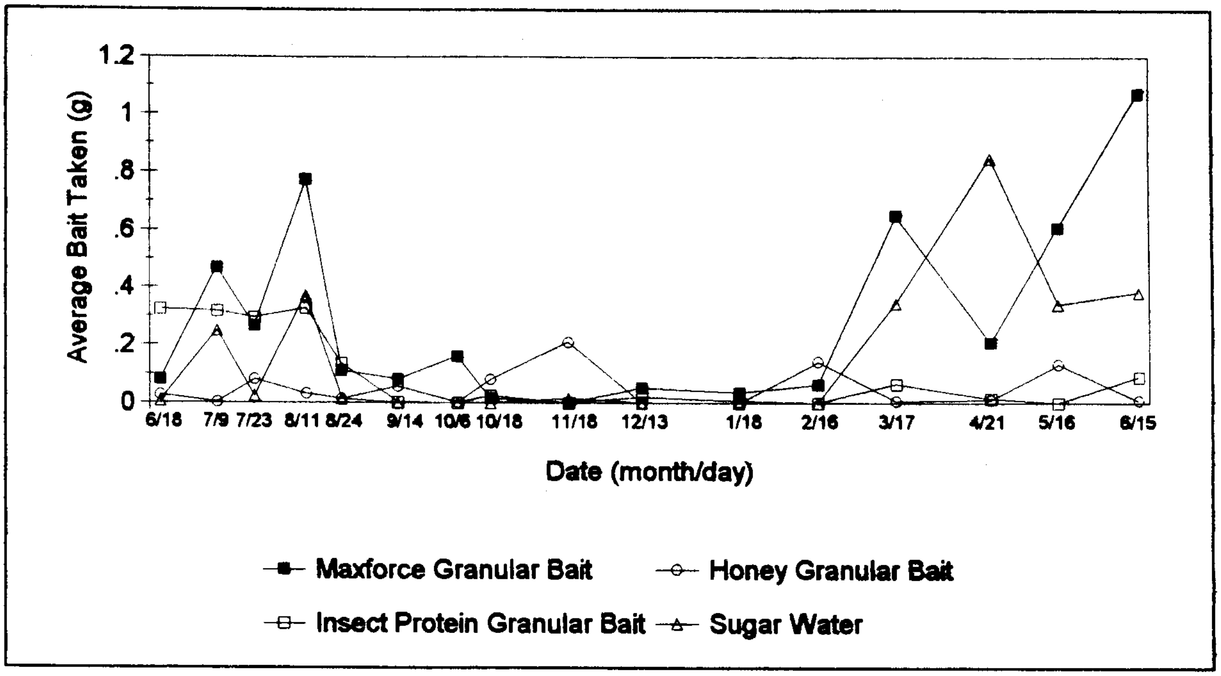

Figure 4 - Average amounts of the four most popular baits taken during each bait preference test at the upper elevation

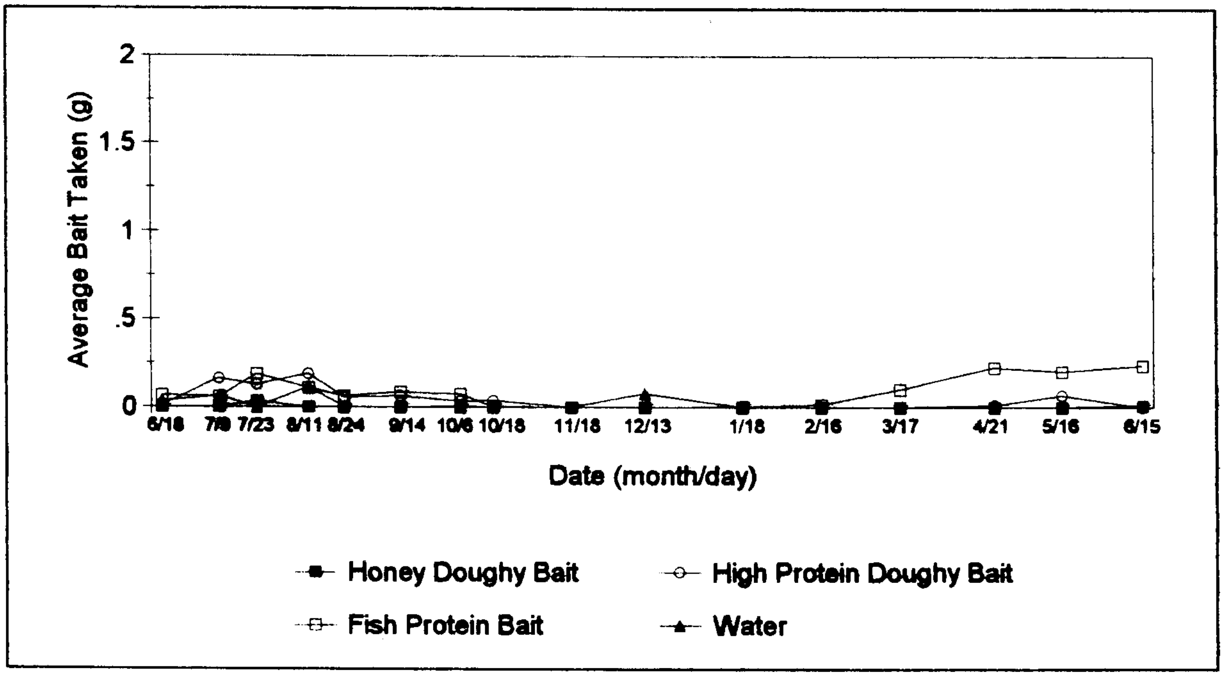

Figure 5 - Average amounts of the four least popular baits taken during each bait preference test at the upper elevation

DISCUSSION

A year of bait preference tests at the two sites of Argentine ant infestation at Haleakala National Park indicated that of the eight baits tested, the commercially available Maxforce bait was most attractive. Produced by the Clorox Corporation of Pleasanton, California, Maxforce is a granular protein bait consisting mainly of ground-up silkworm pupae and formulated with 0.9% of the active ingredient hydramethylnon. When formulated without this toxicant, more Maxforce was taken by the ants over the course of the 16 bait tests than any of the other baits (Table 4). This was true for both the upper and lower elevation ant populations. Maxforce out-performed such potentially attractive baits as honey granules, straight insect protein granules and fish protein bait. While it has been found that the fermented fish paste used for the efficacy test ant counts is very attractive to the Argentine ant at Haleakala, the fish protein bait formulated by Clorox for our bait preference tests was much less attractive, most likely due to loss of freshness and odor in manufacturing.

Maxforce was taken in even greater amounts than a 25% sugar water solution, although this difference was not statistically significant. This stands in contrast to the results obtained by Baker et al. (1985), where sugar water was much more popular than any protein solid bait tested with Argentine ants in the laboratory and in a citrus grove. The ant's large appetite for insect protein at Haleakala has previously been documented by Cole et al. (1992) in their efforts to measure the Argentine ant's impact on the native arthropod fauna.

Amount of baits taken by the ants typically displayed a strong seasonal trend. This was true for all popular baits, including Maxforce. Seasonal variation in the amount of bait taken can be linked to two trends--seasonal variation in colony size and seasonal variation in food type preference. Both of these trends are strongly correlated with the Argentine ant's yearly life cycle.

At Haleakala the ant's main reproductive period lasts from Spring until Fall, and appears to peak in early Summer (Krushelnycky, pers. obs.). In the Spring, reproduction increases, signaled by the appearance of the first large batch of worker brood. This brood generally precedes and helps provide for the intense sexual brood production that follows (Markin 1970b). While males can be found in small numbers year-round, these sexual forms are most abundant from late March to September. In late Spring to early Summer, the pupae of this caste may sometimes represent up to 90% of a nest's brood composition (Krushelnycky, unpub. data). The production of new queens usually occurs shortly after heavy male production is under way (Markin 1970b), but this caste is difficult to observe and therefore is not as good an indicator of reproductive cycle status. After Fall, sexual production drops off sharply, as does worker production, and nest size decreases during the winter months.

A decline in the amount of Maxforce taken in Winter months can be attributed in part to the decrease in nest size in colder periods. However, it can also be explained by a shift in food type preference and requirements. While ants need protein year-round to provide for the development of larvae and the nourishment of the queens, this need increases tremendously in the Spring and Summer when egg production and larval growth explode. This pattern is reflected in the trends of Maxforce consumption seen in Figures 2 and 4. Consumption of honey granules and sugar water also generally fit this trend, as these are important energy sources needed to fuel the many workers foraging for food and tending to the brood and queens. It is interesting that sugar-based bait consumption exceeded protein-based bait consumption in the late Fall (Figures 2 and 4). This shift in food type preference is likely a result of brood production being low while the remaining workers were still searching for an energy source.

Because the effectiveness of the hydramethylnon toxicant relies heavily on bait retrieval and sharing within the nest, it is critical that the control effort implemented maximizes bait popularity and ant foraging levels. Maxforce was therefore chosen as the bait carrier because it proved to be the most attractive bait at both ant populations at Haleakala. Timing of the subsequent efficacy tests was associated with Maxforce consumption trends. The tests were therefore scheduled for mid to late Summer, as Maxforce attractiveness is then at its highest.

Results of the efficacy tests indicated that while treatment with Maxforce was followed by great reduction in ant numbers, complete eradication of ants from test plots was not achieved. The monitoring of ant numbers using ant counts at bait stations appeared to provide a fairly accurate method of estimating actual foraging levels in the plots. With this technique, it was possible to detect a dramatic crash in foraging ant numbers as soon as two days post treatment (Figures 6-8). This crash was characteristic

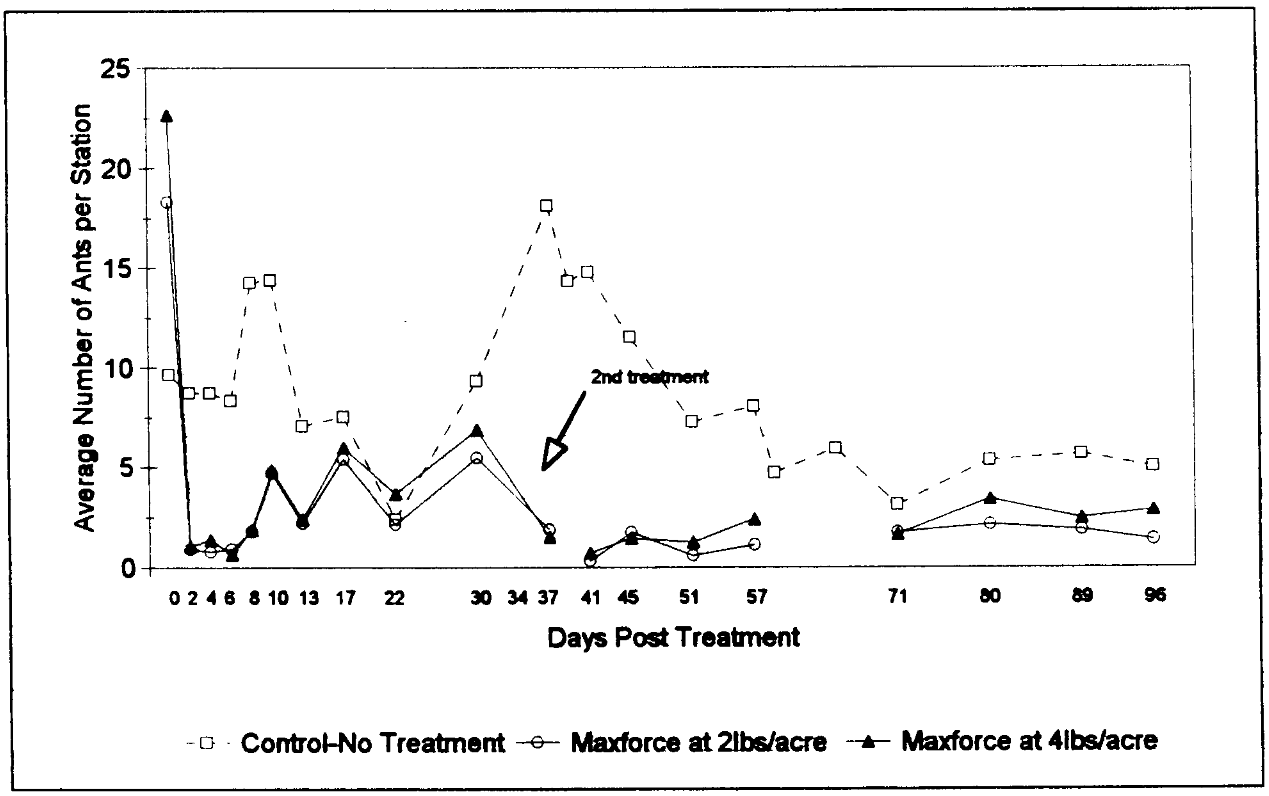

Figure 6 - Average numbers of ants per station over time in plots treated with Maxforce at 2lbs/acre, Maxforce at 4lbs/acre and control

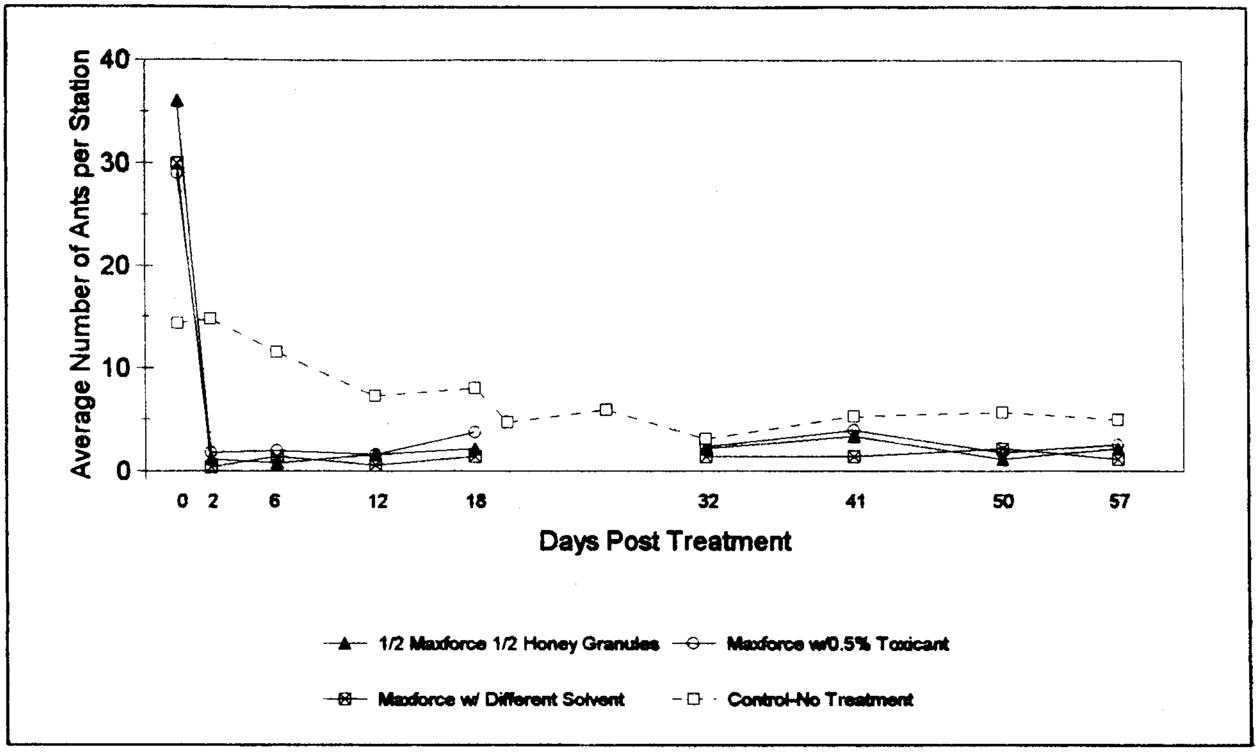

Figure 7 - Average numbers of ants per station over time in plots treated with a Maxforce/honey granule mix, Maxforce with 0.5% hydramethylnon, Maxforce with a different solvent and control

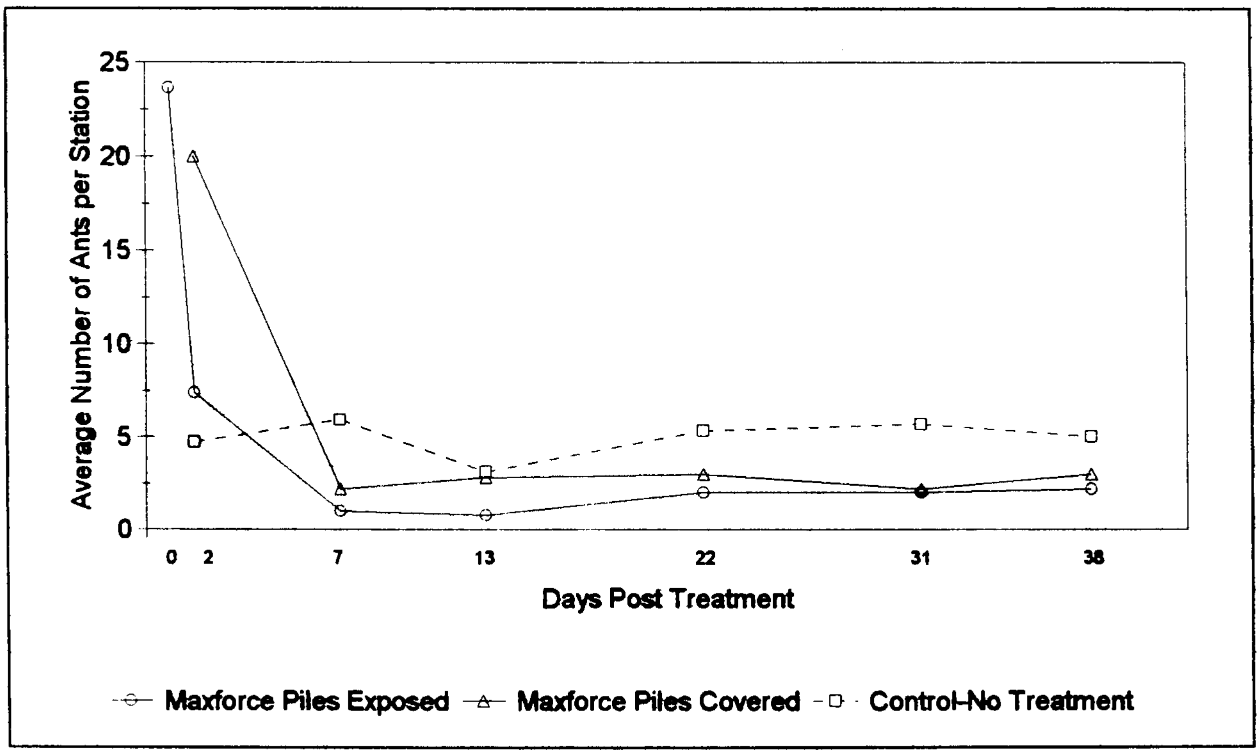

Figure 8 - Average numbers of ants per station over time in plots treated with exposed piles of Maxforce, covered piles of Maxforce and control

of all plots and all treatments (except control). However, the average number of ants per station never reached zero in any of the plots.

Treatments 1 and 2 (Maxforce at 4lbs/acre and Maxforce at 2lbs/acre, respectively) were the central focus of the study since they utilized regular, commercially available Maxforce distributed by a broadcast method. The remaining five treatments were implemented as secondary efforts after it became apparent that the first two were not achieving total eradication. Three of the additional five treatments were specially formulated for these tests by the Clorox Company, and are not normally available. The remaining two treatments utilized regular Maxforce, but the granules were distributed in carefully spaced piles, a method not practical on a large scale.

Examination of the efficacy of these five additional treatments revealed that they resulted in low numbers of foraging ants at the bait stations (Table 5, Figures 6-8). While the average numbers of ants per station for these five treatments were found to be statistically different from treatments 1 and 2, this was most likely due to large differences in sample size. And while treatment 5 (Maxforce with 0.5% hydramethylnon and a different solvent) yielded the lowest average number of ants per station and was significantly different from treatments 4 and 7, the important point is that none of these five treatments resulted in zero foraging ants at the bait stations. In light of the fact that a treatment of Maxforce with 0.5% hydramethylnon and a different solvent only produced an average of one less ant per bait station than a regular Maxforce treatment, it is doubtful that this and the other four secondary treatments would be worth their additional manufacturing costs when used on a large scale.

Based on a study testing the control of big-headed ants with Amdro--another bait utilizing hydramethylnon as the active ingredient--it was judged that control of the Argentine ants in the test plots should be achieved in 7-10 days (Reimer 1989). After it became clear that the treatments of Maxforce at 2 and 4lbs/acre did not completely control the ants and ant numbers at bait stations were inching slowly back up from a 95.1% reduction two days after treatment to a 70.0% reduction 34 days after treatment, it was decided to try a second application of the same treatments. Ant numbers at bait stations once again dropped (Figure 6), and retained an 89.9% reduction at bait stations two months after the second treatment. The second treatment did not, however, succeed in eradicating the ants.

In the end, analysis of the ant count data for plots treated with Maxforce at 4lbs/acre and Maxforce at 2lbs/acre found little difference in the results yielded by each. In fact, plots treated at 2lbs/acre had a slightly lower average number of ants per station over the length of the study (Table 5). With this in mind, it is clear that there was no benefit gained from treating infested areas at the higher application rate, yet the cost was considerably higher.

While the ant counts revealed that the maximum reduction in forager numbers averaged 97.0% for all the treatments, and all plots treated with scattered granular bait (not in piles) averaged a retention of 92.1% reduction in foraging ant numbers two months after treatment, this only represents a portion of the total ant populations in the test plots.

Foraging workers typically make up 10 to 20% of the adult individuals in a nest (Holldobler and Wilson 1990), so a survey of this group alone is incomplete. In a rather

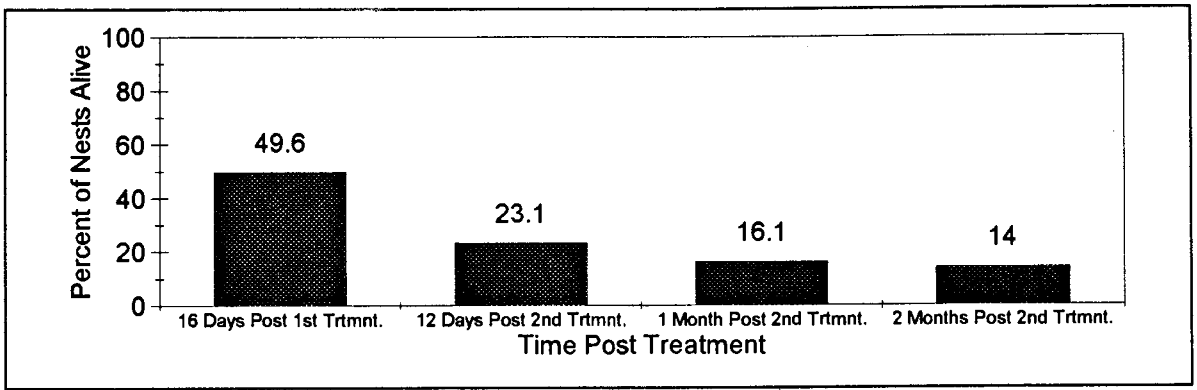

Figure 9 - Nest survival in plots treated with Maxforce at 4lbs/acre

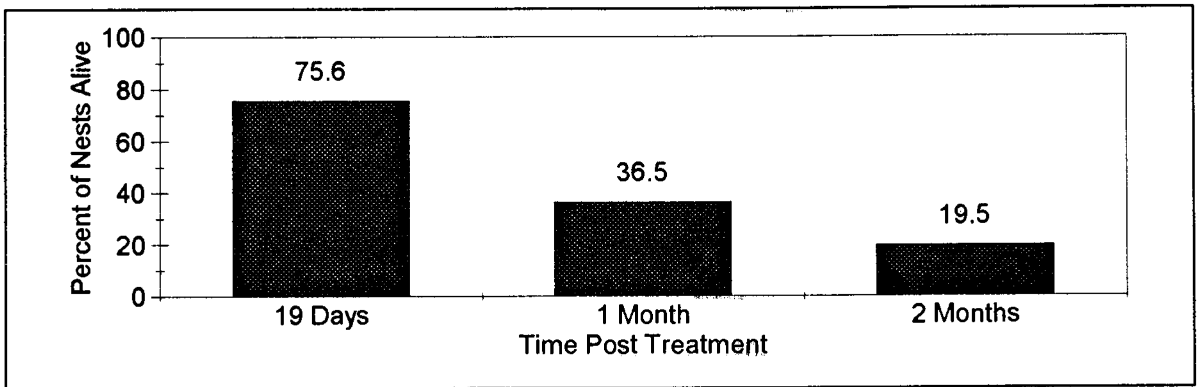

Figure 10 - Nest survival in plot treated with a Maxforce and honey granule mix

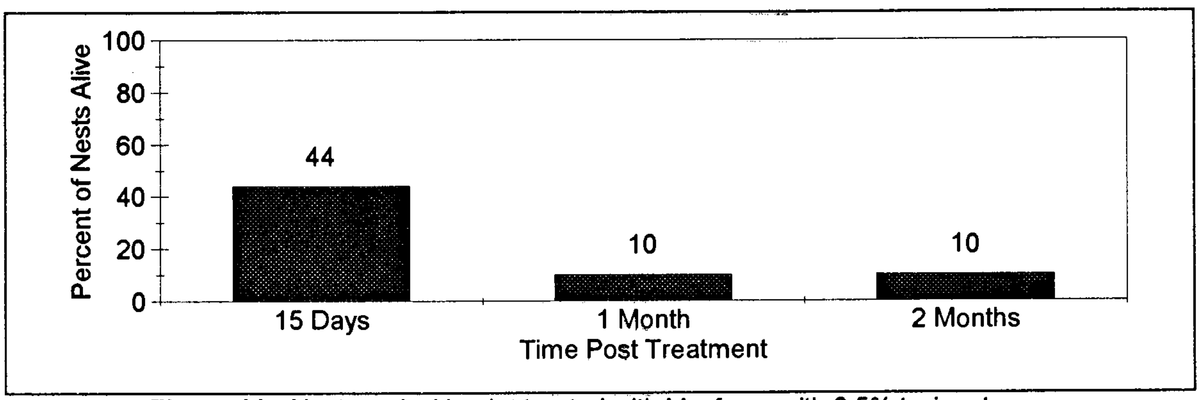

Figure 11 - Nest survival in plot treated with Maxforce with 0.5% toxicant

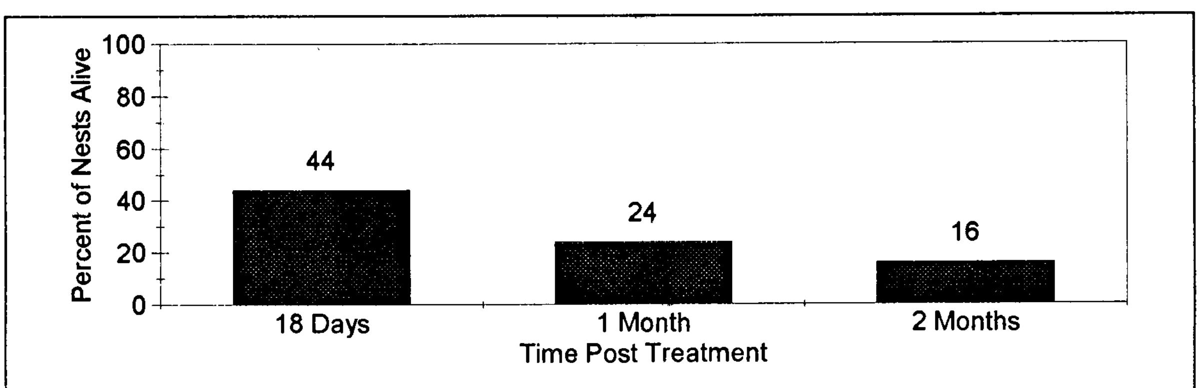

Figure 12 - Nest survival in plot treated with Maxforce with a different solvent

fortuitous development, molding of the Maxforce bait in the often damp conditions under rocks allowed it to be visible against an otherwise nearly identical looking soil and cinder ground surface. The mold therefore served as a sort of natural marker, often making it possible to trace the distribution of the bait to nests in the plots. Because of this discovery, nests in plots representing four of the treatments (Maxforce at 4lbs/acre, Maxforce and honey granule mix, Maxforce with 0.5% hydramethylnon, and Maxforce with a different solvent) were surveyed for activity and the visible presence of bait. Plots treated with Maxforce at 2lbs/acre were not surveyed in this manner as ant counts showed the effects of treatment to be similar to Maxforce at 4lbs/acre.

Because plots were first surveyed approximately two and a half weeks post treatment, it was not possible to recognize all of the nests that were active at the time of treatment. Therefore, only nests that had brood or queens present or had visible bait present at the time of the survey were counted as active. It was assumed that nests with bait present had been alive at the time of treatment and workers from these nests had retrieved the bait. Nests that still had some workers present but no brood or queens or bait were ignored, as it was impossible to determine if the brood and queens in these nests had died or had merely moved prior to treatment. This has some implications on the interpretation of the results, as it may have artificially inflated the measured nest survival rates discussed below.

The first nest survey sixteen days after treatment revealed 49.6% of all surveyed nests treated with Maxforce at 4lbs/acre were still active (Figure 9). The rest were inactive, indicating that they had died or moved. Twelve days after the second treatment of Maxforce at 4lbs/acre, only 23.1% of all surveyed nests were still active. In other words, 53.5% of the nests active after the first treatment had become inactive by the time of the survey following the second treatment. At one month after the second treatment, 16.1% of the nests remained active, and at two months, only 14.0% were still active (Figure 9). Figures 10-12 show these results for the plots of the other three treatments surveyed in this manner. At one month post treatment, nest survival rate was found to be significantly higher when treated with the Maxforce and honey granule mix, and significantly lower when treated with Maxforce with 0.5% hydramethylnon. However, at two months post treatment, there were no significant differences in nest survival rates among the four treatments.

While it appears that the numbers of surviving nests in the plots declined significantly over the course of the study and may have eventually dropped to zero, this conclusion is erroneous. As previously mentioned, the toxicant hydramethylnon causes mortality within two days after ingestion, so its effect on a colony or treated population should be seen within seven to ten days. After that, it is doubtful that much active bait remained. Exposed bait became inactive by UV radiation in several days, and retrieved bait stored under rocks became moldy in about a week and a half. Bait protected from the sun under vegetation or drier underground conditions in nests may have lasted longer, and may account in part for the apparent long-term decline in nest survival.

A more likely explanation, however, is that most of the surviving nests simply moved. This conclusion is supported by the ant count data, which showed a continued, relatively constant presence of foraging ants from the time after treatment until the end of the study (Figures 6-8). Examination of the nest survey data revealed that in the interval

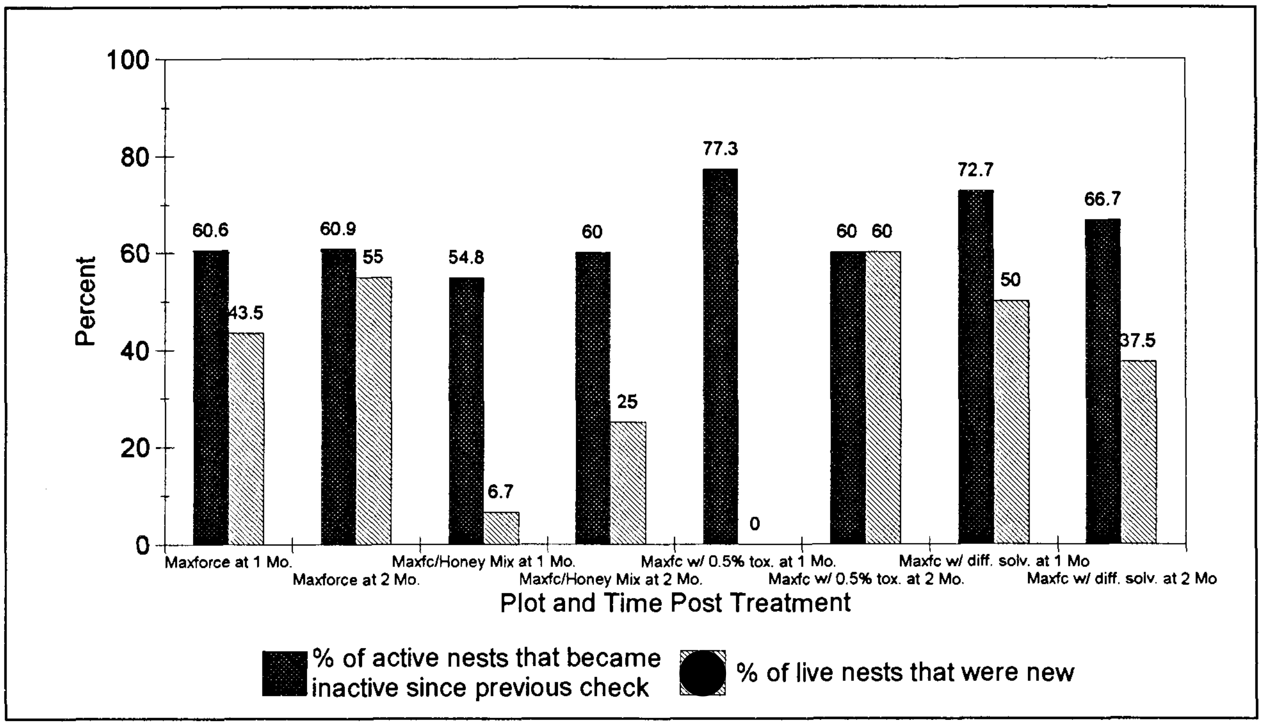

Figure 13 - Percent of nests that became inactive between nest surveys versus percent of active nests that were new

between each survey, and for all treatments, at least half of the previously active nests became inactive, meaning that they died or moved (Figure 13). However, the data also indicated that "new" nests were often found (Figure 13). ("New" nests were defined as surveyed nests that were previously inactive and then were discovered to be active at a later date.) This indicates that a fair amount of nest movement was measured in the plots, which didn't even account for movement to the many nest sites not surveyed. As Argentine ants at Haleakala nest under rocks, it is not difficult for them to shift to a new rock and construct a suitable nest. This behavior has been observed frequently, and the disturbance caused by the repeated lifting of the nest rocks in the course of the nest surveys alone was probably sufficient to prompt a move. Disturbance of this nature is the primary reason nest surveys were not conducted prior to treatment. While it is clear that in most plots at least 50% of the nests died soon after treatment, conclusions concerning nest survival at one and two months after treatment are confused by the phenomenon of nest movement.

What then are the possible reasons for Maxforce's inability to deliver complete control of the Argentine ant? Nest survey data shed light on this topic. The locations of nests in the plots that had definitely retrieved bait indicated that bait was well dispersed among the nests. Although it was somewhat difficult to know if the bait was being spread evenly at the time of treatment, the distribution of nests with molding bait showed that the bait had gotten to all sections of the plots. Furthermore, nests without signs of bait were often found next to nests with bait, demonstrating again that bait dispersal was not an issue. In fact, 72.0% of all nests surveyed in the Maxforce treated plots showed signs of bait retrieval (Figure 14). This can be considered a conservative estimate, as some of the nests may have consumed all of the retrieved bait or taken it below ground. The remaining 28.0% of the surveyed nests were all active. This percentage varied for the other treatments (Figure 14).

There are three possible explanations for the survival of nests in the tests plots: the bait is not attractive enough and so was not retrieved, the bait was retrieved but is not attractive enough to be consumed once in the nest, and the bait was consumed but not in large enough quantities to kill the entire nest. The 28.0% of nests in the Maxforce treated plots that were active and had no bait supports the partial validity of the first explanation, and suggests that some nests found the bait more attractive than others. This level of attractiveness varied for the other baits/treatments (Figure 14), with regular Maxforce apparently the highest. High rates of worker interchange and sharing between nests has been documented with the Argentine ant (Markin 1968), however, which contradicts this apparent phenomenon of differential attractiveness among nests to a particular bait.

The second explanation for nest survival is also supported by nest survey data. It was found that of all the active nests in the Maxforce plots at two and a half weeks post treatment, 43.7% of them had visible molding bait (Figure 14). This occurred in the other plots as well, but to a lesser degree (Figure 14). For some reason, these baits were retrieved by the foragers and then set aside and left to rot. Initial observations seemed to indicate that the baits probably didn't begin rotting until at least one week after treatment; however, more recent data has shown that the molding of Maxforce bait is visible as soon as five days after treatment and probably begins sooner. The molding itself may therefore be a factor in the issue of bait attractiveness. Repellency tests prior to treatment found

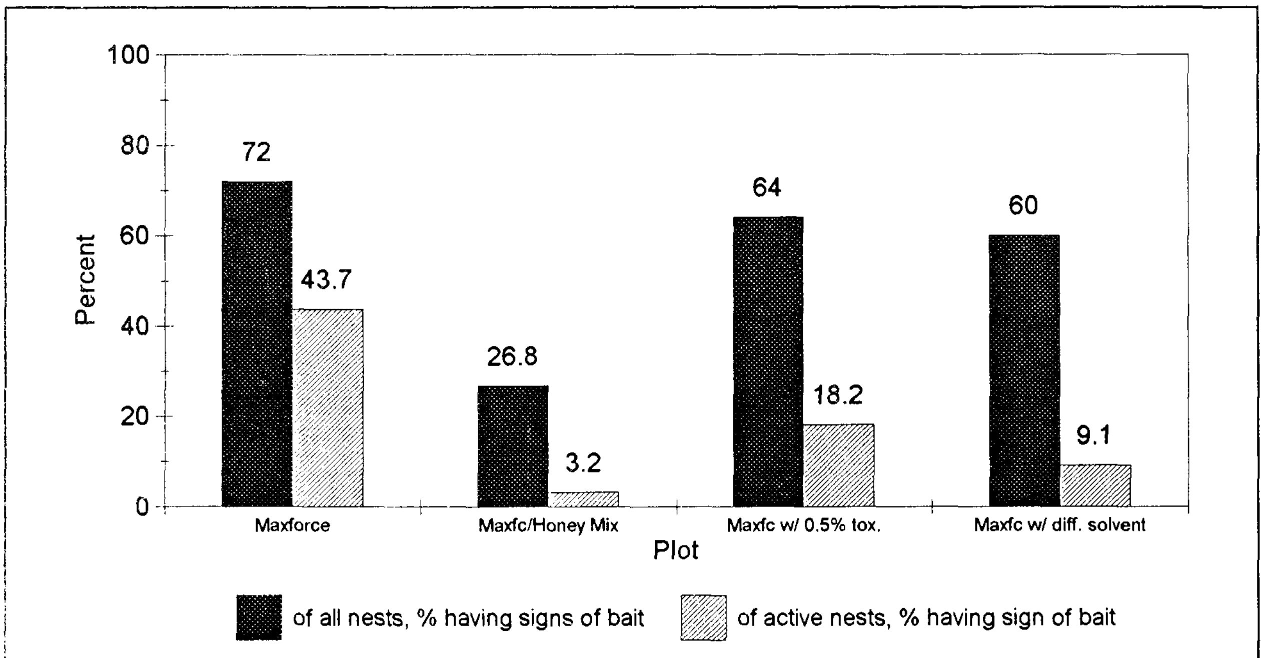

Figure 14 - Percent of surveyed nests showing visible signs of bait retrieval at two and a half weeks post treatment

regular Maxforce to have no detectable repellent qualities. Nevertheless, treatments with 0.5% active ingredient, a different solvent and a honey granule mix for greater attractiveness were attempted. Figure 14 shows that smaller percentages of the active nests in these plots left the baits to rot, but after two months, there was no significant difference in the nest survival rates of these plots compared with regular Maxforce.

The third explanation, namely that the baits were not consumed in large enough quantities, cannot be supported or contradicted with the data, but again points to a lack of attractiveness of the baits. This seems to be the main obstacle to Maxforce's effectiveness in eradicating ants at Haleakala.

Because it was initially believed that hydramethylnon has a half life of approximately 45 minutes in direct sunlight, test plots were treated at sunset to prolong the period of effective bait exposure to the ants. It was estimated that bait would be largely inactive by midmorning, so cold nighttime temperatures were thought to be a major factor influencing bait collection prior to the breakdown of the active ingredient. Rhoades and Davis (1967) showed that the effectiveness of certain bait insecticides against the red imported fire ant decreased considerably with decreasing foraging activity, and a similar effect could be expected with Maxforce and the Argentine ant. However, it has since been learned that when formulated in Maxforce granules, a significant portion of the hydramethylnon is shielded from the sun, and the half life of Maxforce granules in sunlight is approximately 57 hours (Clorox, unpublished data). The bait is therefore highly active for at least several days, and nighttime temperatures should play an insignificant role in overall bait retrieval success. Morning treatment times may be considered for future Maxforce tests.

Ultimately, the majority of the problem appears to be one of bait attractiveness, whether further complicated by molding or not. This may prove to be an extremely difficult obstacle in a natural area such as Haleakala National Park, where natural food sources seem to be much more attractive than current manufactured baits. Forschler and Evans (1994) were able to achieve Argentine ant control using Maxforce in a lawn area of an apartment complex, but the level of competing food resources in that situation is undoubtedly much less. In addition, the ants in their study had extended access to Maxforce protected from the sun, whereas at Haleakala intense direct sun and other weather conditions produce a comparatively short window of opportunity for bait retrieval and detract from the bait's effectiveness.

Although total eradication of the Argentine ant from the test plots was not realized, a secondary goal of the project is to attempt to prevent further expansion. A huge decrease in ant numbers occurred as a result of treatment with Maxforce, and a cursory examination of test plots five months post treatment found relatively few live nests. Future research should include a study examining the effect of this reduction on rates of expansion, as well as the longevity of the bait's efficacy. Of particular interest is the effect of treating expanding edges of populations. If large scale management of the Argentine ant proves to be feasible and desirable, the recommendation of this study is to use regular, commercially available Maxforce granular bait broadcast at an application rate of 2lbs/acre. It has proven to be as effective as other formulations at higher application rates, and would be the most cost effective management strategy.

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REFERENCES

Abedrabbo, S. 1994. Control of the little fire ant, *Wasmannia auropunctata*, on Santa Fe Island in the Galapagos Islands. Pages 219-227 in D. F. Williams, editor. Exotic Ants: Biology, Impact, and Control of Introduced Species. Westview Press, Boulder, Colorado.

Apperson, C. S., R. B. Leidy, and E. E. Powell. 1984. Effects of Amdro in the red imported fire ant (Hymenoptera: Formicidae) and some nontarget ant species and persistence of Amdro on a pasture habitat in North Carolina. J. Econ. Entom. 77:1012-1018.

Aron, S., J. M. Pasteels, and J. L. Deneubourg. 1989. Trail-laying behavior during exploratory recruitment in the Argentine ant, *Iridomyrmex humilis* (Mayr). Biology of Behavior 14:207-217.

Aron, S., J. M. Pasteels, S. Goss, and J. L. Deneubourg. 1990. Self-organizing spatial patterns in the Argentine ant *Iridomyrmex humilis* (Mayr). Journal of Insect Behavior 3(2):438-451.

Baker, T. C., S. E. Van Vorhis Key, and L. K. Gaston. 1985. Bait-preference tests for the Argentine ant (Hymenoptera: Formicidae). J. Econ. Entomol. 78:1083-1088.

Beardsley, J. W. 1980. Haleakala National Park Crater District resources basic inventory: insects. Technical Report 31. Cooperative National Park Resources Studies Unit, Department of Botany, University of Hawaii, Honolulu, Hawaii, USA.

Bond, W. and P. Slingsby. 1984. Collapse of an ant-plant mutualism: the Argentine ant (*Iridomyrmex humilis*) and myrmecochorous proteaceae. Ecology 65(4):1031-1037.

Brian, M. V. 1983. Social Insects. Ecology and Behavioral Biology. Chapman and Hall, Cambridge, Great Britain.

Bristow, C. M. 1991. Are ant-aphid associations a tritrophic interaction? Oleander aphids and Argentine ants. Oecologia 87:514-521.

Brockie, R., L. L. Loope, M. B. Usher, and O. Hamann. 1988. Biological invasions of island nature reserves. Biol. Conserv. 44:9-36.

Carr, G. D., E. A. Powell, and D. W. Kyhos. 1986. Self-incompatibility in the Hawaiian Madiinae (Compositae): An exception to Baker's rule. Evolution 40(2):430-434.

Clark, D. B., C. Guayasamin, O. Pazamino, C. Donoso, and Y. Paez De Villacis. 1982. The tramp ant *Wasmannia auropunctata*: Autecology and effects on ant diversity and distribution on Santa Cruz Island, Galapagos. Biotropica, 14:196-207.

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(4):1313-1322.

Erickson, J. M. 1971. The displacement of native ant species by the introduced Argentine ant *Iridomyrmex humilis* Mayr. Psyche 78:257-266.

Evesham, E. J. M. 1984. Queen distribution movements and interactions in a semi-natural nest of the ant *Myrmica rubra* L. Insectes Soceaux 31(1):5-19.

Fellers, J. H. and G. M. Fellers. 1982. Status and distribution of ants in the Crater District of Haleakala National Park. Pacific Science 36:427-437.

Fluker, S. S. and J. W. Beardsley. 1970. Sympatric associations of three ants: *Iridomyrmex humilis*, *Pheidole megacephala*, and *Anoplolepis longipes* in Hawaii. Annals of the Entomological Society of America 63:1290-1296.

Forschler, B. T. and G. M. Evans. 1994. Argentine ant (Hymenoptera: Formicidae) foraging activity response to selected containerized baits. Journal of Entomological Science 29(2):209-214.

Gaston, L. K. and T. C. Baker. 1984. Toxic bait to control Argentine ant field tested. Citrograph 69(7):188.

Gillespie, R. G. and N. Reimer. 1993. The effect of alien predatory ants (Hymenoptera: Formicidae) on Hawaiian endemic spiders (Araneae: Tetragnathidae). Pacific Science 47(1):21-33.

Haines, I. H. and J. B. Haines. 1978. Colony structure, seasonality and food requirements of the crazy ant, *Anoplolepis longipes* (Jerd.), in the Seychelles. Ecological Entomology 3:109-118.

Haney, P. 1984. A different approach to the Argentine ant problem. Citrograph 69(6):140-146.

Holldobler, B. and E. O. Wilson. 1990. The Ants. The Belknap Press of the Harvard University Press, Cambridge, Massachusetts.

Holway, D. A. In press. The distribution of the Argentine ant (*Linepithema humile*) in northern California: A twenty year record of invasion. Conservation Biology.

Huddleston, E. W., and S. Fluker. 1968. Distribution of ants species of Hawaii. Proceedings of the Hawaiian Entomological Society 20:45-69.

Illingworth, J. F. 1917. Economic aspects of our predaceous ant. Proceedings of the Hawaiian Entomological Society 3(4):349-368.

Jenkins, C. F. H. and P. N. Forte. 1973. Chemicals for Argentine ant control. J. Agric. West. Aust. 14(2):195-196.

Kaufman, B., J. J. Boorsma, L. Passera, and K. N. Petersen. 1992. Relatedness and inbreeding in a French population of the unicolonial ant *Iridomyrmex humilis* (Mayr). Insectes Sociaux 39: 195-213.

Keller, L. 1988. Evolutionary implications of polygyny in the Argentine ant, *Iridomyrmex humilis* (Mayr) (Hymenoptera: Formicidae): an experimental study. Animal Behavior 36:159-165.

Keller, L. and L. Passera. 1988. Energy investment in gynes of the Argentine ant *Iridomyrmex humilis* (Mayr) in relation to the mode of colony founding in ants (Hymenoptera: Formicidae). International Journal of Invertebrate Reproduction and Development 13:31-38.

Keller, L., L. Passera, and J. Suzzoni. 1989. Queen execution in the Argentine ant, *Iridomyrmex humilis*. Physiological Entomology 14:157-163.

Keller, L. and L. Passera. 1992. Mating system, optimal number of matings, and sperm transfer in the Argentine ant *Iridomyrmex humilis*. Behavioral Ecology and Sociobiology 21:359-366.

Keller, L. and L. Passera. 1993. Incest avoidance, fluctuating assymmetry, and the consequences of inbreeding in *Iridomyrmex humilis*, an ant with multiple queen colonies. Behavioral Ecology and Sociobiology 33:191-199.

Knight, R. L. and M. K. Rust. 1990. Repellency and efficacy of insecticides against foraging workers in laboratory colonies of Argentine ants (Hymenoptera: Formicidae). Journal of Economic Entomology 83(4):1402-1408.

Knight, R. L. and M. K. Rust. 1991. Efficacy of formulated baits for control of Argentine ant (Hymenoptera: Formicidae). J. Econ. Entom. 84(2):510-514.

Loope, L. L. and D. Mueller-Dombois. 1989. Characteristics of invaded islands, with special reference to Hawaii. Pages 257-280 in J. Drake, H. Mooney, F. di Castri, R. Groves, F. Kruger, M. Rejmanek, and M. Williamson, editors. Biological invasions: a global perspective. John Wiley & Sons, Chichester, United Kingdom.

Macdonald, G. A., A. T. Abbot, and F. L. Peterson. 1983. Volcanoes in the Sea: the Geology of Hawaii. University of Hawaii Press, Honolulu. 517 pp.

Majer, J.D. 1994. Spread of Argentine ants (*Linepthema humile*), with special reference to Western Australia. Pages 163-173 in D. F. Williams, editor. Exotic Ants: Biology, Impact, and Control of Introduced Species. Westview Press, Boulder, Colorado.

Markin, G. P. 1968. Nest relationship of the Argentine ant, *Iridomyrmex humilis* (Hymenoptera: Formicidae). Journal of Kansas Entomological Society 41(4):511-516.

Markin, G. P. 1970a. Food distribution within laboratory colonies of the Argentine ant, *Iridomyrmex humilis* (Mayr). Insectes Sociaux 17(2):127-158.

Markin, G. P. 1970b. The seasonal life cycle of the Argentine ant, *Iridomyrmex humilis* (Hymenoptera: Formicidae), in southern California. Annals of the Entomological Society of America 63(5): 1238-1243.

Medeiros, A. C., L. L. Loope, and F. R. Cole. 1986. Distribution of ants and their effects on endemic biota of Haleakala and Hawaii Volcanoes National Parks: a preliminary assessment. Proceedings of the Sixth Conference in Natural Sciences, Hawaii Volcanoes National Park. Cooperative National Park Resources Studies Unit, Department of Botany, University of Hawaii, Honolulu, Hawaii, USA.

Moulton, M. P. and S. L. Pimm. 1986. Species Introductions to Hawaii. Pages 231-249 in H. A. Mooney and J. A. Drake, editors. Ecology of Biological Invasions of North America and Hawaii. Springer Verlag, New York.

Newell, W. 1909. The life history of the Argentine ant. Journal of Economic Entomology 2:174-192.

Passera, L., L. Keller, and J. P. Suzzoni. 1988. Control of brood male production in the Argentine ant *Iridomyrmex humilis* (Mayr). Insectes Sociaux 35(1):19-33.

Passera, L. and S. Aron. 1993. Factors controlling dealation and egg laying in virgin queens of the Argentine ant *Linepithema humile* (Mayr) (= *Iridomyrmex humilis*). Psyche 100:51-63.

Passera, L. and S. Aron. 1993. Social control over the survival and selection of winged virgin queens in an ant without nuptial flight: *Iridomyrmex humilis*. Ethology 93:225-235.

Passera, L. and L. Keller. 1994. Mate availability and male dispersal in the Argentine ant *Linepithema humile* (Mayr) (= *Iridomyrmex humilis*). Animal Behavior 48:361-369.

Porter, S. D. and W. R. Tschinkel. 1987. Foraging in *Solenopsis invicta* (Hymenoptera: Formicidae): Effects of weather and season. Environmental Entomology 16(3):802-808.

Reimer, N. J. 1989. Bait efficacy, reinfestation rates and colony composition for *Pheidole megacephala* (F.) in pineapple in Hawaii. 1989 ADAP Crop Protection Conference pg. 16-18.

Reimer, N. J., J. W. Beardsley, and G. Jahn. 1990. Pest ants in the Hawaiian Islands. Pages 40-50 in R. K. Vander Meer, K. Jaffe, and A. Cedeno, editors. Applied Myrmecology: A world perspective. Westview Press, Boulder, Colorado.

Reimer, N. J., B. M. Glancey, and J. W. Beardsley. 1991. Development of *Pheidole megacephala* (Hymenoptera: Formicidae) colonies following ingestion of fenoxycarb and pyriproxyfen. Journal of Economic Entomology 84(1):56-60.

Reimer, N. J. 1994. Distribution and impact of alien ants in vulnerable Hawaiian ecosystems. Pages 11-22 in D. F. Williams, editor. Exotic Ants: Biology, Impact, and Control of Introduced Species. Westview Press, Boulder, Colorado.

Rhoades, W. C. and D. R. Davis. 1967. Effects of meteorological factors on the biology and control of the imported fire ant. Journal of Economic Entomology 60(2):554-558.

Shattuck, S. O. 1992. Review of the Dolichoderine ant genus *Iridomyrmex* Mayr with descriptions of three new genera (Hymenoptera: Formicidae). J. Aust. ent. Soc. 31:13-18.

Simon, C. M., W. C. Gagne, F. G. Howarth, and F. J. Radovsky. 1984. Hawaii: A natural entomological Laboratory. Bulletin of the Entomological Society of America 30:8-17.

Sokal, R. R. and F. J. Rohlf. 1981. Biometry. Second edition. W. H. Freeman and Company, New York.

Su, T. H., J. W. Beardsley, and F. L. McEwen. 1980. AC-217,300, a promising new insecticide for use in baits for control of the bigheaded ant in pineapple. J. Econ. Entomol. 73(6):755-756.

Tremper, B. S. 1976. Distribution of the Argentine ant, *Iridomyrmex humilis* Mayr, in relation to certain native ants of California: ecological, physiological, and behavioral aspects. Ph.D. Thesis, U.C. Berkeley.

Usher, M. B. 1986. Invasibility and wildlife conservation: invasive species on nature reserves. Phil. Trans. R. Soc. Lond. 314:695-710.

Van Vorhis Key, S. E. and T. C. Baker. 1986. Observations on the trail deposition and recruitment behaviors of the Argentine ant, *Iridomyrmex humilis* (Hymenoptera: Formicidae). Annals of the Entomological Society of America 79(20:283-288.

Vitousek, P. M., L. L. Loope, and C. P. Stone. 1987. Introduced species in Hawaii: biological effects and opportunities for ecological research. Trends in Ecology and Evolution 2:224-227.

Wagner, W. H. and F. S. Wagner. Unpublished. Revised checklist of Hawaiian pteridophytes.

Wagner, W. L., D. R. Herbst, and S. H. Sohmer. 1990. Manual of the flowering plants of Hawaii. University of Hawaii Press, Honolulu, Hawaii.

Ward, P. S. 1987. Distribution of the introduced Argentine ant (*Iridomyrmex humilis*) in natural habitats of the lower Sacramento Valley and its effects on the indigenous ant fauna. Hilgardia 55(2):1-16.

Wetterer, J. K., P. C. Banko, and L. Laniawe. In press. Ants at high elevations on Mauna Kea, Hawaii.

Williams, D. F. 1994. Control of the introduced pest *Solenopsis invicta* in the United States. Pages 282-292 in D. F. Williams, editor. Exotic Ants: Biology, Impact, and Control of Introduced Species. Westview Press, Boulder, Colorado.

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

Zimmerman, E. C. 1948. Insects of Hawaii. Volume 1. Introduction. University of Hawaii Press, Honolulu, Hawaii, USA.

Appendix 1 - Common Plant Species Within the Lower Elevation (2070-2260 m) Population of the Argentine Ant in Haleakala National Park[2]

Shrubs and Trees

Taxon	Family	Status
Styphelia tameiameiae	Epacridaceae	Indigenous
Sophora chrysophylla	Fabaceae	Endemic
Vaccinium reticulatum	Ericaceae	Endemic
Dubautia menziesii	Asteraceae	Endemic
Dodonaea viscosa	Sapindaceae	Indigenous
Santalum haleakalae	Santalaceae	Endemic

Ground Vegetation

Taxon	Family	Status
Pteridium decompositum	Dennstaedtiaceae	Endemic
Pellaea ternifolia	Pteridaceae	Indigenous
Polypodium pellucidum	Polypodiaceae	Endemic
Asplenium [x] adiantum-nigrum (A. cuneifolium x oropteris) (Wagner and Wagner unpubl.)	Aspleniaceae	Indigenous
Asplenium trichomanes	Aspleniaceae	Indigenous
Pityogramma austroamericana	Pteridaceae	Introduced
Geranium cuneatum	Geraniaceae	Endemic
Holcus lanatus	Poaceae	Introduced
Anthoxanthum odoratum	Poaceae	Introduced
Deschampsia nubigena	Poaceae	Endemic
Agrostis sandwicensis	Poaceae	Endemic
Carex wahuensis	Cyperaceae	Endemic
Carex macloviana	Cyperaceae	Indigenous
Gahnia gahniiformis	Cyperaceae	Indigenous
Luzula hawaiiensis	Juncaceae	Endemic
Hypochoeris radicata	Asteraceae	Introduced
Oenothera stricta	Onagraceae	Introduced
Plantago lanceolata	Plantaginaceae	Introduced
Rumex acetosella	Polygonaceae	Introduced

[2] Nomenclature for vascular plants follows Wagner et al. (1990) and Wagner and Wagner (unpubl.)

Appendix 2 - Common Plant Species Within the Upper Elevation (2740-2830 m) Population of the Argentine Ant in Haleakala National Park[3]

Shrubs

Taxon	Family	Status
Styphelia tameiameiae	Epacridaceae	Indigenous
Dubautia menziesii	Asteraceae	Endemic
Sophora chrysophylla	Fabaceae	Endemic
Vaccinium reticulatum	Ericaceae	Endemic

Ground Vegetation

Taxon	Family	Status
Pteridium decompositum	Dennstaedtiaceae	Endemic
Pellaea ternifolia	Pteridaceae	Indigenous
Polypodium pellucidum	Polypodiaceae	Endemic
Asplenium trichomanes	Aspleniaceae	Indigenous
Asplenium [x] adiantum-nigrum (A. cuneifolium x oropteris) (Wagner and Wagner unpubl.)	Aspleniaceae	Indigenous
Carex wahuensis	Cyperaceae	Endemic
Carex macloviana	Cyperaceae	Indigenous
Luzula hawaiiensis	Juncaceae	Endemic
Deschampsia nubigena	Poaceae	Endemic
Hypochoeris radicata	Asteraceae	Introduced
Oenothera stricta	Onagraceae	Introduced
Plantago lanceolata	Plantaginaceae	Introduced
Tetramalopium humile	Asteraceae	Indigenous
Argyroxiphium sandwicense macrocephalum	Asteraceae	Endemic
Rumex acetosella	Polygonaceae	Introduced
Polycarpon tetraphyllum	Caryophyllaceae	Introduced
Arenaria serpyllifolia	Caryophyllaceae	Introduced

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[3] Nomenclature for vascular plants follows Wagner et al. (1990) and Wagner and Wagner (unpubl.)