



## Detrimental effects of two widespread invasive ant species on weight and survival of colonial nesting seabirds in the Hawaiian Islands

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**Abstract** Invasive ants are a significant conservation concern and can have far-reaching effects in ecosystems they invade. We used the experimental control of ant numbers on two pairs of small (<5 ha) offshore islets dominated by either the big-headed ant, *Pheidole megacephala* or the tropical fire ant, *Solenopsis geminata* to investigate the influence of these species on seabird hatching success, fledging success and weight. Limited unpublished observations of both ant species attacking nesting seabirds exist, but the frequency of attacks or how they affect seabird growth and survival are unknown. Island-wide treatments with hydramethylnon resulted in the eradication of *P. megacephala* and the temporary reduction of *S. geminata* densities. No difference in hatching success, growth, or fledging success of Wedge-tailed Shearwaters (*Puffinus pacificus*), a common colonial nesting seabird in the Hawaiian Islands was observed on the pair of islets dominated by *P. megacephala*. On islets dominated by *S. geminata*, ant control resulted in a temporary increase in fledging success. Injury frequency increased dramatically on the untreated islet (8.3–100%) while remaining the same on the treated islet (27–38%). Severely injured chicks (i.e., chicks that

lost >20% of tissue on their feet) weighed significantly less than uninjured chicks and did not fledge. It is unclear if the chicks were being preyed upon or stung in defense of nearby ant colonies. Radical changes in invasive ant populations have been noted, and booming ant populations could cause short-term, but widespread damage to seabird colonies. The negative effects of invasive ants on seabirds may be difficult to detect, and therefore unknown or underestimated throughout the world where the two groups overlap.

**Keywords** Ant eradication · Invasive ants · *Pheidole megacephala* · Seabird breeding biology · *Solenopsis geminata* · Wedge-tailed Shearwater

### Introduction

In most of the world ants are one of the dominant arthropods, capable of shaping ecosystems by redirecting energy flow, turning soil, and facilitating, preying upon and/or competing with each other and other members of the insect fauna (Hollolbier and Wilson 1990). Thus it is not surprising that invasive ants, given their steadily increasing ranges, have become a significant threat to biodiversity (Hollolbier and Wilson 1990; Moller 1996; Holway et al. 2002). The magnitude of changes in species composition and relationships resulting from ant invasions is poorly known in most areas as are the

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effects and mechanisms involved in bringing about these changes. Most studies focus on the effects of invasive ants on arthropod and plant communities (Risch and Carroll 1982; Bach 1991; Cole et al. 1992; Gillespie and Reitter 1993; Green et al. 1997; LaPolla et al. 2000; Hill et al. 2002; O'Dowd et al. 2003; Gerlach 2004), however other groups of species, including vertebrates may also be negatively affected, but are not as well studied.

Throughout the world, four species of invasive ants [*Solenopsis invicta* (Drees 1994; Mueller et al. 1999; Allen et al. 2000; Legare and Eddleman 2001; Tschinkel 2000; Smith et al. 2007), *Anoplolepis gracilipes* (Feare 1999; Meek 2000), *Linepithema humile* (Fisher et al. 2002; Suarez et al. 2005), and *Wasmannia auropunctata* (Jourdan et al. 2001)] are known to have negative effects on growth and/or survival of vertebrate species, including approximately 19 species of birds, 13 species of mammals, and more than 15 species of reptiles and amphibians (Holway et al. 2002). *Solenopsis invicta* is implicated in the majority of these cases and is also the most widely studied (Drees 1994; Allen et al. 2000; Legare and Eddleman 2001; Holway et al. 2002; Tschinkel 2006). Invasive ants are known to negatively affect oviparous animals by causing nest site abandonment (Feare 1999), increasing energy expenditure of parent birds (Smith et al. 2007), and reducing hatching success (Giuliano et al. 1996), growth rates (Giuliano et al. 1996; Allen et al. 1997), and survival (Drees 1994; Moulis 1996; Mueller et al. 1999; Allen et al. 2001).

Seabirds may be especially susceptible to harm from invasive ants since the vast majority nest in colonies where food resources in the form of guano, boluses, eggs, chicks, and dead adults are abundant. To our knowledge, study of the effects of invasive ants on nesting seabirds is limited to three descriptive studies comparing invaded and uninvaded areas (Lockley 1995; Feare 1999; Krushelnycky et al. 2001). Lockley (1995) found that *S. invicta* had negative effects on nesting Least Terns (*Sterna albifrons*). On Bird Island (Seychelles), attacks on Sooty Terns (*Sterna fuscata*) by *A. gracilipes* resulted in nest site abandonment (Feare 1999). In contrast, on Maui, Hawaii, there was no difference in nest success of Hawaiian Petrels (*Pterodroma sandwichensis*) nesting in areas invaded by Argentine ants

(*I. humilis*) versus uninvaded areas (Krushelnycky et al. 2001).

Also in the Hawaiian Islands where ants are not represented in the native fauna (Wilson 1996), there are anecdotal observations of nest failure and injuries possibly caused by three of the more than 44 invasive ant species now present (Nishida 1992). Negative effects on vertebrates by two of these species (*P. megacephala* and *S. geminata*) have not been documented outside the ants' native ranges. Both species are among the six most widespread and harmful invasive ant species (Holway et al. 2002). *Pheidole megacephala*, also known as the big-headed ant (BHA) is native to Africa and has been widely introduced to other continents where it is known to prey upon and displace other arthropods (Hollдобler and Wilson 1990; Gillespie and Reimer 1993; May and Heterick 2000). There are only anecdotal observations of *P. megacephala* attacking adult seabirds and chicks (specifically Sooty Tern (*Sterna fuscata*), Wedge-tailed Shearwater, Laysan Albatross (*Phoebastria immutabilis*) and Bonin Petrel (*Bulweria bulwerii*) on Kure Atoll (Cynthia Vanderlip, pers. comm.; S. Plentovich, pers. obs.).

*Solenopsis geminata*, the tropical fire ant (TFA) is native to the southeastern United States, central America and northern South America and is known to harvest seeds and prey upon invertebrates (Hollдобler and Wilson 1990; Taber 2000; Holway et al. 2002). The TFA possesses a venomous sting that may improve its ability to prey upon or subdue vertebrate species and larger invertebrates (Holway et al. 2002). Within its native range the TFA has been reported to prey upon hatching Bob-white Quail (*Colinus virginianus*) eggs and young chicks (Stoddard 1931; Travis 1938). There are observations of TFA attacking seabird chicks on islets offshore of Oahu and Kahuolawe (Heashi and Plentovich, pers. obs.; Ken Wood, pers. comm.). Injuries similar to those observed on other offshore islets (i.e., holes and lesions in the webbing of the feet) were reported on Manana and Moku Manu by Richardson (1948), who was unsure of the cause of the injuries, but noted that they were sustained apparently during the first few weeks of life and suggested that "small carnivorous ants" (p. 224) may be the culprits. The frequency of occurrence and the effects of these injuries on nesting seabirds are unknown.

Our objective was to quantify the effects of these two commonly occurring species of invasive ants on weight and survival of Wedge-tailed Shearwater chicks nesting in the Hawaiian Islands. To do this, we experimentally tested for the effects of each species on the hatching success, fledging success, and weight of Wedge-tailed Shearwater chicks. Using pairs of ecologically similar nesting islets—Pair 1 dominated by the BHA and Pair 2 dominated by the TFA, we reduced ant populations on one islet from each pair and measured seabird parameters and ant density 1 year before and 2 years after reductions in ant populations. We hypothesized that the hatching success, fledging success and weight of chicks would be higher on experimental versus control islets.

## Methods

### Study area and methodology

We chose two pairs of small (<5 ha) islets offshore of windward Oahu, Hawaii (Fig. 1). Islets within a pair were geologically similar and supported the same dominant plant and animal species, including nesting Wedge-tailed Shearwaters. The BHA was the numerically dominant arthropod on Popoia and Mokuauia (Pair 1) and the TFA was one of two numerically dominant arthropods on Moku Nui and Moku Iki (Pair 2) depending on time of year. The crazy ant (*Paratrechina longicornis*) was also abundant, however this species was not suspected of harming seabirds. Fifteen sampling points were established by navigating to randomly generated waypoints. Three Wedge-tailed Shearwater burrows were associated with each sampling point during three breeding seasons from 2002–2004. The three burrows closest to each of the 15 points were selected in June once each burrow contained an egg and followed until the nest failed or the chick fledged in late November. Burrows were monitored at least four times: after the egg was laid, during the week the egg hatched, in the middle of the nestling phase, and again 1–2 weeks prior to fledging. Chicks were weighed and the tarsus, culmen and wing chord were measured at each visit. Damage to the feet of chicks was quantified by counting number and measuring diameter of holes and tears in webbing and then estimating the percent of tissue lost or damaged.

Following a year of baseline data collection, we attempted to reduce ant populations in February 2003 using a granular protein-based ant bait with the active ingredient hydramethylnon (AMDRO<sup>®</sup>) on one randomly selected islet from each pair (Mokuauia and Moku Nui). The application of AMDRO<sup>®</sup> occurred after the shearwaters left the islets in December and prior to their return in March, with reapplication 1 year later in February 2004. Application rates were 1 lb per acre as directed on the label. Ant densities were monitored by counting the number of each species of ant attracted to index cards baited with peanut butter, honey and putted meat. Fifteen bait cards were set along a transect bisecting each islet. Bait cards were set concurrently on islets in each pair and left out for approximately 1.5 h.

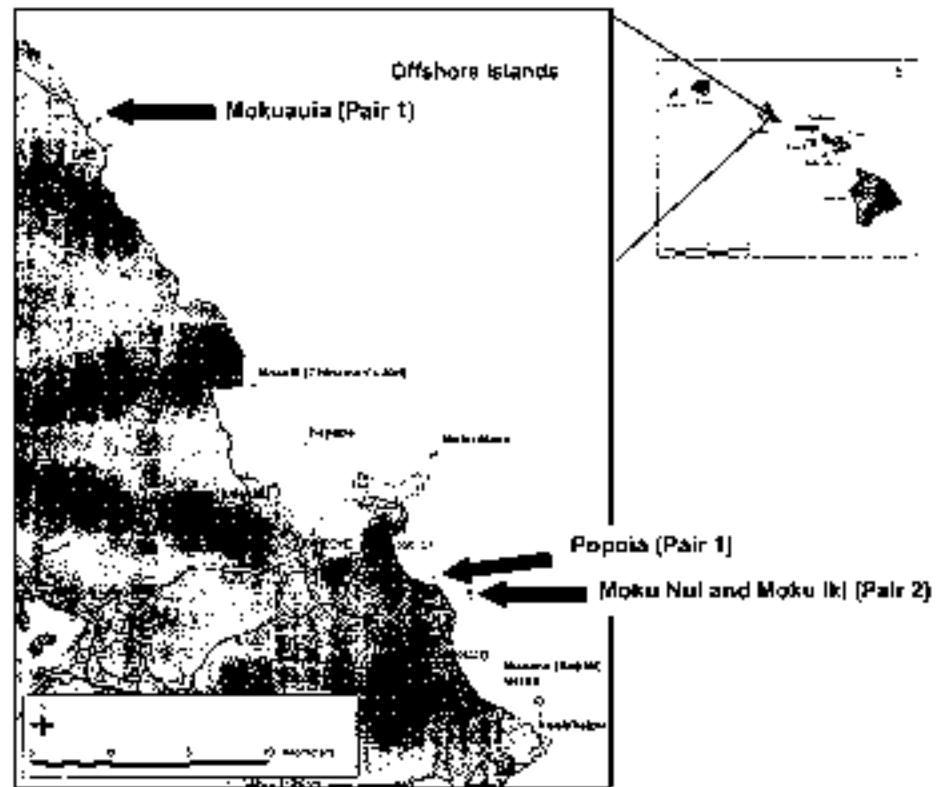
In addition, we made a short visit to Green Island on Kure Atoll, the northernmost atoll in the Northwestern Hawaiian Islands (lat: 28 N, long: 178 W). We visited Kure Atoll to assess BHA densities since this is the only location where BHAs are regularly reported attacking seabirds. Using the same methodology outlined above, we set bait cards at 23 points randomly located throughout the island on 8 June 2007 to get an estimate of ant density that we could compare to densities on Popoia and Mokuauia (Pair 1).

### Data analysis

We compared the number of injured chicks, eggs that hatched successfully, and chicks that fledged between islets (i.e., treatment vs. control) and years using a binary logistic regression. The data were analyzed as a 2 × 3 factorial with islet and year as main effects and a year × islet interaction term. Year was treated as a categorical variable. Direct comparisons between years were done using a Chi-Squared likelihood ratio test. Daily growth-rates of chicks were compared between islets and among years using a repeated measures mixed model analysis of variance (ANOVA) with “point” analyzed as a random effect nested within “islet”. Data were analyzed as a 2 × 3 factorial with islet and year as main effects and a year × islet interaction term.

Ant numbers present on bait cards over time on control and treatment islets were also compared using a repeated measures mixed model ANOVA with “point” analyzed as a random effect nested within

**Fig. 1** Location of four islets offshore of the windward coast of Oahu, Hawaii (lat 21° N, long 157° W) used as sites to study the effects of the big-headed ant (*Pheidole megarephala*) and the tropical fire ant (*Solenopsis geminata*) on weight and survival of nesting seabirds



"islet". Data were analyzed as a  $2 \times 3$  factorial with islet and year as main effects and a year  $\times$  islet interaction term. Average values are given as mean  $\pm$  standard error and we considered differences to be significant at an alpha of less than 0.05. All tests were performed using JMP version 3.2.1 (SAS Institute Inc.).

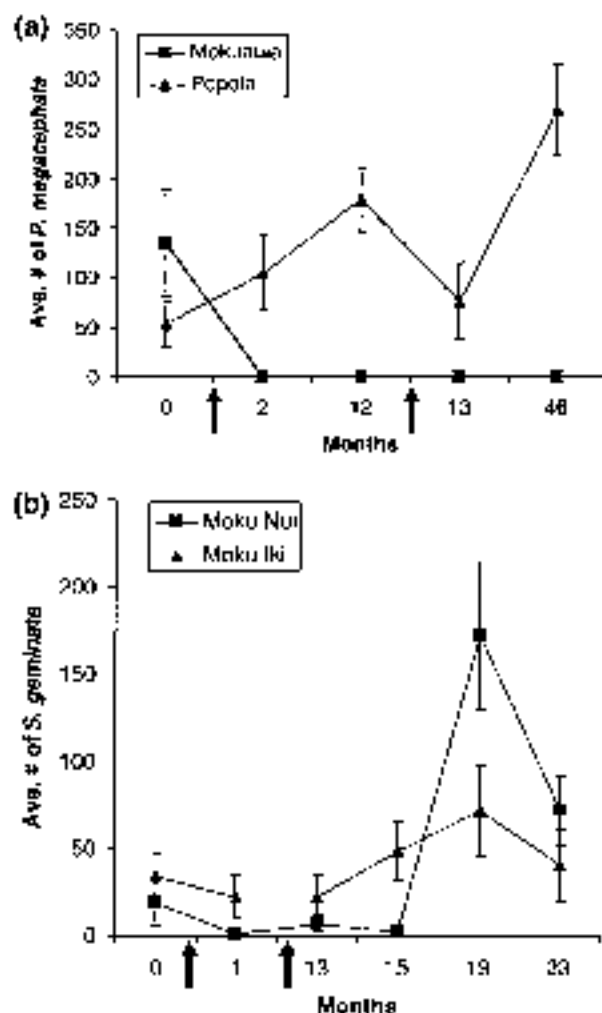
All chicks were assigned to one of four categories: none, mild (0–5% of tissue on feet missing or stings present but no tissue missing), moderate (5–20% of tissue missing), and severe (>20% of tissue missing). Weights from 121 chicks on Moku Nui and Moku Iki were pooled to examine the effect of the degree of injury on weight. We plotted chick weights for a given age and then fitted a polynomial to the data. Using residuals as our response variable, we compared the effects of degree of injury (i.e., none, mild, moderate, severe) on weight at a given age using a one way ANOVA (Minitab Release 14 2005) with multiple comparisons. *P*-values were adjusted for multiple comparisons using Tukey 95% simultaneous confidence intervals. *T*-tests were used to compare weights of severely injured chicks prior to injury with

other chicks of the same age to determine if severely injured chicks consistently weighed less, even prior to injury.

## Results

Following the February 2003 application of AMDRO<sup>®</sup>, the dominant ant species were eradicated (Mokuauia) and reduced (Moku Nui). The BHA was eradicated from Mokuauia after a single application of AMDRO<sup>®</sup> (Fig. 2). No evidence of reinvasion was found on subsequent visits to the islet through November 2006 (Fig. 2). Mean BHA densities were five times higher (676 vs. 135 individuals per bait card) on Kure Atoll in 2007 than at any time on Mokuauia (prior to 2003 eradication) and Popoia from 2002–2005. BHA densities were 2.5 times higher on Kure Atoll when compared to the highest ant density recorded on Popoia (i.e., November 2006).

On Moku Nui, TFA numbers declined between March 2003 and May 2004, following two applications of AMDRO<sup>®</sup>, but numbers rebounded by September



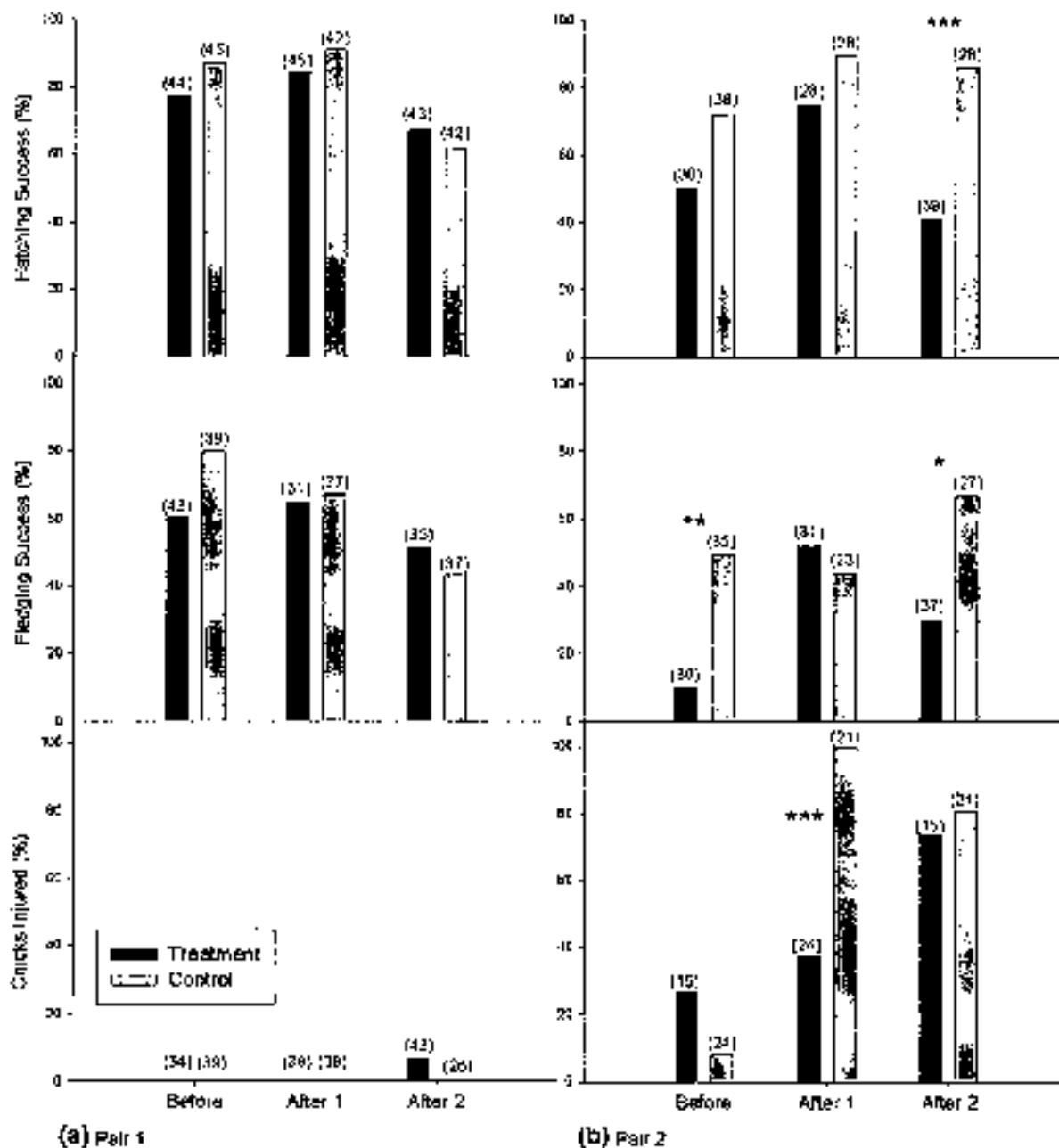
**Fig. 2** Average number of big-headed ants (*Pheidole megacephala*) on Pair 1 (Mokuauia and Popoia) and tropical fire ants (*Solenopsis geminata*) on Pair 2 (Moku Nui and Moku Iki) ± mean standard error (n = 15) on banks baited with honey, peanut butter, and peated meat. Fifteen bait cards were set on each islet during sampling periods from January 2003 to November 2006 on Popoia and Mokuauia and February 2003 to January 2005 on Moku Nui and Moku Iki before and after the application of AMDRO® on treated islets (Mokuauia and Moku Nui) in February 2003 and February 2004 (indicated by arrows). *Pheidole megacephala* was not observed on Mokuauia following a single application of AMDRO®. *Solenopsis geminata* densities were significantly, but temporarily reduced following the application of AMDRO® and prior to the rebound in September 2004.

2004, within 7 months of the second treatment (Fig. 2). Because of this obvious and unpredicted rebound in ant numbers we did the analysis for two different time periods (March 2003–May 2004 and September 2004–January 2005) while realizing that

this decision was not a priori but was made after observing data on ant abundances. When only data through May 2004 were included in the model, islet was the only significant effect ( $F = 9.17$ ,  $df = 1$ ,  $P = 0.0033$ ). When data from September 2004 to January 2005 were included in the model, both islet ( $F = 5.54$ ,  $df = 1$ ,  $P = 0.026$ ) and time ( $F = 5.53$ ,  $df = 1$ ,  $P = 0.026$ ) were significant effects.

We observed no evidence of injuries to shearwater chicks by BHAs on Pair 1 (Mokuauia and Popoia). Each variable (i.e., hatching success, fledging success, and percentage of injured chicks) remained relatively stable throughout the 3 years with parallel changes on both treated and untreated islets during any period (Fig. 3). Logistic regression analysis of data collected from 2002 (pre-treatment) to 2004 on hatching and fledging success indicated differences among years (hatching success: Wald  $\chi^2 = 13.44$ ,  $df = 2$ ,  $P = 0.0012$ ; fledging success: Wald  $\chi^2 = 9.8$ ,  $df = 2$ ,  $P = 0.007$ ), but not between islets (hatching success: Wald  $\chi^2 = 1.45$ ,  $df = 1$ ,  $P = 0.23$ ; fledging success: Wald  $\chi^2 = 0.53$ ,  $df = 1$ ,  $P = 0.47$ ). In addition, there was no indication of an islet  $\times$  year interaction (hatching success: Wald  $\chi^2 = 2.02$ ,  $df = 2$ ,  $P = 0.36$ ; fledging success: Wald  $\chi^2 = 3.05$ ,  $df = 2$ ,  $P = 0.22$ ). Injuries observed on three chicks on Mokuauia in 2004 were consistent with injuries received on islets occupied by TFAs and TFAs were observed in all three burrows. TFAs were first observed in low densities on Mokuauia in May 2004, approximately 15 months after the eradication of BHAs (Plentovich, unpubl. data).

Shearwater chicks were observed with injuries caused by TFAs on Moku Nui and Moku Iki (Fig. 5). These injuries were characterized by small swollen circular areas approximately 1–2 mm in diameter that later formed distinct holes. Severe injuries sometimes lead to the loss of all or part of the webbing and sometimes parts of the phalanges. There was no difference in the number of injured chicks on Moku Nui compared to Moku Iki in 2002 prior to the treatment (Chi-squared likelihood ratio:  $\chi^2 = 2.30$ ,  $df = 1$ ,  $P = 0.39$ ) or in 2004 (Chi-squared likelihood ratio:  $\chi^2 = 0.29$ ,  $df = 1$ ,  $P = 0.59$ ). However, in the first year following the application of AMDRO® (i.e., 2003), there were significantly more injured chicks on Moku Iki (Chi-squared likelihood ratio:  $\chi^2 = 25.53$ ,  $df = 1$ ,  $P = 0.000$ ). In fact, the percentage of chicks observed with injuries from fire ants



**Fig. 3** Hatching success, fledging success and number of chicks injured by invasive ants on four islets offshore of Oahu, Hawaii before (2002) and after (2003, 2004, respectively) the reduction of the invasive ant species *Pheidole megacephala* on

Mokuauia and *Solenopsis geminata* on Moku Nui. Sample sizes are in parentheses. Significance between treatment and control is denoted as follows: \* $P \leq 0.05$ , \*\* $0.05 > P \geq 0.005$ , \*\*\* $P < 0.005$

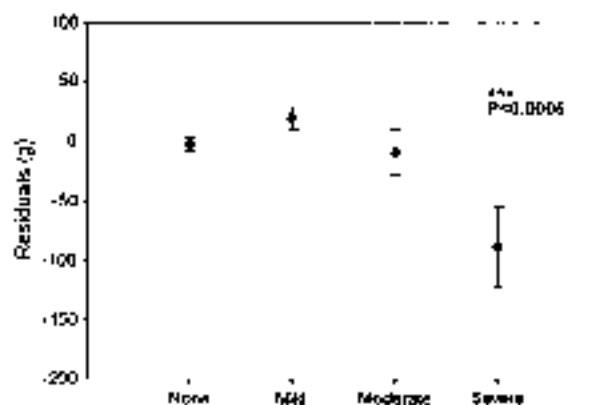
increased dramatically on the untreated islet (Moku Iki) from 8.3% to 100%, while only increasing on the treated islet from 26.7% to 57.5% (Fig. 3).

Logistic regression analysis of hatching success on treated and untreated islets indicated significant year (Wald  $\chi^2 = 6.25$ ,  $df = 2$ ,  $P = 0.04$ ) and islet (Wald

$\chi^2 = 13.84$ ,  $df = 1$ ,  $P = 0.0002$ ) effects, but the interaction between the two was not significant (Wald  $\chi^2 = 2.39$ ,  $df = 2$ ,  $P = 0.30$ ). There was no difference in hatching success on Moku Nui compared to Moku Iki in 2002 (Chi-squared likelihood ratio:  $\chi^2 = 3.4$ ,  $df = 1$ ,  $P = 0.18$ ) and 2003 (Chi-squared likelihood

ratio:  $\chi^2 = 2.0$ ,  $df = 1$ ,  $P = 0.96$ ). However there was a significant decrease in hatching success on Moku Nui in 2004 (Chi-squared likelihood ratio:  $\chi^2 = 14.6$ ,  $df = 1$ ,  $P = 0.0003$ , Fig. 3). Logistic regression analysis of fledging success on treated and untreated islets indicated significant year (Wald  $\chi^2 = 7.19$ ,  $df = 2$ ,  $P = 0.027$ ) and islet (Wald  $\chi^2 = 11.2$ ,  $df = 1$ ,  $P = 0.0008$ ) effects including a significant year  $\times$  islet interaction (Wald  $\chi^2 = 8.89$ ,  $df = 2$ ,  $P = 0.01$ ). Fledging success was higher on the untreated islet (Moku Iki) in 2002 (Chi-squared likelihood ratio:  $\chi^2 = 12.2$ ,  $df = 1$ ,  $P = 0.0015$ ) and 2004 (Chi-squared likelihood ratio:  $\chi^2 = 9.5$ ,  $df = 1$ ,  $P = 0.006$ ), but there was no difference in 2003 (Chi-squared likelihood ratio:  $\chi^2 = 0.20$ ,  $df = 1$ ,  $P = 0.96$ , Fig. 3).

There was no difference in daily growth rates of chicks on treated and untreated islets. A scatter plot of age versus weight of all chicks on both Moku Nui and Moku Iki was fit with a polynomial ( $R^2 = 0.89$ ) and the residuals were used to compare weight and injury category (i.e., none, mild, moderate, severe). Severely injured chicks from both islets had lower weights than chicks with no, mild and moderate injuries (ANOVA with pair-wise comparisons,  $F = 6.78$ ,  $df = 3$ ,  $P = 0.000$ , Fig. 4). A total of 5.1% (6/118) of chicks sustained severe injuries. When we compared pre-injury weights of one 11 and one 12 day old severely injured chicks with seven uninjured, mildly injured, or moderately injured



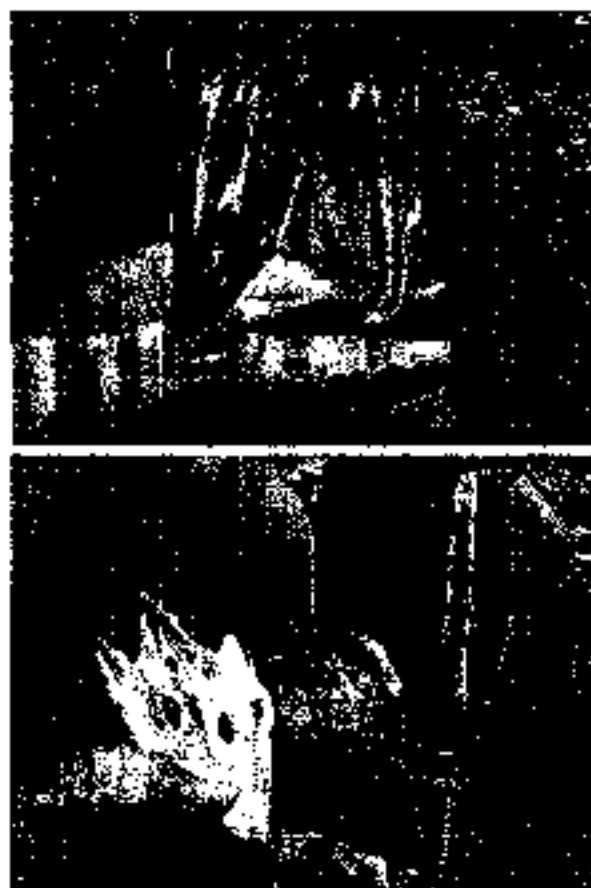
**Fig. 4** Comparison of age versus residuals of weight (g) of Wedge-tailed Shearwater (*Puffinus pacificus*) chicks with one of four degrees of tropical fire ant (*Solenopsis geminata*) induced injury: none, mild, moderate or severe. Chicks with mild damage lost less than 5% of the tissue on their foot. Those with moderate damage lost 5–20% of their feet. Those with severe damage lost more than 20% of their feet. Significant differences are denoted by \*\*\*

chicks of similar ages and one 5-day old severely injured chick with eight 5-day old uninjured or mildly injured chicks, we found that prior to injury, severely injured chicks weighed more than or the same as chicks that were not severely injured ( $T$ -test:  $t = 2.85$ ,  $df = 7$ ,  $P = 0.025$ ;  $T$ -test:  $t = 1.37$ ,  $df = 7$ ,  $P = 0.211$ , respectively). We did not have pre-injury data on the remaining three chicks in this category. Injuries to chicks in this category ranged from the loss of 22–70% of their feet, especially their webbing and parts of their phalanges (Fig. 5).

## Discussion

### Seabird weight and survival

Invasive ants are a significant conservation concern and can have far reaching effects in ecosystems they



**Fig. 5** Wedge-tailed Shearwater (*Puffinus pacificus*) chicks uninjured (top) and severely injured (bottom) by the tropical fire ant (*Solenopsis geminata*)

invade (Holway et al. 2002). We found that the BHA and TFA had differential effects on nesting seabirds. On Pupoia and Mokuauia (Pair 1), the BHA did not change the hatching success, fledging success, or weight of wedge-tailed shearwater chicks. We found no evidence that the BHA harmed seabird chicks on Pupoia or Mokuauia. This contradicts our expectations from unpublished observations of BHAs attacking several species of seabirds (e.g., Wedge-tailed Shearwaters; Booby; Petrels; Laysan Albatrosses; Sooty Terns; C. Vanderlip, pers. comm.; S. Plantavich, pers. obs.) on Kure Atoll in the Northwestern Hawaiian Islands. Similar observations do not exist on Pupoia and Mokuauia and differential observations between the two sites are likely linked to the considerably higher ant densities present on Kure Atoll (e.g., 2.5–5 times more ants were present on bait cards on Kure Atoll compared to Pupoia and Mokuauia). Although BHAs are regularly reported attacking seabirds on Kure Atoll, how these attacks effect seabird growth and survival is unknown.

On Moku Ika and Moku Nui (Pair 2), our results differed in 2003 and 2004 based on the success of our ant control efforts. In 2003, the temporary reduction in TFA numbers to undetectable levels (Fig. 3) corresponded to an increase in fledging success and fewer injuries to shearwater chicks relative to the untreated islet. The number of chicks injured increased insignificantly during this period on the treated islet while it skyrocketed on the untreated islet from 8 to 100% (Fig. 3). In 2004, ant numbers rebounded on the treated islet (Fig. 2) and we observed a corresponding decrease in fledging success on the treated islet (Fig. 3). Hatching success was consistently lower on Moku Nui compared to Moku Ika over the three years. The low baseline hatching success on Moku Nui was possibly due to regular visitation by humans and therefore increased chances of crushed burrows due to human traffic. This was difficult to assess because unstable soil on both islets made differentiating burrows crushed by foot traffic and burrows that collapsed following heavy rains difficult to distinguish.

Severely injured chicks weighed less than chicks with no, mild, or moderate injuries (Fig. 4). However, prior to attacks these individuals were not significantly lighter than non-severely injured chicks. These data indicate that attacks by TFAs caused

chicks to either lose weight or gain weight at a slower rate than other uninjured, mildly injured or moderately injured individuals. To our knowledge this is the first documentation of the TFA negatively affecting any vertebrate outside the ant's native range. These results are in agreement with a variety of studies showing that TFA's congener, *S. invicta*, can decrease hatching success, fledging success and/or growth rates of at least 24 different species of oviparous vertebrates (Holway et al. 2002; Tschinkel 2006). Bob-white quail chicks exposed to the maximum number of individuals of *S. invicta* (200 individuals for 60 s averaging 34 ants on body) gained weight more slowly than chicks exposed to fewer individuals (Giuliano et al. 1996). We did not assess the exact number of TFAs attacking chicks; however we similarly found the effects most prominent in severely injured birds (Fig. 4).

Injuries were observed only on the feet, legs and rarely around the cloaca of shearwater chicks. Injuries were never observed around the eyes or on the bill. It was suggested that some of these lesions may be associated with infection by the avian pox virus (*Poxvirus avium*), but pox lesions have not been observed on Oahu's offshore islets (D. Smith, DLNR, pers. comm.) and the types of injuries we saw are only found on islets invaded by TFAs. In fact, we observed the species attacking chicks on several occasions and, in one case, found the head of a TFA soldier attached to the foot of an injured chick. It is unclear if the TFA is preying upon chicks or if it is stinging the chicks in defense. The TFA is undoubtedly attracted to hatching eggs. As previously mentioned, *Solenopsis* spp. have also been observed attacking pipping eggs, puncturing eggs and preying upon hatchlings of a variety of egg-laying vertebrates (Holway et al. 2002). If shearwater chicks are able to hatch successfully, their movement may agitate ants already attracted to the burrow or hatching egg. Richardson (1948) noted that severe injuries seemed to occur during the first few weeks after hatching. In our study, moderate or severe injuries occurred throughout the nestling period, but the majority of injured chicks showed evidence of injuries from live ants within the first 3 weeks of hatching. Although we did not test this, it is also possible that chicks with burrows near fire ant nests are attacked more often by ants defending their nests or incidentally moving through seabird burrows.



In summary, the TFA can have significant negative effects on hatching success, fledging success and weight of seabird chicks. At least 5% of Wedge-tailed Shearwater chicks in this study sustained severe injuries from fire ants. In these severe cases, the fire ant reduced weight of seabird chicks following attacks and relative to chicks with none, mild and moderate injuries (Fig. 4). Since shearwaters and many other seabirds use their feet for diving and paddling while foraging, the loss of significant portions of their feet along with a low fledging weight make post-fledging survival questionable.

## Conclusion

Nesting seabirds drive ecosystem processes by digging burrows and depositing marine derived resources on the land in the form of guano (see Maron et al. 2006). Loss of colonies or reductions in their sizes could have significant effects on ecosystem processes (Hutchinson 1950; Fukami et al. 2006). Invasive ants can have negative effects on nesting seabirds, sometimes causing widespread nest abandonment (Pearle 1999). On two of our study sites, invasive ants attacked birds more often some years than others, even when the ant population remained relatively stable. In 2002, the year we collected baseline data, we observed the lowest incidence of injuries from the TFA (8.3%) on Moku Iki and no severe injuries were observed (Fig. 3). In 2003, 100% of chicks were injured by the TFA on Moku Iki, the untreated islet, but we documented only modest increases on the treated islet. These data suggest the effects of the TFA and other invasive ant species on seabird chicks can change markedly from year to year. Such changes may be related to variation in environmental factors (e.g., rainfall) or variation in food resources associated with other disturbances (e.g., rat eradication, Pearle 1999, J. Eijzena, pers. comm.; or changes in populations of homopterous insects). Since negative effects of ants on nesting seabirds may be difficult to detect and are typically not monitored, they may be largely unknown and/or underestimated throughout the world where the two groups overlap. As the ranges of invasive ants continue to expand, we expect interactions between these two groups of species to increase.

Although eradication of most invasive ant species is very difficult, this study and others including the successful control of the BHA in pineapple plantations in Hawaii (Reimer and Beardsley 1990) and the eradication of the BHA from Kakadu National Park in Australia (Hoffmann and O'Connor 2004) indicate that this species can be effectively eradicated using AMDRO<sup>®</sup> (Stanley 2004). Additional research is needed to find effective ways to eradicate other invasive ant populations and to predict and mitigate resulting changes in arthropod communities. Unanticipated changes in the natural community resulting from removal of invasive ants, including expansion or colonization by other harmful ant species, need to be considered. Currently, eradication of BHA may be most beneficial in isolated areas where no other invasive ants occur and in situations where the invasion is limited to a small area.

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