Discovering Cryptic Breeding Sites by Radio Tracking Coconut Rhinoceros Beetles, *Oryctes rhinoceros* (Coleoptera: Scarabaeidae)

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Coconut rhinoceros beetle (CRB), *Oryctes rhinoceros* L., is a serious pest of coconut trees and other palms throughout Southeast Asia and on several Pacific Islands. Adults kill palms when they bore into crowns to feed on sap. Larvae feed only on dead plant material at breeding sites. Eradication is possible if all breeding sites are located and destroyed. A field trial was performed on Guam to test the feasibility of using radio-tagged adults to discover cryptic breeding sites. Of 34 radio-tagged beetles that were released, 19 were successfully tracked to landing sites, 14 were lost when they flew beyond the range of our receivers and one beetle did not fly. Two of the landing sites were confirmed breeding sites as indicated by presence of other CRB at the same site. Ten landing sites in coconut palm crowns were considered to be potential breeding sites. None of the radio-tagged beetles were caught in numerous pheromone traps near release sites. Ten landing sites in coconut palm crowns were considered to be potential breeding sites.

Using animals to find aggregations of conspecifics is not a new idea. For example, by exploiting the gregarious nature of goats, the Judas goat method is a vital tool for detecting goats at low densities and a monitoring tool to confirm eradication (Campbell and Dolan 2005). Radiotelemetry collars are fitted to select goats, which are released and allowed to seek out other goats. Judas goats are then radio tracked, either on foot or by helicopter, and accompanying goats are shot.

This approach allows the last individuals to be removed. Judas goats have been used successfully in a number of island eradication programs. Recent development of light-weight, miniaturized radio-tracking transmitters now allows application of this technique to insects and other small animals which aggregate. Here, we report on a field trial to determine the feasability of radio-tracking coconut rhinoceros beetles (CRB), *Oryctes rhinoceros* (L.) (Coleoptera: Scarabaeidae) to find cryptic breeding site aggregations.

CRB is a major pest of coconut palm, *Cocos nucifera* L. (Arecales: Arecaceae). Adult beetles defoliate and kill palms when they bore into crowns to feed on sap. When Pacific Islands are invaded by this pest, coconut palm mortality may reach greater than 50% with in a few years (Gressitt, 1953). In contrast to adults, CRB larvae feed on decaying vegetation and do no economic damage. CRB aggregate at breeding sites which include dead standing coconut palms, fallen coconut logs, rotting coconut stumps and decaying wood of many tree species. They also are found in piles of compost, sawdust and manure where these materials are available.

CRB first was detected in Guam in the Tumon Bay tourist hotel area in September, 2007. A delimiting survey indicated that the infestation was restricted to only a small are of the island (<1,000 acres) and an eradication project was launched Smith and Moore (2008). The project relied on mass trapping using pheromone traps to capture adults, and sanitation to remove rotting vegetation used as breeding sites. The traps were baited with the CRB aggregation pheromone, ethyl 4-methyloctanoate (Hallett et al. (1995)) commercially available as oryctalure (P046; ChemTica Iternacional, Heredia, Costa Rica). Four detector dogs were trained to assist in finding breeding sites on the ground by sniffing out CRB grubs.

Despite these efforts, CRB damage in central Tumon Bay remained high and the infestation spread to all parts of Guam by 2010 making eradication unfeasable. Attempts at population suppression using *Oryctes* nudivirus (OrNV), the preferred biocontrol agent for CRB, also failed. It has recently been determined that the Guam CRB population is genetically different from other populations in Asia and the Pacific and it is considered to be a new invasive biotype of of CRB which has escaped from biocontrol by OrNV Marshall et al. (2015). In addition to being resistant to all currently available isolates of OrNV, it appears that the CRB-Guam biotype behaves differently. CRB breeding sites are commonly found in coconut palm crowns on Guam but only occasionally elsewhere (Moore et al., 2015) and pheromone traps baited with oryctalure are not very attractive.

Eradication of CRB from an island is difficult once this pest has become established. The only proven tactic for eradication of this pest is a vigorous sanitation program which discovers and destroys all active and potential breeding sites. The single successful CRB eradication to date occured on the tiny (36 km^2) Niuatoputapu Island (also known as Keppel Island), which lies between Samoa and Tonga, using sanitation alone (Gressitt, 1953; Catley, 1969). Currently available pheromone traps, although useful for detection and surveillance, are not attractive enough to provide significant population suppression in mass trapping operations. Mass trapping coupled with sanitation during 1971 through 1974 failed to eradicate CRB on two islands in Fiji. The eradication attempt was abandoned when it was determined that there was "a low but persistent population which could not be trapped. ... It appeared that possible results from the indefinite continuation of the trial were no longer commensurate with the costs" (Bedford, 1980).

As previously mentioned, four detector dogs for CRB were trained and employed for the first time on Guam. The dogs were trained to sniff out CRB grubs and it was hoped that they would enable us to find remaining, cryptic breeding sites in the final stages of eradication. The detector dogs were a very expensive component of the Guam CRB eradication program and they were retired after two years of service when it became evident that eradication was no longer feasable.

In this article, we report results of a field trial intended to test the concept of following radio-tagged CRB to cryptic breeding sites as an alternative to using detector dogs. Radio tracking of mammals and birds has been employed for many years and recent progress in miniatuization of radio transmitters now makes this technique available for insect studies.

Materials and Methods

Radio Tracking Equipment

All radio tracking equipment was purchased from Advanced Telemetry Systems, Isanti, Minnesota. We used A2414 glue-on transmitters which weighed 300 mg. Each of 32 transmitters used in the trial operated at a unique frequency allowing us to track multiple targets simultaneously. Two transmitters were reused on two different beetles.

We used four R410 scanning receivers equiped with three-element folding Yagi antennas (Fig. 1). Two recievers operated in the 146 to 150 MHz frequency band and two operated in the 162 to 166 MHz band.

Each of the 4 trackers used a GPS reciever (Garmin Oregon 650) to record waypoints.

Collection, Selection and Preparation of Test insects

CRB used for radio tracking were caught in pheromone traps baited with ethyl 4-methyloctanoate (Oryctalure; P046; ChemTica Iternacional, Heredia, Costa Rica). Beetles were removed from the traps within one week of capture, placed in tubs containing moist peat moss, fed fresh banana slices and allowed to rest for at least three days.

Beetles were selected for flight capability at least one day prior to use in the radio-tracking trial. Groups of about 30 beetles were placed in moist peat moss in a metal bowl which they could exit only by flight. The bowl was supported on a stand inside a flight chamber consisting of a large (121 liter) grabage container and a lid was afixed. Beetles were left in the flight chamber overnight. Those that ended up on the flight chamber floor were deemed to have flown. All others were rejected from the radio-tracking field trial.

Flight-capable beetles were marked with a unique four-digit code engraved on one elytrum using a laser engraver (Fenix Flyer, Synrad Inc., Mukilteo, WA, United States). The sex, mass and elytral dimensions of each beetle were then recorded.

A transmitter were glued to the pronotum of each beetle using a hot-melt glue gun (Fig. 1). Prior to transmitter attachment, the beetle pronotum was abraded with sandpaper to improve adhesion. Each glue-on transmitter had a mass of approximately 300 mg and was secured with approximately 250 mg of adhesive.

Test insects were stored and transported in lidded plastic bins approximately (45 cm by 30 cm by 18 cm) containing about 12 cm of damp peat moss. Because not all beetles were released when first taken into the field, some beetles remained in storage for up to six days.

Tracking Procedure

Tagged CRB were radio tracked after release at two locations on Guam: Yigo and Asan (Fig. 3). Triton Farm University of Guam, Dededo (13°31'56.8"N 144°52'24.0"E) and Asan Beach National Park, Hagåtña (13°27'57.5"N 144°42'39.4"E). Triton Farm is an inland experimental farm bordered by a residential area and uncultivated forest areas that include coconut palms along with other trees. Asan Beach National Park is roughly triangular with the ocean bordering one side, coastal wetlands on another, and forested hillside on the third. The park itself is a large, open, grassy field and includes with coconut palms on the edges, many of which displayed CRB damage at the time of the study. Thus, both sites feature relatively accessible terrain that provides a variety of potential breeding sites as well as adult food sources. At each study location, a grassy, open area was chosen for CRB release.

Weather conditions during the experiment were mainly clear with occasional periods of rain and overcast skies. On release dates, August 8 to August 14, average temperature ranged from 27°C to 29°C while relative humidity was 80% to 88%. Beetles were generally tracked under clear skies with the exception of August 9 during which light showers occurred.

Beetles were transported to release sites in plastic storage bins. The lid of the bin was removed at dusk (roughly 19:30) and the container was closed at roughly 21:30. Once the containers were opened, CRB activity was carefully monitored using an infrared camera. Observation under the infrared camera revealed that beetles thermal profile would change just prior to flight, and thermally active beetles observed emerging from the peat moss were briefly viewed under red light to record the identification number and determine the frequency of the radio transmitter. Though nearly all beetles flew independently, several beetles that had not yet flown by the end of experimentation were encouraged to flight by removing them from the peat moss and throwing them into the air to facilitate takeoff.

CRB were pursued on foot following release and were tracked until a landing site was determined or until the transmitter signal was lost. In either case, a waypoint was recorded at the landing site or the last point of signal reception using a GPS unit.

Landing sites were visited on the following morning, and attempts were made to more precisely determine the location of each beetle. Beetle locations were monitored over several days, and beetles and or transmitters were recovered when possible at the end of the experiment. CRB and transmitters were successfully recovered by digging up beetles that buried into soil or compost; however the locations of CRB tracked to coconut crowns could not be as exactly determined due to the density of the frond foliage.

Analysis

In assessing the flight patterns of beetles for trends between sex and size, percent emergence weight (%EW) was calculated as an additional consideration. Percent emergence weight describes CRB mass at the time of measurement relative to its estimated mass upon emergence. This value can be estimated based upon a linear equation relating elytral measurements and emergence weight (Vander Meer and Mclean, 1975). This value is significant in data analysis because %EW reflects the present life stage of a beetle and how much stored energy it has available; CRB emerge at their heaviest weight and gradually lose weight over their lifespan.

-GIS (Diego)

-stats (Matt)

Results and Discussion

trial done in August 2015 - weather

Breeding Site Discovery

Of 34 radio-tagged beetles that were released, 19 were successfully tracked to landing sites, 14 were lost when they flew beyond the range of our receivers and one beetle did not fly (Fig. 2). Most of CRB tracked to landing sites were in tree tops (n=11) and the rest were on or below the ground (n=8).

Two of the landing sites were confirmed breeding sites as indicated by the presence of other CRB at the same site.

The first breeding site we discovered by radio-tracking was in an extremely cryptic and unsuspected microhabitat: in a hole in a large rotting branch of a breadfruit tree (*Artocarpus altilis*), about six meters above the ground. In this case, the receiver had become detached and the marked beetle was not recovered. However, 3 other CRB adults were occupying the hole. It is highly likely that this breeding site was in a branch broken by high winds experienced when Typhoon Dolphin passed over Guam in May 2015, about 3 months before the radio-tracking trial.

The second breeding site we discovered was beneath a barrel trap. ... NEED DESCRIPTION

Ten landing sites in coconut palm crowns were considered to be potential breeding sites but we did not have time or equipment to confirm these. Arboreal breeding sites may be common on Guam (Moore et al. (2015)).

Tracks and Displacement

Distance between release sites and landing sites for the 19 beetles tracked to a landing site. The remaining 14 beetles flew beyond the range of our radio receivers, about 500 m. Mean displacement could not be estimated, but median displacement was 333 m, with no significant difference between release sites (Fig. 4).

Maximum range for a single straight-line flight is 4 km, as measured in a lab experiment with tethered beetles on a flight mill. However, from field observations it appears that natural flight is limited to a few hundred meters. In a mark-release-recapture experiment, Kamarudin and Washid measured a dispersal rate of 19m per day. References: Hinckley, A. D. 1973. Ecology of the coconut rhinoceros beetle, Oryctes rhinoceros (Coleoptera: Dynastidae). Biotropica 5 (2):111–116. "Beetles freshly fed on a palm were flown on a tether in the laboratory. Their flight duration averaged between 2 and 3 hours. Distances traveled were between 2 and 4 km. Beetles exhausted by such long flights were held in moist soil or wood for a day or two, after which they could again fly, although seldom longer than 30 minutes." Kamarudin, Norman and Mohd B. Washid. 2004. Immigration and activity of Oryctes rhinoceros within a small oil palm replanting area. Journal of Oil Palm Research 16 (2):64–77. "Based on the capture, mark, release and recapture experiment using pheromone traps, the beetle's ability to fly was estimated at about 19 m day-1 or more than 130 m in a week. The range covered was estimated at 10-23 m day-1. This suggests that the flight of beetles within a replanting area is quite limited because of the abundance of food and breeding sites." "Earlier reports have suggested the ability of the beetle to fly considerably long distances (Nirula, 1955; Hinckley, 1973). A distance recorded in the field was about 700 m (Monty, 1974). However, a laboratory experiment has indicated that the beetle can fly up to 2 to 4 km in 2 to 3 hr (Hinckley, 1973). Liau and Ahmad (1991) reported a flying distance of 140 m into a replanting area. This was in the case of migration to new breeding areas. But in this study, which was done within a replanting area, the beetle was noted to fly less (estimated around 19 m day-1, and about 133 m a week) (Table 5). These values may be below the actual flight potential as their flights were monitored using pheromone traps. However, the conducive environment, availability of food and abundant breeding sites in the replanting area logically play a role in the flight distance."

Mass relationships

Masses of CRB landing on the ground were not significantly different than those landing in treetops for females (4.486 g, 4.407 g; Welch's $t = 0.117$; $p = 0.914$) and males (3.638 g; 5.043 g; Welch's $t = -2.2749$; $p = 0.053$).

However, percent emergence weights of CRB landing on the ground were higher than those landing in treetops (Fig. 5). A possible explanation for this observation is that individuals with low percent emergence weight were hungry and therefore flew to treetops in order to bore into crowns to feed and beetles with lower percent emergence weight were searching for breeding sites and/or mates.

Response to Traps

Despite the fact that beetles were released within proximity of active phermone traps, none were trapped. The mean trap catch rate of pheromone traps at the Yigo experiment station during August 2015 was 0.03 beetles per trap-day for standard bucket traps (n=3 traps), 0.13 for barrel traps (n=31), and 0.15 for DeFence traps (n=4). In addition, no marked beetles were trapped in fish gill netting draped over a greenwaste pile at the Yigo site. This pile trapped 0.50 beetles per trap-day during August 2015. **TRAP CATCH DATA FOR ASAN NEEDED.**

If we assume that the wild beetles respond to traps in the same way as the radio-tagged beetles, then we can estimate that the suite of traps in the vicinity of the the release points catches less than one in 33 (<3%) of wild beetles. The low trap performance is consistant with results from previous mark-release-recapture data from Guam (Moore, unpublished). It is possible that oryctalure is less attractive to individuals of the CRB Guam biotype is lower than to individuals of other other biotypes. Results indicate that none of the currently available CRB trapping methods are usefull for population reduction of CRB-Guam.

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BEGIN EXTRA

The following stuff is from previous versions. Kept here for reference and possible inclusion.

The coconut rhinoceros beetle (CRB), *Oryctes rhinoceros* L. (Coleoptera: Scarabaeidae: Dynastinae), is a serious pest of coconut trees, *Cocos nucifera* L., and other palms throughout the Pacific and Southeast Asia. CRB damage to coconut trees can result in a mortality rate of up to 50% as reported in Palau (**?**). Although CRB damage does not always result in coconut tree mortality, the characteristic V-cut damage to palm fronds can adversely affect the aesthetic value of ornamental trees, which is especially problematic in tourist areas. Such is the case in Guam, where unmanaged palms show CRB damage in close to 100% of the palms near the highly touristic Tumon waterfront area (Moore, Jackson 2010).

CRB damage to palms is caused almost exclusively by adult CRB feeding in coconut tree crowns, with larvae causing little or no economic damage as they feed on decaying plant material. Typically, adult beetles bore into the apical meristematic tissue of palm trees and feed on the base of unopened fronds, resulting in V-cuts once fronds open (Bedford 2013, Hinckley 1973). Once fed, adult CRB fly in search of breeding sites to mate. Adult CRB generally repeat this cycle of feeding and mating until they can no longer fly from feeding to breeding sites (Paper). This behavioral pattern is problematic for pest management efforts since CRB can breed in a wide range of locations, which tend to be difficult to find (Bedford 2013, Hinckley 1973). Sources in Malaysia and Guam have reported breeding sites in shredded palm trunk material, palm frond debris, compost heaps, and dead palm trunks, all of which are abundant in these tropical countries, and this high abundance of breeding sites leads to higher damage by CRB (Bedford 1976, Bedford 2013).

CRB monitoring and control utilizes a number of management techniques. These include biological control methods, which have played an essential role in the control of CRB populations. Biocontrol of CRB larvae mainly consists of using the fungal species Metarhezium anisopline, which has been reported to effectively control larvae populations (Arura 1984, Bedford 2013, Ferron et al. 1974). On the other hand, adult CRB biocontrol relies on the use of viral control agents. Infection with Baculovirus oryctes has successfully decreased CRB populations in various nations of Southeast Asia and the Pacific where infected individuals were released (Bedford 1985, Lomer 1985, Gorick 1980). However, recent studies report that the Guam CRB biotype has seemingly developed resistance to the viral control agent, creating an even more dire situation for the control of CRB (Moore, Jackson 2010).

Traps and lures have also been employed in CRB monitoring and surveillance efforts. Bioassay studies have reported several lures that attract adult CRB. Of these lures, ethyl 4-methyloctanoate, the CRB aggregation pheromone, has had fairly good results (PAPER, Vander Meer 1979, Vander Meer 1983). However, traps utilizing this lure in Papua New Guinea have had moderate success with an average of 131 CRB caught per trap over a 19 week period (Bedford 1975). The situation is worse in Guam, where trap systems have not provided successful control of CRB, with catching rates as low as 0.0006 beetles per trap per day (Moore, Jackson 2010). Finding and destroying breeding sites has been an integral part of CRB eradication programs both in Guam and in Hawaii. However, the cryptic nature of CRB breeding sites makes them difficult to discover. Therefore, there is a pressing necessity to develop methods to reliably discover cryptic CRB breeding sites. Trained dogs have been utilized to detect pest insect locations with olfactory cues in several studies with moderate success (sources). However, the training of dogs is an expensive process and may have limited usefulness for discovering breeding sites in trees. Alternatively, predators/parasitoids or conspecifics of pest insects have evolved superior sensory systems to find either prey or mates in a complex natural environment and are the most adequate agents to detect a species. Following this idea, a novel way to detect pest insects in the wild has been recently discovered. Swink (et al.) described the use of the predatory wasp Cerceris fumipennis, a natural predator of different beetles in the Buprestidae family, to specifically monitor the emerald ash borer. Although this biological control agent succeeded in capturing a large number of beetles, C. fumipennis could not serve as a selective control agent as it collected samples of 52 different species in 11 different genera (Swink 2013). An obstacle to using conspecifics is the necessity to have the capability of following the marked individual. This problem is thoroughly addressed by using radio telemetry to investigate insect populations and behavior. Rink and Sinsch have utilized radio telemetry to study population migration and connectivity of the stag beetle Lucanus Cervus in order to define conservation efforts for the species (Rink and Sinsch 2007). Similarly, Beaudoin-Olliver (et al.) has implemented radio telemetry to successfully describe the flight behavior of the species Scapanes australis of the Dynastinae subfamily, to which CRB belongs (Beaudoin-Olliver 2003). In both of these cases, radio telemetry proved to be able to successfully track individual beetles, elucidating its potential use in the control of insect pests with conspecifics.

The semio-chemical communication adult CRB utilize to find mates in breeding sites provide a prime opportunity to locate cryptic breeding sites. This chemical communication signaling can be exploited by using radio telemetry to follow adult CRB that are seeking these cryptic breeding sites. This study seeks to develop a control mechanism that uses laboratory-reared CRB equipped with miniature radio-tracking devices to identify cryptic breeding sites, which could then be treated, removed or destroyed.

The tagging and radio tracking of CRB in this study led to the successful location of multiple cryptic breeding sites at both experiment sites. CRB were most active from approximately 19:30 to 21:00, and flight activity did not appear to be heavily influenced by the prevailing weather conditions. Transmitters did not inhibit the flight mechanics of CRB to an observable degree. Over the course of experimentation, it was observed that beetles employed thermogenesis in flight muscles directly prior to flight, allowing a reliable prediction to be made as to which beetles were about to fly by detecting thermal radiation with an infrared camera.

A total of 33 out of 34 beetles tagged for release flew during the course of this study. Of the 33 beetles that flew, 19 were successfully tracked to landing sites (Figure 1). The % EW for CRB that were successfully located, 78 ± 2%, and for CRB that were lost, 72 ± 2%, differed significantly (t-test: $P = 0.021$). However, EW ($P = 0.822$) and weight ($P = 0.510$) did not differ between CRB that were successfully tracked or lost after release. Additionally, there were no differences in the numbers of male and female CRB that were successfully located or lost (Fisher's: $P = 1.000$).

No relationship was found between the distance beetles moved from the release point and beetle EW ($R2 = 0.0686$), %EW ($R2 = 0.0462$), or weight ($R2 = 0.0465$). There was no difference in the mean distance beetles moved at the two experimental sites, Yigo, 276 ± 42 m, and Asan, 215 ± 57 m ($P = 0.408$). Additionally, no differences were found between the mean distances male (254 ± 44 m) and female (233 ± 61 m) beetles moved ($P = 0.778$).

Landing locations of CRB were categorized by microhabitats described as other trees, coconut crown, traps, base of trees, or soil unassociated with trees or traps. Percent emergence weight varied significantly by the microhabitat to which CRB were tracked (Figure 2a., ANOVA: F = X.XXX, P = X.XXX). Microhabitats of CRB were further clustered as arboreal (> 1 m above ground) or terrestrial destinations (< 1 m above ground) (Figure 2b.). When microhabitats were grouped as either arboreal or soil-associated, the difference in mean %EW between the groups, arboreal, 74 ± 2%, soil-associated, 82 ± 3%, was found to be highly significant (t-test: $P < 0.001$). In addition, while emergence weight (EW) was significantly different between arboreal (6.5 ± 0.4 g) and soil-associated (4.9 ± 0.5 g) microhabitats (t-test: $P = 0.020$), there were no differences in weight ($P = 0.160$) or distance travelled ($P = 0.908$) between these microhabitat groupings. The numbers of male and female beetles did not vary between arboreal and soil-associated microhabitats (Fisher's: P = 1.000).

Arboreal destinations were most commonly the crowns of coconut palms damaged by bore holes; however, beetles also landed in the branches of other species of trees. For example, an upper branch of a large breadfruit tree damaged in a recent typhoon was the final destination of one beetle. Upon investigation, several other beetles and grubs were found in the rotting limb along with the radio transmitter. In another instance, two beetles flew to the crown of the same highly damaged coconut tree independently of one another.

In soil associated landing site, CRB tended to bury into the soil upon landing at depths up to approximately 15 centimeters. Typically, these sites were at the base of a tree. Four out of five of these landing sites were at the base of coconut palms, though CRB also landed in less predictable locations. For example, one beetle landed beneath a trailer parked on a grassy lawn in a residential area surrounding Triton Farm. In another example of particular interest, one beetles was found beneath a CRB barrel trap baited with oryctalure at each experiment site. Other beetles and larvae were found also beneath one of these traps.

This study was successful in tracking CRB to cryptic breeding sites at two locations on the island of Guam. The two areas where CRB were tracked differed both in topography and vegetation and the effective location of tagged beetles in these different environments shows promise for the applicability of this technique in the varied habitats were CRB infestations may occur. Out of 33 released CRB, a total of 19 were retrieved either as an individual or as a fallen radio transmitter resulting in a 58% retrieval rate. This comparatively high retrieval rate required an input of approximately 1 hour per CRB immediately after release and at least the same amount of time on the following day. The tracking of CRB to an approximate location during the night followed by a more precise pinpointing during the daytime proved to greatly facilitate the retrieval of released CRB.

ANECTDOTAL LOCATIONS

Although a majority of the released CRB were successfully tracked to discrete locations, 14 CRB were lost presumably due to out-of-range flights. Interestingly, those CRB that flew out of range had statistically significantly lower percent emergence weights than those that stayed within the detection range of the radio devices, suggesting that lighter CRB fly longer distances. State average %EW. Although the distance flown by retrieved CRB had no statistically significant correlations with percent emergence weight, distance flown by all 33 CRB, lost and found, would most likely correlate with percent emergence weight if the distance of the lost CRB were to be determined. This observation raises the ability to minimize the loss of CRB while radio tracking. Prior to release, CRB must be fed to above 70 percent of their emergence weight to ensure that the individuals will remain within the detection radius.

Moreover, percent emergence weight of released CRB had a strong association with the microhabitats in which tagged CRB were found. Of the 19 retrieved CRB, 11 landed arboreal microhabitats whereas 8 landed in soil-associated microhabitats. The CRB that landed in the arboreal microhabitats had a statistically significantly lower percent emergence weight than those CRB that landed on soil-associated microhabitats, 74.43% compared to 82.73% respectively. It has been noted that adult CRB spend their time either feeding on the crown of palms or breeding in either soil or compost piles (Zelazny 1975). As CRB alternate between these microhabitats, individuals fluctuate in their percent emergence weight making it possible to determine the behavioral pattern that CRB will engage in by noting their percent emergence weight (Source). CRB at a higher percentage of their emergence weight will very likely refrain from further feeding and fly in search of breeding sites whereas CRB at a lower percentage of their emergence weight will likely forage in search for food.

Therefore, it is not coincidental that the CRB that landed in ground microhabitats, associated with breeding, had statistically significantly higher percentage emergence weights than those that landed in palm crowns, associated with feeding sites. This characteristic of the CRB life cycle makes this tracking method specific and controllable. In order to have CRB fly directly to breeding sites, the individuals must be fed to above 80 percent of their emergence weight. In doing so, monitoring and eradication teams can ensure that the released CRB will not lead them to feeding sites rather than breeding sites and will increase the effectiveness of CRB control methods. It is reasonable to hypothesize that heavier CRB landed on lower microhabitats due to the comparative inability to reach higher altitudes than the ones reached by lighter CRB. However, all of the released CRB flew several meters vertically into the air before displacing horizontally. If heavier CRB experienced a hindered vertical displacement in comparison to lighter CRB, then takeoff would have notably different between these two groups. Since hindered vertical displacement was not observed during CRB takeoff, it is reasonable to conclude that the difference in landing microhabitats was most likely due to the percent emergence weight of released CRB.

The use of radio telemetry to monitor flying species is generally constrained by the weight of radio transmitters (Robinson et al. 2009, Cochran et al. 2004, Thorup et al. 2007). This limitation is especially true when monitoring flying insects since a small increase in weight may severely hinder flight behavior (Source). In recent years, though, the gradual miniaturization of transmitters has circumvented this obstacle allowing for more precise monitoring of flying insects (Sato Maharbiz 2010). One of the factors determining the feasibility of this study was whether or not adult CRB could fly undisturbedly with the attached radio transmitters. Adult CRB are excellent fliers and can exert force much larger than their body weight when fighting and boring, so it was reasonable to expect that the miniature radio transmitters would have little to no effect on CRB flight capability. As expected, the flight capability of CRB was seemingly unaffected by the extra weight of radio transmitters. Each radio transmitter amounted to between 5.04% and 9.72% of the CRB weight at the time of release, and there was no correlation between the increased percentage weight and the single flight distance of CRB indicating that CRB could fly carry the extra burden of the radio transmitters. Note about whether it went over 100% It is also important to note that the 14 CRB were lost did present not statistically significant differences in the radio transmitter percentage weights compared to the CRB that stayed in range. These observations are consistent with other studies monitoring members of the Scarabaeidae family which found that radio transmitters did not noticeably affect beetle flight capabilities (Beaudoin-Ollivier 2003, McCollough 2006, Rink and Sinsch 2007). Also, the duration of commercially available radio transmitters (10-14 days) is appropriate for this type of CRB monitoring. However, the battery life of the transmitters must guide monitoring protocol timelines. CRB should be pinpointed to a final location within 2-3 days after initial release to prevent the loss of CRB due to battery drainage.

Another important factor to consider is the distance over which CRB can be monitored. Radio telemetry monitoring typically covers only short to medium displacement distances usually limiting the applications of the technology (Robinson et al.2009). The radio devices employed in this study had an effective range of localization that varied with topological conditions. In this study, the range of detection was appropriate for monitoring since the overall CRB flight distance from release sites to landing sites ranged from 52.8 meters to 564.6 meters. This range also roughly delineates a radius for breeding site discovery from released CRB; the detector CRB must be released no further than approximately 500 meters from breeding sites. This might present difficulties for eradication teams since the breeding sites in question occur in cryptic locations presumably unknown to those searching for them. The relatively short detection radius of the radio devices obligates teams to close in on the cryptic sites through other investigative means. In order to effectively estimate possible locations of CRB breeding site, visual monitoring of damage and trapping should assess the presence of CRB populations. Once visual monitoring and trapping indicates the existence of CRB in a particular location, the detector CRB would be released in the vicinity to pinpoint the exact location of the breeding sites. Stats about monitoring and visual in Guam and HI This combination of monitoring methods would ease the control and eradication of CRB, and since traps and visual monitoring are already widespread, it would not be complicated to craft an integrated strategic plan.

END EXTRA

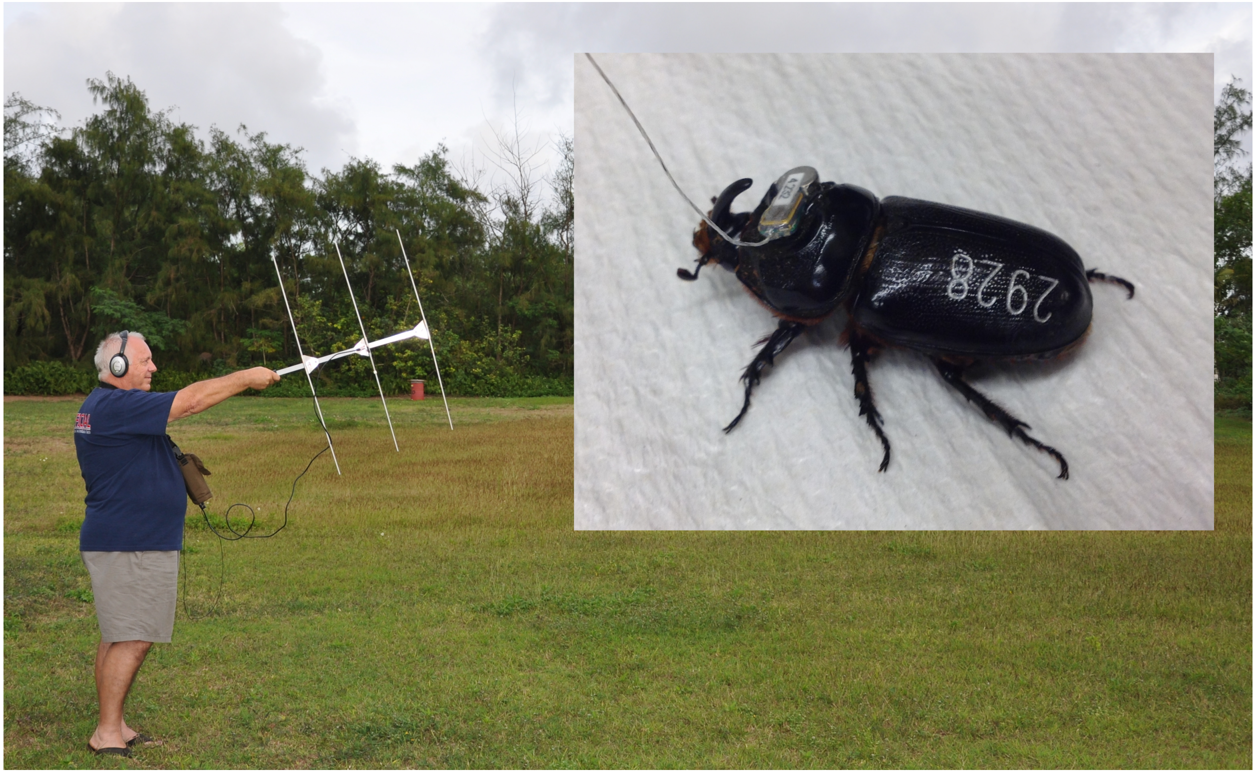


Figure 1: Radio-tracking reciever and coconut rhinoceros beetle with transmitter glued to pronotum.

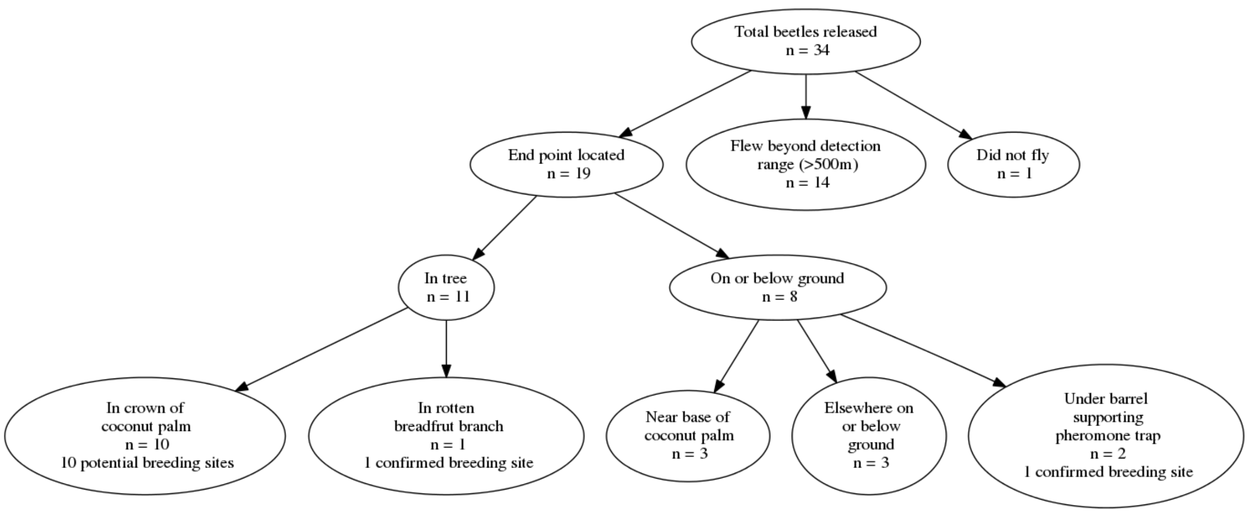
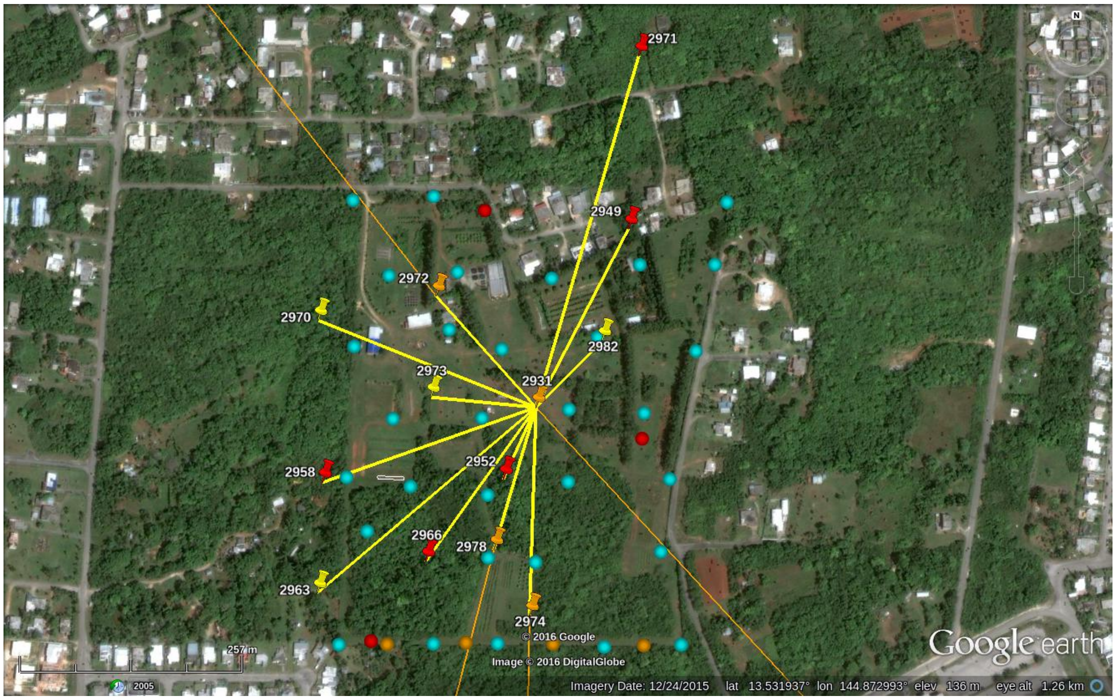
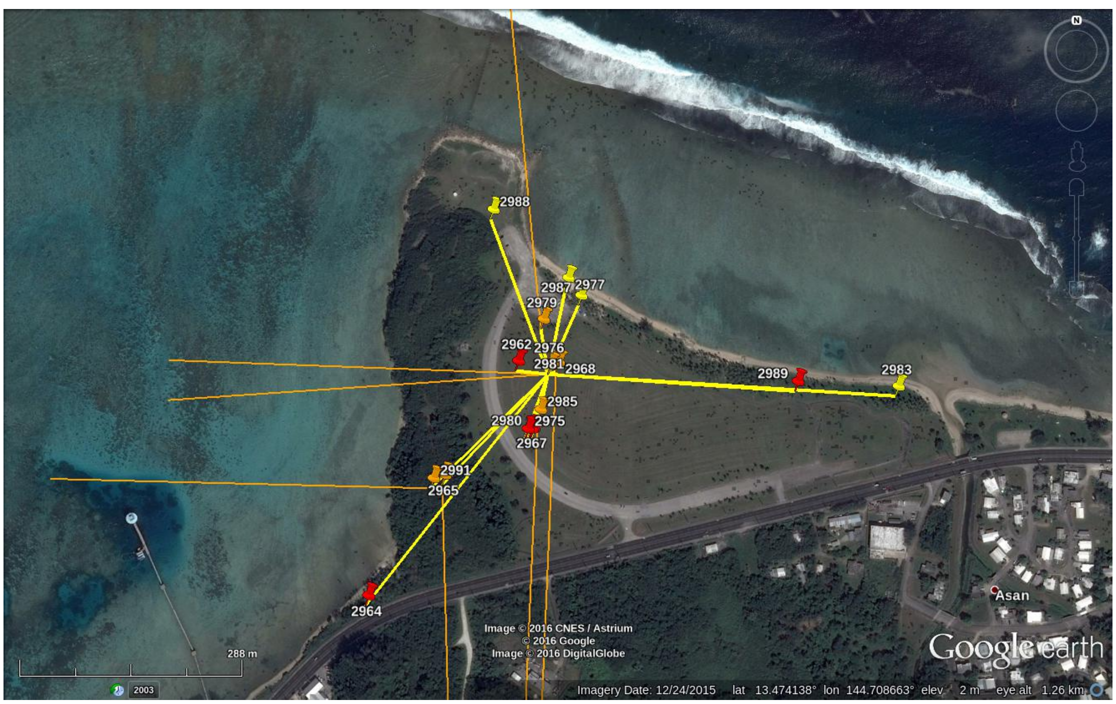


Figure 2: Outcomes for radio-tracked beetles.



(a) Yigo release site.



(b) Asan release site.

Figure 3: Results of radio-tracking coconut rhinoceros beetles at the Yigo and Asan release sites. Pushpin icons represent waypoints for tracked beetles (color code: red = beetle ended up in crown of tree; yellow: beetle ended up on or below the ground; orange: beetle was lost when it flew beyond the range of radio-tracking receivers, orange lines are extrapolated tracks based on last observed bearing of radio signal). Circular icons represent pheromone traps (color code: cyan = barrel trap; orange = DeFence trap; red = bucket trap).

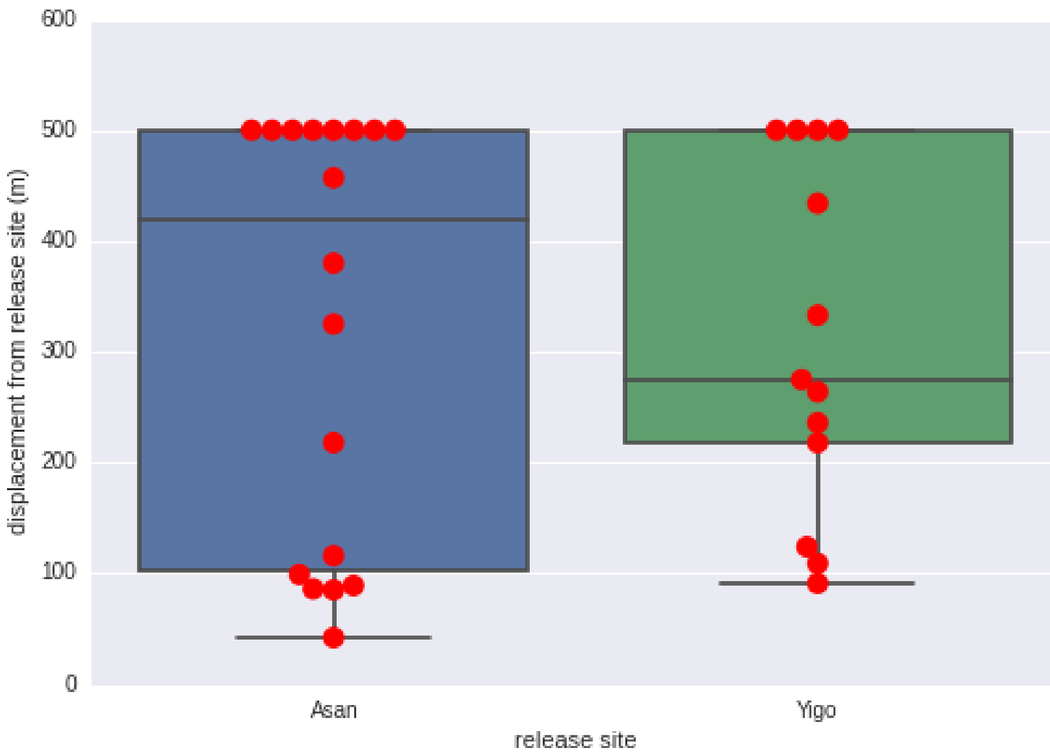
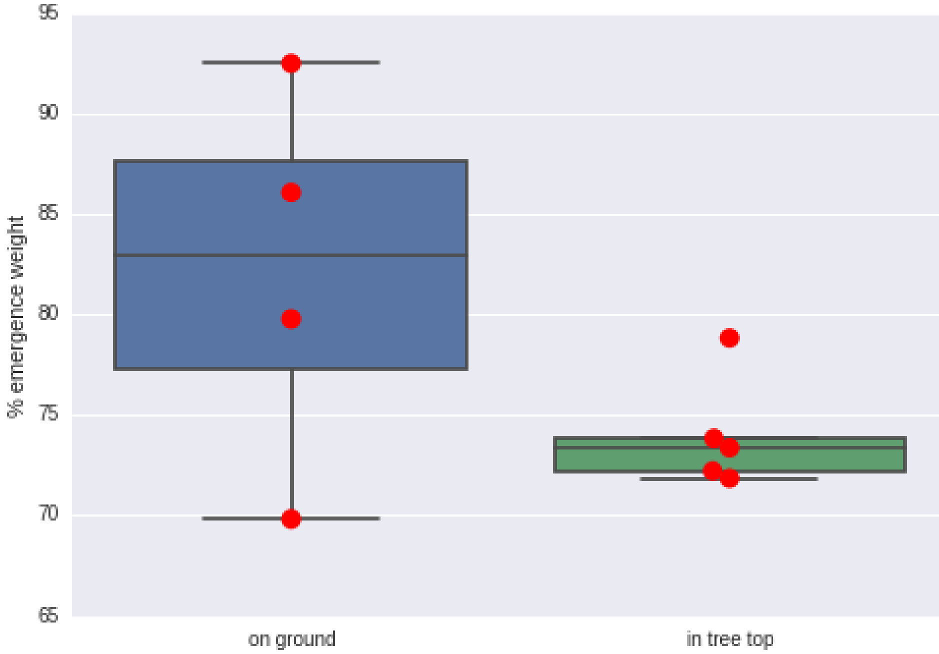
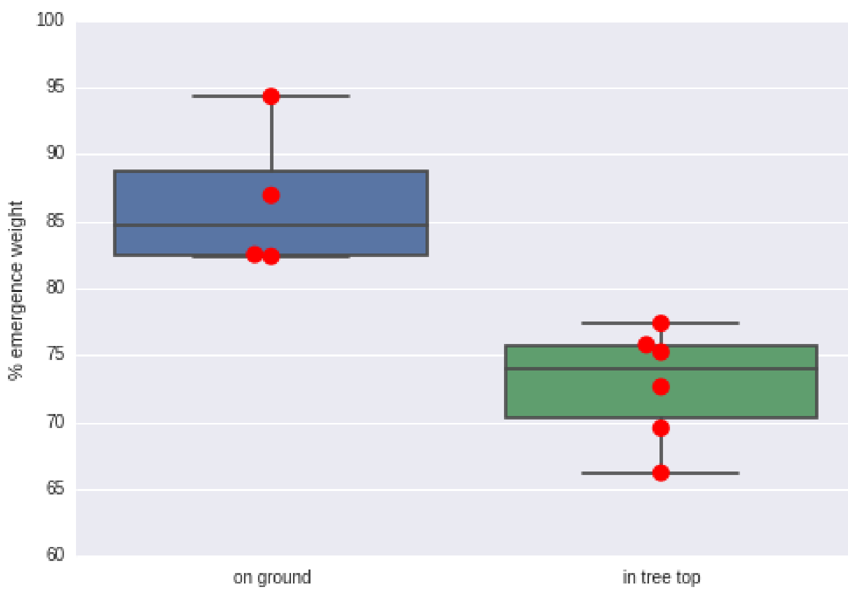


Figure 4: Displacement of beetles from release points within 48 h. The points at 500 m indicate beetles that flew beyond the range of the radio-tracking recievers. Difference between medians for beetles released at the two sites (Asan: 418 m; Yigo: 275 m) are not significantly different (p = 0.36; bootstrap resampling with 10,000 iterations). Pooled median displacement was 333 m.



(a) Females. Mean percent emergence weights for female beetles tracked to ground and tree top sites were not significantly different (82%, 74% respectively; Welch's t = 1.608; p = 0.195).



(b) Males. Mean percent emergence weights for female beetles tracked to ground and tree top sites were not significantly different (87%, 72% respectively; Welch's t = 4.174; p = 0.008).

Figure 5: Percent emergence weight of beetles tracked to ground sites and tree top sites.