Practical concerns in the eradication of island snakes

G. H. Rodda[1], T. H. Fritts[1], E. W. Campbell III[2,3], K. Dean-Bradley[1], G. Perry[2,4], and C. P. Qualls[2,5]

[1] USGS Midcontinent Ecological Science Center, 4512 McMurry Avenue, Fort Collins, Colorado 80525, USA. E-mail: Gordon_Rodda@usgs.gov [2] Ohio State University, Columbus, Ohio, USA.
[3] Present address: National Wildlife Research Center, Hilo, Hawaii, USA.
[4] Present address: University of Wisconsin, Madison, Wisconsin, USA.
[5] Present address: University of Southern Misssissipi, Hattiesburg, Mississipi, USA.

Abstract Successful eradication of the introduced and invasive brown treesnake (*Boiga irregularis*) from two 1 ha areas on Guam led us to suggest that the snakes could be eradicated from large nature reserves if immigration of snakes from adjoining areas could be eliminated or greatly reduced with perimeter snake barriers. Practical problems encountered in the design of snake barriers on Guam include the extraordinary climbing abilities of brown treesnakes, high levels of rat damage to chewable barrier surfaces in snake-reduced areas, and frequent and destructive cyclonic storms. Four successful snake barrier designs have been developed, and one 23 ha site on Guam has been largely trapped out following erection of a snake fence around the perimeter. Unresolved problems include the failure to capture all snakes within the 23 ha exclosure, and the fragility and high maintenance requirements of low-cost barriers. Our attempt to use brown treesnake traps for control of introduced wolf snakes (*Lycodon aulicus*) on Ile aux Aigrettes, Mauritius was unsuccessful, possibly due to low snake densities, size selectivity of the traps, or seasonal cessation of feeding activity.

Keywords snake eradication; *Boiga irregularis*; Guam Island; snake exclosure; *Lycodon aulicus*; Ile aux Aigrettes; Mauritius; trap selectivity.

INTRODUCTION

Our experience with eradication of island snakes derives primarily from study of the brown treesnake (*Boiga irregularis*) on Guam. Aside from a tiny, subterranean termite-eating worm snake, the remote oceanic island of Guam had no snakes prior to arrival of the brown treesnake shortly after World War II (Savidge 1987; Rodda *et al.* 1992a). In the half century following arrival of the snake, Guam lost virtually all of its native forest vertebrates, including 10 of 13 birds (Savidge 1987), two of three mammals (all bats), and half of its 10-12 lizards (Fritts and Rodda 1998). In addition, some wetland birds disappeared or declined inexplicably, sea birds ceased nesting on Guam, and a large number of the introduced forest animals declined in abundance. The causes of extinction are rarely clear, but the commonality in most of these declines was the unprecedented level of predation each species experienced due to the snake. We judge that most of the bird declines and perhaps half of the lizard losses are attributable to the snake (Rodda *et al.*1997, 1999c). The circumstances surrounding the loss of the bats are shrouded in mystery (Wiles 1987). The snake undoubtedly played a role, but human persecution may also have been a contributing factor (Wiles *et al.* 1995).

One commonality among these extinction stories is that the prey species lacked co-evolutionary experience with snakes (Rodda *et al.* 1999c). An anecdote will illustrate this familiar point. During the course of her avian disease studies, Julie Savidge (Savidge 1987) maintained an aviary with bridled white-eyes (*Zosterops c. conspicillatus*), a diminutive flocking bird that roosts communally. A brown treesnake gained entry to the aviary one night and was discovered while preying on the birds, which were perched immediately next to each other in a row. Lacking co-evolutionary experience with a nocturnal arboreal predator, the unconsumed birds remained in place on the branch as their neighbours were eaten (Jaffe 1994).

This phenomenon, sometimes called island tameness, is characteristic of islands lacking mammalian predators. Thus insularity was a contributing cause to the ecological catastrophe that happened on Guam when the snake arrived. On the other hand, insularity also made it practical to keep the problem from spreading. The U.S government, though its Wildlife Services agency, has embarked on a rigorous programme to keep the snake from spreading to other places (Oldenburg and Worthen 1997). Had Guam been part of a much larger landmass, the snake's spread would have been difficult or impossible to contain. For example, in 1993 a brown treesnake reached Corpus Christi, Texas (McCoid *et al.* 1994). Had the brown treesnake become established in coastal south Texas, what would have blocked its spread from there throughout the southeastern U.S and possibly the Neotropics?

CREATING INSULARITY

Guam's wildlife suffered catastrophic loss when their protective insularity was breached by human introduction of an alien predator. However, humans can also restore insularity by creating artificial islands of snake-free habitat. Specifically, we have found it possible to create small, predator-free nature reserves using a combination of snake barrier and eradication methodologies (Rodda *et al.* 1999a). The first example of this was Campbell (1996), who eliminated brown treesnakes from two 1 ha snake

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exclosures and compared the densities of prey species in the year following snake removal to those of similar but snake-occupied 1 ha plots nearby. There were no birds or bats present in his study site, so changes in those populations could not be detected. The remaining lizard species, however, showed a dramatic response. Within a year their numbers roughly doubled (Campbell 1996). It would be easy to understate the magnitude of the accomplishment of building an effective snake barrier. Most snakes are good climbers; the brown treesnake is one of the very best.

Campbell's work showed that snake removal and wildlife restoration were possible, but it did not show that they were practical. To be practical the cost has to be within reason, the protected area has to be large enough to support viable populations of the prey species, and the barrier must be durable enough to withstand challenges by humans and natural forces. The Campbell barriers brought attention to two acute problems: typhoons and rats. Rats chew holes in all things chewable, particularly barriers that bisect their home ranges. A larger problem is that Guam is subjected to irregular but severe cyclonic storms. For example, in December 1997 Supertyphoon Paka pummelled Guam with steady winds of up to 265 kph, and with gusts topping out at around 380 kph (from news reports). During the 1990s, Guam was subjected to 15 typhoons, of which about half had sustained winds over 150 kph (based on our list compiled from reports of the US Naval Oceanographic Command/Joint Typhoon Warning Center). Thus to protect wildlife from brown treesnakes in perpetuity on Guam, a snake barrier must be extremely durable.

Over the past decade we have studied barrier effectiveness and durability (Perry *et al*. 1996, 1997, 1998; Rodda *et al.* 1998; Campbell 1999). Barrier designs are tested progressively through three types of challenges. First, we build a door-sized mock-up of the design in the wall of a laboratory test chamber. Snakes attempting to escape from the test chamber are videotaped under infrared illumination in total visible-light darkness to determine the mechanism of escape, if any. Barriers that pass this test progress to the next stage, in which we confine snakes in a small octagonal enclosure built entirely of the proposed design. If the number of escapes is trivial or zero, the design is then tested in a large outdoor enclosure that we stock with a high density of snakes (for methodological details see Perry *et al.* 1996, 1997, 1998; Rodda *et al*. 1998; Campbell 1999). In brief, we have identified four classes of successful designs: temporary, bulge, masonry, and vinyl. Temporary barriers are used for interdicting snakes in commerce; they are not suitable for restoration of endangered species. Bulge barriers are retrofitted on a chain-link fence, and are therefore vulnerable to damage by strong typhoons, though they have been used as a low-initial-cost alternative to more permanent designs. The vinyl barrier uses material designed for long-term use as seawall; it is mechanically durable, but we have some unresolved concerns that the surface finish may degrade over time in the Guam environment. Surface finish must remain smooth to keep snakes from climbing the barrier. Our favoured masonry material is a pre-stressed moulded concrete design that is 100% successful in repelling snakes, and impervious to rat and typhoon damage, but has a fairly high initial cost (*c.* USD300/m). A conservative life expectancy of fifty years for the concrete barrier makes the cost reasonable (USD6/m/y), but it is challenging to pay for this entire cost "up front."

FIRST WILDLIFE APPLICATION ON A SNAKE EXCLOSURE

One practical experience in the use of such barriers is the 23 ha patch of forest on Andersen Air Force Base that is surrounded by a bulge barrier exclosure and is generally known by its military designation, "Area 50." The Area 50 project has been managed by Guam's Division of Aquatic and Wildlife Resources (GDAWR), with technical assistance and funding provided by a variety of federal agencies (US Geological Survey, US Fish and Wildlife Service, Wildlife Services). Snake control in Area 50 was initiated prior to construction of the barrier in 1997 (Searle and Anderson 1998). Sixteen radio-collared Guam rails (*Gallirallus owstoni*) were released in the area in 1998, when the snake population had been reduced but not eliminated (Beauprez and Brock 1999). Snakes continue to be caught in the area; persistent capture rates vary from zero to seven snakes per week (Diane Vice, GDAWR, pers. comm. 2001). Guam rails are federally listed as endangered. Except for Area 50, they are extinct in their native range (endemic to Guam), though a small extralimital population has been established on the nearby snake-free island of Rota. Because they are essentially flightless, they are exceptionally vulnerable to terrestrial predators, though they are agile and fecund, and adults have some ability to defend themselves against brown treesnakes, at least during the day. The fate of the 16 rails in Area 50 has not been established, but some survived (an average of 198 days, with five birds alive at the end of the 318 day reporting period: Beauprez and Brock 1999), and some have been recovered from feral cat stomachs (R. Beck, GDAWR, pers. comm. 2000). One problem with a fenced artificial island such as Area 50 is that the fence can be used by a clever carnivore such as a cat for assistance in capturing flightless birds. In the future we will conduct multi-species predator tests of barriers.

More troubling to us is the persistence of snakes in Area 50. After four years of nearly continuous trapping, substantial numbers of snakes are still being captured in Area 50. Our tests on smaller exclosures (Campbell 1996) indicated that snakes could be eradicated, not merely depressed in abundance, from snake exclosures. Is there some attribute of snake capture that does not scale up in going from 1 to 23 ha exclosures? Or is the barrier used in Area 50 allowing penetration by snakes? Unfortunately, there is no obvious way to identify the source of snakes that have been captured inside Area 50. Nine percent (seven) of 78 marked snakes released outside the area after the barrier was completed were subsequently captured inside

(Searle and Anderson 1998). Thus, some penetration has occurred. But are all or the majority of snakes invaders? Opinions differ, and direct evidence is lacking because the nature of the conservation activity in Area 50 precludes release of marked snakes.

Snakes encountered inside Area 50 could have: (1) breached the barrier, (2) grown up inside the exclosure, or (3) been present as adults inside the exclosure throughout the trapping period (i.e., refractory to trap capture). The reason for distinguishing the latter two conditions is that traps are known to have difficulty capturing small snakes (Rodda and Fritts 1992; Rodda *et al.* 1999b). It is less troubling if the failure to capture is due to a known phenomenon such as reduced success in trapping small snakes. Failure to capture an adult snake is a new phenomenon.

Barrier breaches can occur because the design of the barrier is deficient, the construction is defective, or the maintenance is inadequate. During our laboratory tests of the bulge barrier we tested both a meticulously constructed version and a degraded one (Perry *et al.* 1996, 1998). To create the degraded version we added an additional flat piece of hardware cloth to the base of the barrier. The exposed tines of the cut mesh provide numerous minute edges that a snake can use to climb partially up the barrier. The added hardware cloth layer simulated the edges that are present in the seams of bulge barriers that are poorly made. The carefully constructed version stopped 99% of 344 escape attempts, and all of the escapees were unusually large individuals (total length >2200 mm) that could reach over the bulge from the ground (Perry *et al.* 1998). Snakes of such a size constitute less than 1% of the population (Fritts 1988; Savidge 1991; Rodda *et al.* 1999d) and are all male, so they could not re-establish a snake population by themselves. On the other hand, degraded bulge barriers are relatively easily climbed by even small snakes. Given enough time, only 26% of the ordinary sized snakes (total length <1500 mm) failed to escape from an enclosure built with a degraded bulge barrier. This is one of the reasons why we do not recommend the use of this design for nature preserves (Perry *et al.* 1998). The bulge barrier design is not robust; it does poorly if construction is substandard. However, it is attractive to programme administrators because it has a low initial cost.

Another source of difficulty may be the gate that is included in the Area 50 barrier. Gates in exclosures are always problematic and they are difficult to test realistically in a small controlled environment. In our laboratory and field tests of exclosures we omit gates, as realistic gate results depend on site-specific details. The main defence against gate breaches is to deflect travelling snakes away from the gate. The gate used in Area 50 is located in an ideal place (maximally removed from any adjacent trees), but it does not have deflectors, and any snake approaching it would pass through easily.

The calibre of construction on the Area 50 barrier did not conform to our laboratory standards, so the effective breach rate is probably somewhat intermediate between results of the laboratory tests for the meticulously constructed version and the degraded one. Maintenance has also been irregular, facilitating breaches primarily through the growth of vegetation on or through the fence. In addition, oxidised fence components have not always been replaced in a timely fashion, and on occasion animal parts, such as preying mantis egg cases, have been allowed to remain on the fence, providing a purchase for climbing snakes. The frequency of these problems underscores the lack of robustness in the barrier design. To borrow a sporting metaphor, there is no depth to the defence. Unless a great deal of effort goes into quality control and maintenance, snake repulsion will be compromised.

SELECTIVITY IN TRAP CAPTURE

If all snakes are vulnerable to capture, those that breach the fence should eventually be caught, as some level of snake trapping has occurred in Area 50 since its construction in 1997. At that time it was known that small snakes were unlikely to be caught. This conclusion was based on the relative failure of traps to capture snakes smaller than about 800 mm SVL (snout-vent length; Rodda *et al.* 1992b, 1999b). Brown treesnakes hatch at around 300 mm SVL (Fritts 1988; Rodda *et al.* 1999c). Hatchling brown treesnakes are relatively easily sighted, however, so the Campbell (1996) project relied largely on visual searches to ensure that snakes of all sizes had been eliminated from the 1 ha exclosures. Visual searches are relatively tedious and time consuming, however, and were not used for eliminating snakes from Area 50. Instead the managers of that project chose to rely on growth of hatchling snakes to trappable size.

One issue potentially affecting capture probability is the long-term effect of lethal control of snakes using snake traps. Wildlife Services maintains 2000-3000 snake traps on Guam, primarily as a deterrent to snakes spreading to other islands. All snakes captured are killed. While this is highly desirable, it runs the risk of selecting for snakes that are refractory to entering traps. If there is genetic variation in propensity to enter traps, this continuous lethal control may be inducing selection for trap avoidance. In the vicinity of Area 50, however, lethal control has been relatively short term, so it is not yet likely to be a concern.

Another concern is the potential for prey abundances to sharply increase in any effective snake exclosure. As illustrated by Campbell's (1996) study, prey may become more numerous in areas depleted of snakes. Any hungry snake present inside a snake exclosure would then have the option of dining on either the abundant prey present in the area, or entering a trap to get close to the food attractant in the trap (all successful brown treesnake traps to date have relied on a food attractant: Rodda *et al.* 1999b). Thus high prey abundances may depress snake trapping success. This problem may also affect efforts to eradicate an incipient population on a prey-rich island such as Saipan, where numerous brown treesnake sightings have been reported (Fritts *et al.* 1999).

How successful are brown treesnake traps? In relation to literature values on capture success, they are the most successful snake traps known (see Fig. 20.5 in Rodda *et al.* 1999b). The literature values are based on captures per trap night. For the purposes of eradication, however, the key statistic is captures per snake present. Based on our traps for brown treesnakes on Guam, we have captured between about 1% and 25% of the snakes present per night (as determined by open population mark-recapture models: Rodda *et al*. 1999d), with a long-term average of about 12.5% (G. Rodda and K. Dean-Bradley unpub. data). Such a high rate of capture, if it applies to all individuals, should permit the elimination of a population in a few weeks (Rodda *et al*. 1999a).

The 12.5% figure is an average, of course. Is it possible that some snakes are more easily captured and some snakes less so? On logical grounds one would assume so; there is presumably some inter-individual variation in capture vulnerability. More troubling, are there some snakes that are totally refractory to capture? Inter-individual variation in capture vulnerability is relatively easy to quantify if one has a closed population (no ingress/egress/births/deaths). In such a case one can assume that all animals detected at any time were present throughout, allowing precise estimation of their individual capture probability. If the snakes are free to come and go, however, one cannot rigorously distinguish capture probability from the probability of their being in the area. We have found no areas in Guam that are of a practical size for mark-recapture trials and that are demographically closed. This has stymied efforts to quantify individual heterogeneity in capture probability.

Using a variety of trapping studies of our own (Rodda *et al*. 1992b, 1999a,b), we were able to quantify the capture probability of size classes of snakes. We pooled 21 trap history matrices into one large matrix involving 942 individual snakes divided into five size groups by snout-vent length (SVL) (601-700 mm, 701-800 mm, 801-900 mm, 901-1000 mm, and >1000). This pooling created a matrix of limited value for estimating survivorship or other population values, but it maximised our ability to discern capture probability differences among size classes. We used the program MARK's (White and Burnham 1999) open population model (Cormack-Jolly-Seber) to evaluate models involving group and time effects on both "survivorship" (φ, effectively 1 - emigration rate between daily capture occasions) and capture probability (*p*). This analysis revealed no relationship between snake size and survivorship, but it did indicate a strong relationship between size and capture probability (Fig. 1). No snakes below about 600 mm were captured, supporting earlier observations (Rodda *et al.* 1999b).

In the size range 600-900 mm SVL capture probability increases sharply, to a maximal value for snakes 900-1000 mm SVL (brown treesnakes mature in this size range: Rodda *et al.* 1999c). We are testing new trap designs to capture small snakes. In the meantime it should still be possible to eradicate a closed population of brown treesnakes if the smaller snakes are captured as soon as they reach a trappable size. It is not known how long this will take. In captivity, well-fed snakes reach a capturable size in about one year, but growth rates of juveniles in the wild are unknown.

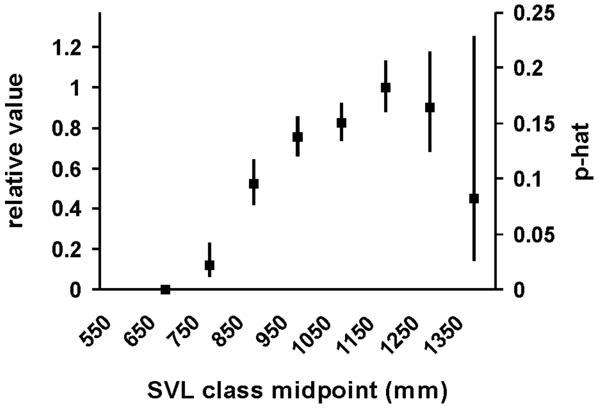

Fig. 1 Capture probability for brown treesnakes on Guam using conventional mesh-flap traps. Analysis is by open model (Cormack-Jolly-Seber), with snake body size defined by snout-vent length (SVL) in 100 mm size classes.

One puzzling result of brown treesnake reproductive studies (F. J. Qualls and C. P. Qualls, unpub. data; Aldridge 1996, 1998) is that reproductively active males appear to be relatively rare. This is surprising, because female reproductive activity occurs at all times of year in brown treesnakes (F. J. Qualls and C. P. Qualls, unpub. data; Rodda *et al*. 1999c). From an adaptive perspective, one would expect males to be able to take advantage of mating opportunities at whatever time of year they encounter a receptive female. Yet reproductively-active males are relatively rare in samples of brown treesnakes (which are collected primarily with food-baited traps). One possible explanation for this phenomenon might be that snakes that are reproductively active are refractory to trap capture. Snake breeders report that male snakes in general avoid eating while they are in reproductive condition (N. Ford, pers. comm.). Females are also refractory to feeding while gravid. Neurochemical studies of the brains of reproductive red-sided gartersnakes (Morris and Crews 1990) indicate that a specific brain chemical (neuropeptide Y) acts both as a feeding inhibitor and reproductive inducer in that species. Thus, reproductive aphagia might account for some of the variability we have seen in capture success, and it might indicate that some individuals are totally refractory to trap capture at certain times. It is not known what role, if any, neuropeptide Y has in brown treesnakes.

ILE AUX AIGRETTES, MAURITIUS

Despite the difficulties we have identified in eradicating snakes from Area 50, we were able to eradicate snakes from the 1 ha (Campbell 1996) study sites. Average trap capture probabilities of 10-20% per night suggested that if barrier leakage was not a problem, eradication should be completed in a few weeks. We were offered an opportunity to test this concept on the island of Ile aux Aigrettes off the east coast of Mauritius, Indian Ocean. The wolf snake (*Lycodon aulicus*) was introduced to Mauritius around 1860 (Cheke 1987), and it no doubt spread to the offshore islet of Ile aux Aigrettes sometime after that. It has been associated with the loss of several native lizards, so the Mauritius Wildlife Foundation elected to restore the islet by removing the introduced snake (C. Jones and S. Harris pers. comm.). We volunteered our trap design and tested it during a short visit to the island in December 1999. The 24 traps that we tested were alternately baited with day geckos (*Phelsuma ornata*), night geckos (*Hemidactylus frenatus*), or laboratory mice (*Mus musculus*). The traps were monitored for a period of about six weeks, during which they failed to capture a wolf snake. We saw one wolf snake during a visual survey and one was eventually found dead in a trap after trap monitoring was discontinued and the attractants were removed (Harris 2000).

Why did we fail to capture wolf snakes in our traps? Unlike our Guam trap experiments, for our work on Ile aux Aigrettes we were able to prepare only a small number of traps, and we have no information on the density of wolf snakes on Ile aux Aigrettes. Wolf snakes might be exceedingly rare, limiting the opportunities for even a single capture with so small a number of traps. The size selectivity of our traps (Fig. 1) might have worked against us, as the average size of a wolf snake is likely to be around 700 mm SVL (no wolf snake size data for Ile aux Aigrettes are available). Note that the size selectivity illustrated for brown treesnakes in Fig. 1 is for a flap trap baited with a mouse attractant; no comparable data exist for the open-cone trap type and attractants used for wolf snakes in Mauritius. Another possibility is that the time of our trapping on Ile aux Aigrettes happened to coincide with the wolf snake's mating season there, in which case capture success might be depressed.

The above-listed concerns appear to be the best candidates for understanding the incomplete success we have seen in elimination of snakes from Area 50 on Guam and Ile aux Aigrettes in Mauritius, but this list of possibilities is not exhaustive. We do not yet know whether the essential condition for eradication – removing snakes faster than recruitment is replacing them – can be met. It may be practical to eradicate invasive snakes from these nature reserves without rectifying these problems, but to accomplish eradication without solving these problems will undoubtedly increase the cost over that originally anticipated. Additional quantitative information on the severity of the problems and the costs of rectifying them will be needed to identify the optimal snake eradication strategy.

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