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ABSTRACT: The brown treesnake (*Boiga irregularis*), accidently introduced to the previously snake-free U.S. island of Guam after World War II, decimated the island's naive wildlife. Today, it periodically stows away on craft going to other islands where the ecological damage may be repeated. Barriers offer an effective tool for keeping the snakes out of areas from which they can disperse off-island, as well as sites identified as critical for the protection of human health, conduct of economic activity, or conservation of endangered species. The authors have developed a variety of barrier designs which repulse at least 95% of snake attempts to scale them under laboratory conditions; the best performing models are 100% effective. Three of the designs are in operational use. Designs for maximizing snake repulsion will be more costly to build, but may have lower annual costs due to reduced expenses for system upkeep.

KEY WORDS: brown treesnake, *Boiga irregularis*, barrier, vertebrate pest control, Guam

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INTRODUCTION

The brown treesnake (*Boiga irregularis*) was accidentally introduced to Guam in the late 1940s. Taking advantage of high densities of introduced and predator-naive prey species, it irrupted to very high levels, causing the extirpation or serious decline of most native vertebrates, millions of dollars in damages due to power outages, costly losses of agricultural stock, and a health risk to human infants (Rodda et al. 1998a).

The snake is an excellent climber, using minute irregularities to ascend almost any structure, is extremely efficient at entering small openings and hiding in them for protracted periods, and can survive for months without food. This allows it to be accidentally transported in both sea and air cargo. The snake's ability to store sperm (Whittier and Limpus 1996) raises the disturbing possibility that even a single dispersing female may be able to start a new population. Brown treesnakes have been found associated with Guam cargo in destinations as diverse as Diego Garcia Island in the Indian Ocean and Spain, but most reports have come from Saipan in the Mariana Islands and Oahu in the Hawaiian Islands (Fritts et al. 1998).

Two main management goals suggest themselves: 1) further spread of the snake should be prevented; and 2) Guam's snake population should be controlled, both to reduce the risk of further spread and to begin restoring affected ecosystems. Until the tools are developed for snake eradication, blocking snakes from entering sensitive areas such as electrical power systems, airports, and conservation areas is likely to be the best strategy (U.S. National Research Council 1996; Rodda et al. 1998b).

Some operational uses will require a temporary barrier (e.g., one-time military exercises); other uses are recurring or continuous (protection of endangered species from snake predation). Over the past seven years, several types of barriers have been developed to prevent movement of brown treesnakes into or away from designated areas (Campbell, 1996; Perry et al. 1996a,b, and 1997). In this paper each of the types of barriers has been described and the advantages and disadvantages have been developed and evaluated for various situations.

METHODS

General Design Features

Besides maximal snake repulsion, each of the barriers discussed below is designed with two important features in mind. First, applications are needed both as an exclosure (preventing entrance of snakes into a protected area) and as an enclosure (preventing snake dispersal away from the enclosed area). Second, exclosures on Guam should be "self-bailing" whenever possible, so that snakes that reach the protected side by any means are able to leave easily or be neutralized with minimal effort. For example, a barrier on Guam should not keep within the exclosure a snake that accidentally enters or is brought into a cargo containment yard. Rather, the barrier should enable the snake to climb back out, or facilitate the snake's capture as it attempts to leave, so that the snake is not kept with the cargo or transported to other islands. On other islands, however, snakes that find themselves on the "wrong" side of the barrier should be trapped and killed rather than be allowed to leave as they would under the "self-bailing" principle.

Four major repulsion features are incorporated into the barriers. Three (smoothness, height, and overhang) are passive and universal. Because wind loading is a major concern in the Pacific, short barriers are more desirable than tall ones. Forcing the snakes to lean back to circumvent the overhang creates a barrier that is

functionally taller, without greatly increasing wind-loading. The third feature, electrification, is active and limited to use on some types of barrier.

General Procedures

Wild-caught snakes were used, spanning the entire size range from hatchling to extremely large individuals that are uncommon in the wild. Larger snakes require taller barriers to stop them than do small snakes. Inclusion of very large snakes in the test pool allowed the authors to make more general statements about the effectiveness of barriers. The use of uncommonly large snakes provides a very conservative test of the functionality of the barrier, however, as the representation of large snakes used in tests was greater than their frequency in the wild population.

Barriers that performed well during laboratory tests advanced to field testing. Laboratory testing was of two types. Some snakes were left in a test arena overnight, and their retention was used as the metric of barrier success. When more detail was deemed necessary, an infra-red time-lapse video camera was used to record snake behavior in total darkness (i.e., no visible light), allowing precise identification of normal behaviors associated with breach attempts.

Outdoor testing was conducted under operationally realistic weather and terrain conditions. On the night they were used for outdoor tests, snakes were temporarily detained outdoors inside cloth bags, which allowed ample air circulation. At the onset of a trial, bags were untied so that snakes were free to exit the bag when they began to move. As in laboratory testing, two evaluation methods were employed. Sometimes the snakes were left in test arenas overnight and assessed their retention per night; when more detail was desired, all-night focal animal observations were conducted, during which detailed observations were made on all breach attempts.

It is not apparent what is the best measure of barrier success. For port enclosure uses, one would like to know what percentage of snakes are able to escape from the enclosure during the time when the snake is likely to be left undisturbed (generally overnight). For this application the best metric of success might be retention rate per snake-night (e.g., five snakes left in an enclosure for two nights constitute ten snake-nights, etc.). For a wildlife enclosure, however, vegetation might conceal snakes that failed to escape after their first night, providing them an opportunity to attempt escape on subsequent nights. In such a case, one might be interested in the retention rate per snake. Snakes on Guam may simply turn away and go the opposite direction if they fail to breach a snake exclosure, suggesting that for evaluating exclosure designs one might wish to know the repulsion rate per breach attempt. To accommodate these different applications, several performance measures were examined. Overall, some 1,600 individual snakes were observed making well over 11,000 breach attempts during more than 4,100 snake-nights.

Temporary Barrier

An enclosure design was tested, similar to what is being used in locations receiving suspect cargo from Guam. Full descriptions of test models were provided by Perry et al. (1996a). Briefly, the structure used in all tests was an eight-panel octagon tested outdoors. Each of the side panels was 2 m long. Number 6 rebar (nominal diameter 1.6 cm, maximum diameter 2.54 cm), inclined at 60° to create a slanting overhang, was used for all supports. Sand bags were used to secure the edge of the barrier to the ground outside the enclosure, on the snake-free side. An observation tower was placed in the middle of the enclosure and provided an elevated point from which snake behavior could be observed in all directions and recorded as it occurred without disturbing the snakes, which persistently tried to escape, repeatedly testing the barrier's efficiency. Testing began in May 1995 and continued until November 1996. Several factors were varied systematically during testing: wall materials, attachment methods, and barrier heights. Additionally, the effect of adding a pendulous flap on the top edge of the barrier was evaluated (Table 1).

RESULTS AND DISCUSSION

Snake Behavior in Test Chambers

Snake escape behavior can be divided into several stereotypical stages. Snakes typically first crawled to the nearest barrier edge, then spent some time (often over an hour) crawling along it, apparently seeking holes. The next stage also involved crawling, but included attempts to nose their way underneath the barrier. Thus, even a small gap in the seal under a long barrier is likely to afford a snake a way out. A door left open and unattended overnight will similarly create a much greater risk of escape than its size alone would suggest.

Next, snakes typically began to try and climb the barrier itself. Normally, early attempts were short, and successive attempts reached greater and greater heights. Inside corners or visual discontinuities attracted disproportionate attention, compared to uniform surfaces. Square corners are especially easy for brown treesnakes to climb, and should be avoided. Eventually, most snakes large enough to top a barrier did so, either by climbing or free-standing. This rarely took less than two hours from when the snake first emerged. In climbing, even minute irregularities in the surface of the wall were used to provide traction and allowed the snake to ascend. For example, sharp irregularities protruding only to a distance equal to the thickness of a single wire of the type found in 1/4" hardware cloth were frequently and handily used by ascending small snakes (larger snakes required larger gripping surfaces). When free-standing, a snake may raise as much as two-thirds of its body length vertically and hook its head on the top of the wall to perform a "chin-up." If the wall is vertical, a snake will prop itself against it and be able to reach greater heights than possible when it is free-standing.

Temporary Barrier

A total of 660 snakes were used in these tests. During 957 snake-nights, 3,843 attempts by snakes to scale barriers were observed. Barrier success measures are presented in Table 1.

Initial model results (test series 1-4) showed a positive relationship between snake size and the maximum height each individual achieved. However, the relationship was weak, and body length explained less than 15% of the

Table 1. Temporary barrier tests. For barrier material, "net" means netting of the kind previously used by Campbell (1996), with a hole size of 8.7 x 7.2 mm; "shade" means Solartex (Gale Group Inc., Orlando, Florida) shade cloth. Attachment method lists the technique by which the barrier was fastened to the rebar: "tie" - nylon cable binders, "sew" - cable binders and sewing, "tube" - longitudinally-slit PVC pipe. Height is minimum vertical height of the top of the barrier from the substrate (in cm). The escape path designation "furrows" indicates that the snakes were able to utilize sags in the mesh material to climb the overhanging walls.

Test Series	Material	Attach-ment	Min. Height (cm)	Flap Present	No. of Snakes Tested	% of Snakes Retained	No. of Attempts Observed	% of Attempts Repulsed	Model Escape Path(s)
1	net	tie	115	no	16	75	147	96.6	furrows
2	net	tie	115	yes	15	80	173	93.1	attach. points
3	net	sew	115	no	35	83	393	98.0	attach. points, over top
4	net	sew	115	yes	13	62	203	96.5	attach. points, over top
5	shade	tube	115	no	84	91.5	1,689	96.9	over top
6	shade	tube	130	no	76	97.4	1,238	99.6	over top

variation observed in scaling ability. This occurred because, with the exception of the smallest snakes, individuals of all size classes were sometimes able to reach considerable heights or breach the barrier altogether. Observations showed that ties and sewing allowed snakes to scale the mesh on the attachments. Also observed were some cases in which smaller snakes escaped through rips in the fabric that had gone undetected during the regular inspections. Despite this, snakes required an average of 27 attempts before finding a way to breach the barrier.

Changing mesh type and improving attachment methods significantly improved barrier performance. The preferred design (number 5) stopped well over 95% of all snake attempts to cross it and nearly 100% of snakes of normal size (the smallest snakes that were ever able to reach the top of the barrier were just under 2,000 mm in total length). This model is described in detail by Perry et al. (1996a), who also provide step-by-step instructions on how to build and best employ it.

Increasing barrier height increased retention rates (only snakes with a total length of at least 2,200 mm were consistently capable of breaching the taller barrier). However, the increase in barrier height did not statistically improve success rate per snake-night. The improvement seen in observed trials had minimal practical significance, as snakes of a size able to top the barrier in series five are very rare in nature (only about 1% of females and 5% of males in recent collections from Guam). Thus, there seems to be little reason to prefer higher (1.3 m) barriers over lower (1.15 m) ones, especially in light of the increased cost and engineering problems associated with greater wind resistance of taller fences.

Permanent Barriers

Due to space limitations, results of the large number of studies covered by this section will not be fully detailed. Instead, the three types of permanent barrier these extensive studies have led the authors to prefer will be described.

Masonry barrier. The current design is a 1.15 m high wall, with a ledge protruding out at the top for 20 cm (i.e., forming an inverted L-shape). To reach past the ledge, a snake must lean out from the vertical barrier surface, contributing to the chance of falling due to reduced contact with potential friction surfaces and the adverse angle of the approach. This shape provides passive protection that, by itself, blocked over 90% of snakes attempting to breach it (Table 2). To maximize this advantage, a 5 cm wide metal swath conducts electricity from a cattle fence charger and delivers a non-lethal high-voltage shock to any snake that reaches it. This active feature increases barrier effectiveness and, under testing conditions, raised it to 100% during nearly 1,500 nights during which a snake was pitted against the barrier.

Metal mesh barrier. This model was made of 1/4" galvanized metal mesh hardware cloth and designed to be attached to chainlink fencing. Its flat lower panel is 1.2 m high and the protruding "bulge" atop the panel has a radius of 15 cm. In this design, the bulge replaces the overhang created by the angled construction of the temporary barrier and the overhang used in the electrified barrier. Of the snakes tested indoors, 99% were prevented from breaching this barrier (Table 3). Both individuals capable of breaching it were unusually large males (total lengths of 2,320 and 2,250 mm). Furthermore, not all snakes of that size range succeeded

in escaping. Retention rate of the more than 100 snakes tested in outside enclosures was statistically indistinguishable from that achieved with laboratory tests. An exclosure design allowed no free-roaming snakes in, a significantly better result than that demonstrated by an exclosure lacking snake-repulsing mesh tested over the same period in the same area.

Vinyl seawall barrier. The seawall-material barrier is constructed from vinyl sheeting (Collins Co., Camano Island, Washington) that comes in 30 cm wide sections that can be cut to a desired height with a hand saw or power tool. The material is manufactured with interlocking tabs and grooves, such that adjacent sections may be assembled into a single unit without adhesives or other anchors. Seawall barriers at heights of 1.15 and 1.52 m were tested (Table 3). The lower barrier showed 97% retention per snake-night and the higher one showed 100% success. The lower barrier was 100% successful with typical size snakes. Future testing will concentrate on larger snakes (>2 m total length) and on the feasibility and efficacy of adding an overhang or electrification.

Table 2. Retention rates for test enclosures using the masonry design. In some cases, the sample sizes include several minor variants; the variant with the highest success rate is reported in the final two columns.

Test Series	Height	Electrification	No. of Snakes Tested	No. of Snake-Nights Tested	No. of Attempts Observed	% of Snake-Nights Retained	n for % Snake Nights Retained
1	0.85	yes	43	256	2,105	20	256
2	1.00	yes	23	64	226	30	64
3	1.15	yes	232	587	3,807	100	82
4	1.15	no	115	307	--	93	307
5	1.30	yes	109	286	1,967	100	174
6	1.45	yes	86	244	--	100	244

Table 3. Retention rates for permanent barrier designs other than the masonry model. The poly mesh (high density polyethylene netting; Memphis Net and Twine, Inc., Memphis, Tennessee) had 6.5 x 6.0 mm parallelogram holes; the tensar mesh was a similar material (Tensar Corp., Morrow, Georgia) but with 24.5 x 5.5 mm oval holes; and the nylon netting had 8.7 x 7.2 mm hexagonal holes and was also used for temporary barrier testing (Memphis Net and Twine, Inc., Memphis, Tennessee). See text for descriptions of the other materials.

Material	Height (m)	No. of Shock Wires	No. of Snakes Tested	% of Snakes Retained	No. of Snake-Nights Tested	% of Snakes or Snake-Nights Retained for Best Variant	n for % of Snakes Retained	n for % of Snake-Nights Retained
Poly mesh	1.10	3-5	83	83.3	>350	100	>50	
Tensar mesh	1.10	3-5	151	92.5	>150	100	10	
Nylon netting	1.10	3-5	152	87	>300	100	>50	
Metal mesh	1.32	0	>300		>700	99		114
Thin vinyl	1.15	0	>150		215	63		215
Thick vinyl	1.15	0	40		221	97		221
Thick vinyl	1.52	0	>140		83	100		83

Choosing a Barrier

Through extensive testing on several scales, snake barriers have been shown to be effective solutions for the problem of preventing snake movement into sensitive areas or out of infected zones. Starting in 1997, three of these models have also been tested operationally. The temporary barrier was first used in conjunction with the Tandem Thrust military exercise originating from Guam. It was built by Wildlife Services (U.S. Department of Agriculture) specialists and Air Force personnel, using guidance and assistance from the research team. The metal mesh barrier was installed around the commercial port on Rota, Northern Mariana Islands. It was constructed by a private contractor, with the researchers' guidance and assistance. A version of the masonry barrier was built on Tinian, Northern Mariana Islands, to quarantine building supplies shipped from or through Guam. It was modified by a construction firm contracted by the Voice of America from plans provided by the research team. The researchers hope to construct a landscape-scale operational vinyl barrier in 1998.

Which barrier should be used for what need?

Temporary or permanent barrier? The primary issue in making this decision is the duration of the need. Temporary barriers provide less protection than permanent barriers and require more frequent inspections, but are also less expensive and time consuming to construct. They can be easily transported and may be set up wherever a suitable flat surface is available. Temporary barriers are ideal for short-term projects, but are not designed for continuous use (in large-scale tests of temporary barrier netting; chronic damage from feral pigs, rats, and solar degradation was encountered). If the short term need is recurring (e.g., military exercises staged from the same base or chronic cargo overflows), then a permanent barrier may offer better protection and lower annual costs.

Which permanent barrier? Permanent barriers may be more economical on an annual basis and they provide a higher degree of protection. Long-term protection is likely to be needed in one of three main contexts: 1) large-scale protection of sensitive installations such as airports; 2) small-scale protection of extra-sensitive installations such as cargo-handling facilities; and 3) protection of conservation sites.

Most large-scale transportation facilities in the Pacific, such as ports and airports, are surrounded by chainlink fencing and hard surfaces such as asphalt. This provides a suitable support structure for the metal mesh barrier. The metal mesh barrier is appropriate for situations where vision through the fence is desirable. All barriers must be monitored to prevent the adherence of animal or plant materials that would give purchase to a climbing snake. The researchers predict that the masonry and metal mesh barriers will be relatively more vulnerable to such problems than will the vinyl barrier. Large-scale applications of the metal mesh barrier to chainlink fences around major facilities, such as airports, are unlikely to provide complete protection against snake incursions, if only because the fence's length makes regular careful inspections expensive. Metal mesh barriers are likely to require periodic replacement due to rust, with survival time depending on the grade of fencing used and on the local conditions to which it is exposed. In the Mariana Islands, metal mesh barriers are likely to fail catastrophically during typhoons (=hurricanes). Wind loading during typhoons may also result in destruction of the chainlink fence, with loss of protection for large areas, at a time when repair materials are unavailable and fencing repair services are likely to be overburdened with competing commitments. Furthermore, the loss of physical security at airports can affect the safety of aircraft operations. Therefore, the use of the metal mesh barrier in areas for which moderate-term breaches in protection cannot be tolerated (e.g., high security transportation facilities, endangered species refugia) is not recommended. If intended for sites where future realignment of fences is anticipated (e.g., port will be expanded in five years), the metal mesh barrier may be the preferred choice, as it minimizes the initial cost and, therefore, the value lost through shorter term replacement.

Examples of especially sensitive sites include power stations and cargo handling facilities. Such needs are likely to be both localized and very long-term, and a higher up-front investment in a more durable barrier may generate savings in maintenance costs. For such needs, the masonry or vinyl barriers, which provide the highest protection and durability are recommended. Both of these models may be used in areas where architectural influences should be considered, and both are opaque, affecting sight distances. For rough terrain, most likely associated with protection of endangered species, the vinyl barrier is preferred at present, although the limits of its applicability to rough terrain have not been explored. It may provide adequate protection without the addition of an overhang or electrification. If so, it would be the simplest model and one with the lowest maintenance costs. Once testing is complete, it is believed the vinyl barrier will be the tool of choice for rough terrain applications, as its modular design allows it to be fit to uneven ground, it can be transported in sections into areas not serviced by roads, and barriers made of this material are easily fabricated using hand tools.

Snake barriers provide a practical solution to many snake encroachment problems, and growing uses for them is foreseen in the coming years.

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