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Brown Tree Snakes Methods and Approaches for Control

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7 Brown Tree Snakes

Methods and Approaches for Control

Larry Clark, Craig Clark, and Shane Siers

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INTRODUCTION

This chapter summarizes the existing and emerging tools and strategies for the control of the invasive brown tree snake (*Boiga irregularis*, or BTS) on Guam and the prevention of its accidental transport to, and subsequent establishment on, other snake-free Pacific islands. The brown tree snake has long served as an example of the ecological and economic damages that can be wrought by a single generalist vertebrate predator upon introduction to ecosystems that evolved in isolation and without native predators (Fritts and Rodda 1998; Wiles et al. 2003; Rodda and Savidge 2007). Our attempt to summarize the state of the art for control technology development and use is not intended to be an exhaustive survey of all the brown tree snake literature. Rather, it is intended to introduce the reader to the main concepts, methods, and strategic management uses of the tools in an effort to control brown tree snakes on the island landscape and interdict their passage at ports. Significant practical advances for brown tree snake control have been made since the first comprehensive summaries were published by Rodda et al. (1999e), and there is great promise for future refinements and broader implementation for control efforts on an islandwide scale.

INVASION AND IMPACTS

The brown tree snake (Figure 7.1) is native to northern and eastern Australia and parts of Indonesia and Melanesia. It is presumed that brown tree snakes were transported to Guam along with shipments of military equipment from the Admiralty Archipelago in Papua New Guinea shortly after World War II. Inference on the origins of the population invasive to Guam was initially based on morphometric analysis (Whittier et al. 2000). Subsequent determination of the source population is supported by genetic evidence. Data suggest that the Guam population was the result of a single introduction of perhaps fewer than 10 individuals (Richmond et al. 2015).

Unchecked by predators or competitors, brown tree snakes on Guam achieved densities reaching as high as 50–100 snakes per hectare at the height of the irruption (Savidge 1991; Rodda et al. 1999d). These densities were sufficient to exert suppression on prey populations such as never before observed in a snake species (Rodda et al. 1997). Originating at Naval Base Guam in the late 1940s or early 1950s, the invasion front spread from there to the southern tip of Guam by the late 1960s and

FIGURE 7.1 Photograph of the brown tree snake, *Boiga irregularis*.

reached the more remote northern limestone forests by the early 1980s (Savidge 1987). This invasion front coincided with a wave of precipitous declines in bird diversity and abundance (Savidge 1987; Wiles et al. 2003), and resulted in the extirpation of 11 of Guam's native forest birds and the extinction of the Guam flycatcher, *Myiagra freycineti*; the Guam subspecies of the bridled white-eye, *Zosterops conspicillatus*; and the rufous fantail, *Rhipidura rufifrons* (Savidge 1987; Wiles et al. 2003). The Guam rail, *Gallirallus owstoni*, and the Guam Micronesian kingfisher, *Todiramphus cinnamominus*, are extinct in the wild, though captive populations have been maintained in the hope of reintroduction subsequent to effective brown tree snake suppression actions. The consequent loss of avian ecosystem function has resulted in cascading ecological consequences, including disturbance of plant reproduction (Mortensen et al. 2008; Rogers 2011), forest regeneration (Perry and Morton 1999), and arthropod release (Rogers et al. 2012). Predation by brown tree snakes has also negatively impacted nearly all native vertebrate populations on Guam (Fritts and Rodda 1998) as well as nonnative and domestic animals (Fritts and McCoid 1991; Wiewel et al. 2009).

In addition to these ecological impacts, economic detriments of the brown tree snake invasion of Guam (reviewed in Rodda and Savidge 2007) include damage to electrical power infrastructure, loss of pet and domestic animals, human envenomations, higher costs of shipping from Guam, and threats to the tourism industry. Such economic damages are likely to be experienced manifold if a similar brown tree snake invasion were to occur in Hawaii (Burnett et al. 2008; Shwiff et al. 2010).

BIOLOGY AND ECOLOGY

Brown tree snakes are rear-fanged colubrid snakes that are well adapted to nocturnal and arboreal foraging, having large eyes with elliptical pupils and long, slender body forms. Because brown tree snakes are primarily arboreal, forests are considered to be their preferred habitats; however, they successfully utilize all of Guam's terrestrial habitats, including savannas and urban areas.

Hatching at a size of approximately 350 mm snout-vent length (SVL) and 5 g of mass, brown tree snakes may undergo a six-fold increase in length and a 400-fold increase in weight throughout their life, reaching up to 2000 mm SVL and 2000 g in weight, with males achieving larger sizes than females. However, subsequent to the collapses of large-bodied prey populations precipitated by brown tree snake predation, very large snakes are now rarely encountered. In a recent sample of 1800 snakes collected by visual detection and hand capture from 18 sites on Guam, stratified by six major habitat types, 84% of all snakes collected were less than 1000 mm SVL (Siers 2015).

Sexual maturity of brown tree snakes is strongly linked to body size. Savidge et al. (2007) found that 95% of female snakes matured between lengths of 910 and 1025 mm SVL, while males matured from 940 to 1030 mm. By these growth benchmarks, the previously mentioned sample of 1800 snakes was composed of 38% immature snakes, 49% maturing snakes, and 13% in the size class at which all snakes were expected to be reproductively mature (Siers 2015).

Brown tree snakes exhibit a pronounced ontogenetic shift in prey preference: smaller snakes prey exclusively on small lizards, with a shift toward feeding on larger endothermic prey (birds and rodents) by larger snakes (Savidge 1988; Greene 1989;

Shine 1991; Siers 2015). This shift goes beyond a mere correlation of snake size with prey size. In free-choice feeding trials, small snakes simultaneously offered a dead gecko, skink, and neonatal mouse of similar mass overwhelmingly preferred the lizards, particularly the geckos, to the mice (Lardner et al. 2009a). This change in prey is accompanied by an ontogenetic shift in venom composition, with greater toxicity to lizards as juveniles and a shift toward greater toxicity to birds and mammals as brown tree snakes grow larger (Mackessey et al. 2006). Smaller snakes are almost exclusively arboreal, with an increased tendency to travel and hunt on the ground as snakes increase in size (Rodda and Reed 2007; Siers 2015). While small snakes subsist almost exclusively on abundant arboreal geckos (Savidge 1988; Siers 2015), the transition of larger snakes to terrestrial foraging appears to be in response to the loss of arboreal bird and rodent prey and an increased dependence upon larger terrestrial lizards, such as the introduced *Carilia ailanpalai*, in the diets of larger snakes, particularly in forest habitats (Siers 2015). The nonresponsiveness of small brown tree snakes to rodent-based lures constitutes one of the major challenges in effectively targeting all size classes of snakes with existing control technologies, to be discussed further in this chapter.

More comprehensive reviews of the origins, biology, and impacts of the brown tree snake on the island of Guam are available in Rodda et al. (1992, 1999c) and Rodda and Savidge (2007).

COORDINATION OF PARTNERSHIPS FOR BROWN TREE SNAKE MANAGEMENT

Subsequent to the discovery that the brown tree snake was the cause of the decline and disappearance of much of Guam's native wildlife, federal, state, and territorial agencies were prompted to management action. Several pieces of federal legislation and interagency agreements have provided a regulatory framework, including the passage by the U.S. Congress of the Brown Tree Snake Control and Eradication Act of 2004 (Public Law 108–384, 118 Statute 2221, 7 U.S.C. 8501), which established the Brown Treesnake Technical Working Group (BTS TWG) to ensure that "efforts concerning the brown tree snake are coordinated, effective, complementary, and cost-effective." The BTS TWG has three overarching long-term goals: (1) preventing the escape of the brown tree snake from Guam to other locations (interdiction), (2) suppression and control of brown tree snake numbers to reduce their impact on the island of Guam and to restore the island's ecosystem, and (3) eradication of the brown tree snake from Guam.

The BTS TWG is formally composed of federal, state, and territorial partner agencies, with periodic informal participation by nongovernmental organizations. TWG membership includes: the U.S. Department of the Interior's (DOI) Office of Insular Affairs (OIA), U.S. Fish and Wildlife Service—Pacific Islands Fish and Wildlife Office (USFWS PIFWO), U.S. Fish and Wildlife Service—Guam National Wildlife Refuge (GNWR), U.S. Geological Survey (USGS), National Invasive Species Council (NISC), and National Park Service (NPS); the U.S. Department of Agriculture—Animal and Plant Health Inspection Service (USDA APHIS) Wildlife Services (WS) Operations and WS National Wildlife Research Center (NWRC); numerous commands under the Department of Defense (DoD); the U.S. Department of Transportation (USDOT); and multiple agencies within the U.S. Territory of Guam (GovGuam), Commonwealth of the Northern Mariana Islands (CNMI), State of Hawaii, and nongovernmental partners.

To more effectively and efficiently build on the research successes of the past, the BTS TWG chartered the BTS Research Committee (BTS RC) in 2012, with the primary goal of developing strategic long-term plans and short-term priorities for advancing research on brown tree snakes, focusing on developing the biological knowledge and technical ability required to meet the management goals of the TWG. The RC has identified three primary "research themes": (1) interdiction, early detection, and rapid response; (2) landscape-scale suppression; and (3) restoration. Priority research areas within these themes are summarized in Table 7.1.

Research on brown tree snakes has traditionally been funded by DOI through grants from OIA, but DoD has provided increasing support for research and operational control through specific grants and contracts. Brown tree snake research is designed to be complementary; NWRC focuses its research on methods development, whereas USGS concentrates on understanding the effects of BTS control and interdiction on natural ecosystems and control tool validation, with this approach clarifying roles while allowing the opportunity to collaborate on projects when necessary.

NWRC conducts research focused on product development and improved methodologies with the objective of improving the overall efficacy of BTS management. Our first commitment is to developing tools that will enhance the ability to conduct large-scale control of brown tree snakes. Second, we develop methods to augment

TABLE 7.1
Draft BTS TWG Research Committee Themes and Priority Research Areas

Interdiction, Early Detection, and Rapid Response	Landscape-Scale Suppression	Restoration (Dependent on Suppression R&D)
• Quantify and increase BTS interception rates • Develop methods to detect snakes at low density, including rapid response • Develop methods to detect satiated snakes in new locations • Develop tools for interdiction of BTS not susceptible to mouse-based methods • Develop and test new irritant and repellent methods • Assess new barriers (physical, chemical, behavioral) and reduce barrier costs	• Automate toxicant delivery (automated aerial broadcast system) • Study effect of suppression on BTS and nontarget species • Develop alternative attractant, lures, and baits • Develop tools for control of BTS not susceptible to mouse-based methods • Integrate current data operational data sets into research programs • Control of BTS in urban environments	• Determine level of BTS suppression required for persistence of native species • Determine size of exclosure required for persistence of various native species • Predict native ecosystem response to toxicant application • Improve barrier cost effectiveness & durability

Order does not imply importance.

the current suite of interdiction tools. We also review operational methods and tools and conduct program analyses to ensure control and interdiction efforts are as effective as possible.

USGS is also a major contributor to brown tree snake research, with a multifaceted program to inform managers about the ecology and biology of brown tree snakes toward enhancement of methods development and operational control. USGS efforts focus on understanding the effect of removal techniques on all segments of the brown tree snake population, including variation in response to control techniques among age or size classes. Additionally, USGS pursues research projects aimed at increasing the ability to detect brown tree snakes at low density and maximize the efficiency of early detection and rapid response.

Both NWRC and USGS are cooperating in research designed to evaluate ecosystem changes that occur through brown tree snake control methods to understand the impact of large-scale control efforts on the environment.

USFWS, GovGuam, and a number of the other parties to the BTS TWG have primarily been concerned with bird recovery, ecological restoration, and prevention of further ecological damages that would ensue from further accidental spread of brown tree snake populations.

Apart from the brown tree snake research agenda, which is the primary focus of this chapter, it should not be overlooked that Wildlife Services Operations on Guam has implemented a very successful integrated program of interdiction. As of 2014, over 150,000 snakes were removed from areas surrounding airports, seaports, and critical infrastructure (e.g., electrical substations). Snakes continue to be removed from these areas at a rate of approximately 10,000 per year. Over 99% of outbound cargo from Guam is inspected by Wildlife Services detector dog teams. Since the canine program's inception in 1993, no live snakes have been found in cargo arriving in Hawaii from Guam. This constitutes a tremendous conservation victory.

MANAGEMENT STRATEGIES AND GOALS

The current management strategies for brown tree snake control on Guam are primarily targeted at achieving the goal of interdiction, preventing the accidental export of snakes to currently snake-free environments. The methods described herein were developed to address the needs for each of these "filters," or interdiction stages, originally conceived for interdiction and control of brown tree snakes by the U.S. federal agencies.

Interdiction tactics, described elsewhere in this chapter, are employed at each stage of movement from areas with high snake density across successive barriers and anthropogenic features toward areas of low snake density (Figure 7.2). This approach is based on the premise that snake density is serially reduced at each step such that risk of "break through" diminishes in a cumulative probabilistic fashion. Prioritization of interdiction activities focuses on likely ports of exit from Guam and entry into vulnerable locations such as the CNMI and Hawaiian Islands.

As snakes transcend each of these stages, the intent is to intercept every individual. While complete interception of all snakes at any one stage is unlikely, the risk of accidental export is decreased greatly by the repeated reduction of potential

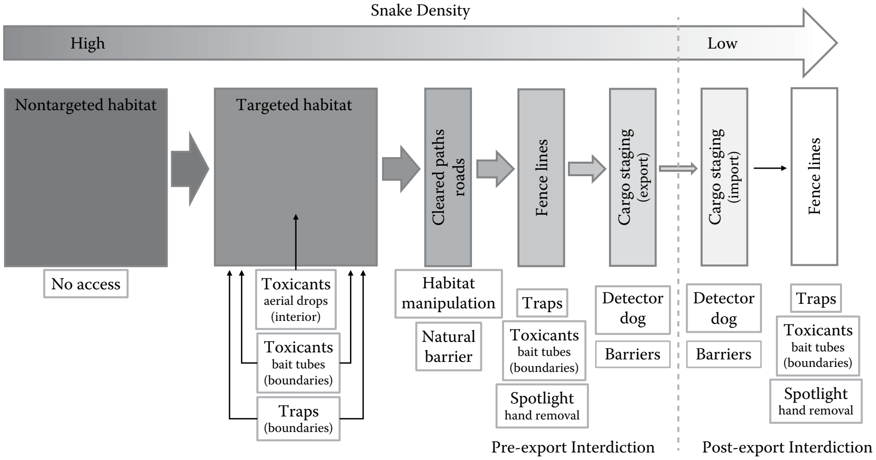

FIGURE 7.2 Stages of opportunity for interdiction of brown tree snakes. A schematic representation of the integration for brown tree snake control and interdiction. Shaded icons represent different habitats, boundaries, activities, or structures. Darker coloration indicates higher snake densities. Arrow size depicts decreasing probability of movement of brown tree snakes. Clear boxes depict the various control methods that might be used.

emigrants through the gauntlet of multiple interception points, to the extent where the odds of any snake penetrating all lines of defense becomes vanishingly small. As any snake penetrates each of these interdiction stages, the risk of potential invasion, and therefore the imperative for intercepting that snake at the next step, is greatly increased. If a hypothetical snake were to penetrate beyond all pre-export and post-export interdiction measures, it would move into the domain of early detection and rapid response. Some of these pre-export interdiction tactics are also implemented around important Guam infrastructure elements such as power plants.

CHEMICAL METHODS FOR BROWN TREE SNAKE CONTROL

Oral and Dermal Toxicants

Toxicants are one in a suite of tools used by managers for the control of invasive and injurious animals (Witmer et al. 2007; El-Sayed et al. 2009), and their discovery and development involves the integration of numerous scientific, regulatory, and business activities (Figure 7.3; Fagerstone et al. 1990; Isman 2006; Ravensberg 2011). For brown tree snake control, toxicant discovery and development was identified as a high-priority need among U.S. federal agencies (Campbell et al. 1999). The goals were to identify a toxicant that acted rapidly, produced little apparent pain and suffering in the target animal, posed low nontarget and environmental risk, was commercially available, could be formulated into various delivery systems, and had a sufficient scientific, clinical, and environmental history such that different aspects of the regulatory requirements of the Federal Insecticide, Fungicide, Rodenticide Act (per Title 40 Code of Federal Regulations, Parts 150–189) could be addressed in the

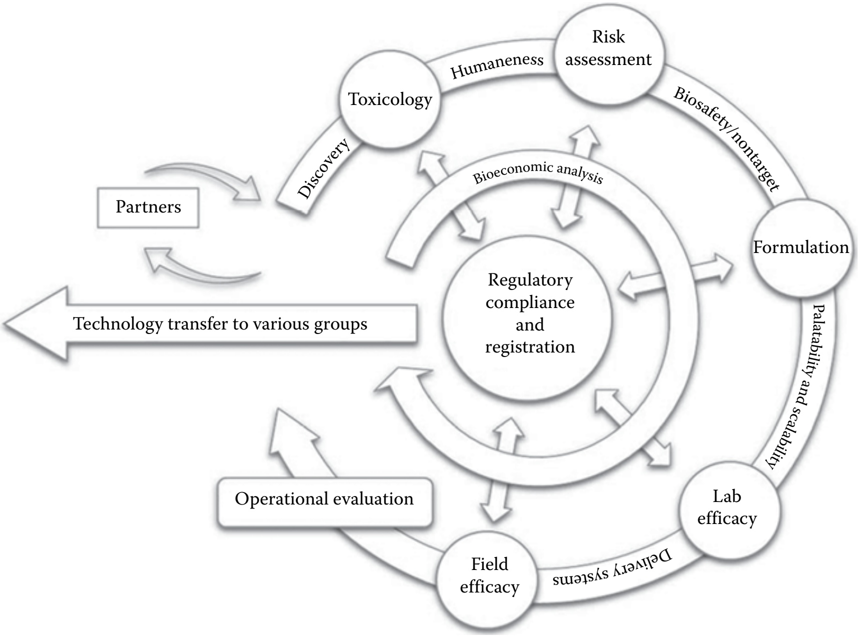

FIGURE 7.3 Schematic of the product registration process. A schematic of the general integration of disciplines and activities requirement to identify, develop, and register a brown tree snake toxicant or other chemical pesticide.

most cost-effective manner. The expense and effort to pass through each of these filters is enormous, and explains why so few chemically based wildlife damage management tools are available (Fagerstone et al. 1990; Fagerstone and Schafer 1998).

Numerous candidate oral and dermal toxicants were screened for efficacy during the discovery phase of product development (Brooks et al. 1998; Savarie and Bruggers 1999; Savarie et al. 2000; Johnston et al. 2001). For practical application reasons, delivery of a toxicant through an oral bait system rather than dermal applications was favored for development by USDA (addressed below: baits/lures). Early screening identified acetaminophen (CAS# 103-90-2) as the toxicant of choice.

Acetaminophen demonstrated efficacy in snakes (Savarie et al. 2000); its mode of action suggested that it would meet humaneness criteria of rapid time to death and low animal awareness (Sharp and Saunders 2011). In brown tree snakes, acetaminophen promotes the formation of methemoglobin, and thus deprives cells of oxygen (Mauldin et al., unpublished). The induced anoxia renders the animal inactive and eventually it passes into unconsciousness, analogous to carbon monoxide poisoning. The low dosage required to produce 100% mortality in brown tree snakes (80 mg/bait for the largest snakes tested; Savarie 2002) is well below U.S. Environmental Protection Agency (EPA) standards for safe human exposure (200 μg/L). Generally, environmental water sampling has shown acetaminophen and other analgesic pharmaceuticals to be two to four orders of magnitude lower than the no-observed-effects-levels (NOELs) for humans. Acetaminophen is rapidly bound and detoxified in soil, decreasing potential for off-site runoff or leaching into groundwater (Li et al. 2014). The environmental load for acetaminophen at anticipated field delivery rates was considered not to represent a human health or environmental risk (Schwab et al. 2005; Kim et al. 2007). For select nontarget, nonhuman standard test species, acetaminophen has an EPA worst-case scenario, acute hazard quotient >0.5, which is generally considered a significant risk (Johnston et al. 2001, 2002). Thus, precautions about toxicant placement and delivery method were considered for distribution on the landscape. Laboratory and field experimental and observation studies showed that nontarget wildlife encounters with the toxicant bait system could be reduced by mechanical exclusion, or that the nontarget species likely to be encountered on Guam either tolerated field delivery doses or ate the bait, but not the toxicant (Avery et al. 2004). The bioaccumulation potential (Primus et al. 2004) and risk quotient for exposure of nontarget organisms eating snake carcasses was considered low to nonsignificant (Johnston et al. 2002). Moreover, video and telemetry monitoring of baits treated with acetaminophen and placed in the field showed that snakes took the vast majority of baits and that nontarget bait take was rare (Savarie et al. 2000; Clark and Savarie 2012). Based on these and other field efficacy studies, U.S. EPA issued a pesticide label to the USDA for acetaminophen for control of brown tree snakes in 2003 (U.S. EPA Registration Number: 56228-34) with provisions for application in polyvinyl chloride (PVC) bait stations or traps and for hand or aerial broadcast.

CHEMICAL FUMIGANTS

Cargo shipments pose a risk for translocating invasive species (Work et al. 2005; Kraus 2007). Fumigation of cargo with a toxicant is used to mitigate against this risk and kill a variety of pest species, and in the case of commercial international trade, it is generally used to ensure phytosanitary standards (e.g., FAO 2006; GATFA 2012). Generally, gaseous pesticides are applied to a confined space (e.g., cargo container, tent enveloping cargo) and pests are suffocated or poisoned. The time period for exposure depends on the registered fumigant being used and the target pest species. Fumigation is a hazardous activity and can only be carried out by licensed pesticide applicators using registered pesticides. Fumigation also requires an operational infrastructure dedicated for its use. Despite these logistical constraints, the use of fumigants for brown tree snakes at cargo facilities was explored by USDA so as to provide managers with another set of tools in their effort to reduce the risk of snakes escaping Guam in outgoing cargo.

Several existing registered fumigant products were evaluated by USDA, with the rationale that the data support for supplementing existing pesticide labels and uses would prove to be a more cost-effective strategy in product development relative to registering a new active ingredient and finding a manufacturer to produce the product. The candidate products contained the following active ingredients: Meth-O-Gas® (methyl bromide); Metabrom Q® (methyl bromide); Vikane® (sulfuryl fluoride); Magtoxin® (magnesium phosphide); Fumi-Cell® (magnesium phosphide).

Fumigant treatments and dosages applied to the cargo containers (19.5 × 7.7 × 7.8 ft) were all within the preexisting registered label application rates for each of the active ingredients. All three active ingredients at label-specified rates killed brown

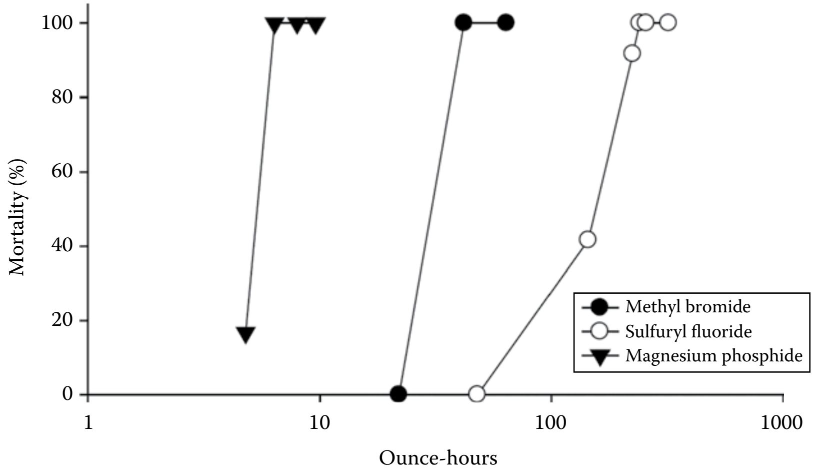

FIGURE 7.4 Brown tree snake mortality resulting from chemical fumigation. Mortality of brown tree snakes in cargo containers fumigated with three toxicants. Ounce-hours is the number of ounces of fumigant applied/1000 ft^3, multiplied by the exposure time in hours. (Data adapted from Savarie, P. J. et al. 1995. Unpublished report on file with the U.S. Department of Agriculture, Fort Collins, Colorado: Animal and Plant Health Inspection Service, National Wildlife Research Center and Savarie, P. J. et al. 2005. *International Biodeterioration & Biodegradation* 56:40–44.)

tree snakes (Figure 7.4). Based on these encouraging results, data were provided to the product owners, and two of the companies filed for amendment to their pesticide labels to include brown tree snakes: Meth-O-Gas (methyl bromide, Great Lakes Chemical Corporation, West Lafayette, IN; EPA Registration No. 5785-41) and Metabrom Q (methyl bromide, ICL-IP America, Inc., Gallipolis Ferry, WV; EPA Registration No. 8622-55). These products are now available for brown tree snake control. Despite the availability of products for the sanitation of cargo, we are not aware of any actual commercial operational use. Nonetheless, any cargo undergoing phytosanitation with any of these products or ingredients for other uses would also *de facto* be sanitizing for brown tree snakes.

THERMAL FUMIGANTS

There may be circumstances that favor nonchemical methods to mitigate against invasive species transport via cargo shipments. “Thermal fumigation” may provide a simple, chemical-free method to sanitize cargo (Heather and Hallman 2008; Hennessey et al. 2014). Because snakes lack the ability to physiologically thermoregulate, extremes in temperature exposure can prove lethal (Christy et al. 2007). For example, snakes as stowaways in aircraft wheel wells can freeze to death owing to the high altitude and low temperature of most commercial flights (Perry 2002). Reliance on passive heating or cooling of cargo, however, may not be a good strategy for reliable control, in that temperatures in surface cargo containers are likely to be too low to consistently kill snakes (Perry and Vice 2007). Recently, Kraus et al.

(2015a) demonstrated that snakes could be driven from simulated cargo refugia by applications of forced heated air streams. Application rates of temperatures between 48°C and 52°C at 3.4 m^3/min were sufficient to induce escape from cargo within five minutes. While there remains work to be done to operationalize this method, it does appear to be a fruitful avenue for further exploration. While snakes demonstrated high variance in their response times to temperatures of forced air streams, "… only eight snakes of 160 tested failed to find the refugium exit, and those that failed died trying" (Kraus et al. 2015a). Ongoing research into thermal fumigation indicates that radiant energy may also be applied to heat cargo to lethal thermal limits, for applications where forced heated air may not be practical, such as in closed cargo containers (Kraus, unpublished data).

REPELLENTS AND IRRITANTS

Chemicals have been used to protect food and crops from animal depredations and to repel animals away from areas (Mason and Clark 1995). This latter use pattern is the one most researchers have focused on in their search for brown tree snake control tools. Chemical barriers prevent snakes from entering refugia or cargo. When acting as a nonlethal fumigant, the chemical repellent is designed to elicit escape behavior of snakes hiding in confined spaces. The primary principle in operation in the applications of almost all repellents is stimulation of chemosensitive nociceptors (pain fibers) that then elicits avoidance behavior (i.e., reflective withdrawal/escape) by the animal (Clark and Avery 2013).

The embodiment of most chemical barrier systems is to expose a snake, through direct contact, to a chemical irritant by treating surfaces with compounds such as camphor, naphthalene, or sulfur (Ferraro 1995; summarized in Clark and Shivik 2002). Tactile products generally are sticky, such as polybutenes. The snake either avoids contact or becomes stuck (Takashi et al. 1992).

Another strategy would be to use the repellent as a "tear gas" (Stevens and Clark 1998). In this case, an aerosolized or vaporized repellent is introduced to an enclosed space. Snakes exposed to the irritant would then try to escape. This use pattern might be desirable once a detector dog identified cargo containing a snake, and would allow verification or capture without dismantling the cargo container or pallet.

A variety of single compounds and essential plant oils known to have high concentrations of chemicals irritating to birds and mammals were screened using brown tree snakes as a model (Clark and Shivik 2002, 2004). Some compounds proved to be toxic under high aerosol or vapor concentration, and some induced narcolepsy. Nonetheless, many compounds and mixtures demonstrated effectiveness in promoting escape behavior in simple simulated cargo configurations. Compounds such as cinnamon oil (containing cinnamaldehyde) were identified as promising because they did not require U.S. EPA registration for this use (USDA 2003). As encouraging as the direct exposures to these irritants were, several challenges remained. Many of the compounds had plasticizing properties (i.e., they would melt plastic), thus their use for certain types of cargo would be restricted. Dispersal of aerosols in the complex confined space of cargo is also problematic. Thus, using vapor would be the preferred embodiment of application because of its superior penetrating properties as opposed to aerosols, which would deposit on surfaces and have limited ability to penetrate the complex interstitial space of cargo. The greatest challenges for this method are vapor generation and penetration of complex cargo. To date, the reliability of the method, given the current technologies, is not sufficient to produce reliable escape behavior from simulated cargo (Kraus et al. 2015b).

CHEMICAL LURES, BAITS, AND DELIVERY SYSTEMS

Chemical lures are odors/scents used to attract animals to a location or object (Linhart et al. 1997). For snakes, the sensory modality mediating these cues is primarily vomeronasal or olfactory (Chiszar 1990; Halpern 1992; Schwenk 1995). The first phase in the behavioral process exploits appetitive exploratory behavior by animals motivated by hunger or reproduction. The second phase in the behavioral process involves consumatory behavior either through ingestion (of a bait) or mating (in the case of pheromones).

As reflected by dietary studies, brown tree snakes are opportunistic feeders (Savidge 1988; Fritts et al. 1989; Fritts and Rodda 1998; Siers 2015). Moreover, brown tree snakes use visual, tactile (vibratory), and chemical cues to locate and capture their prey. Initial research focused on the attractiveness of odors for a variety of prey, for example, skinks, geckos, eggs, birds, bird feces, blood, and small mammals (Chiszar et al. 1988, 2001), to be incorporated as a lure for trapping efforts. Numerous studies focused on the sensory modalities used by brown tree snakes with the goal of designing an optimal lure/trap system. For example, in the laboratory, snakes were temporarily rendered blind by placing electrical tape over their eyes. Relative to controls, blinded snakes had similar accuracy for their strikes and capture, but took three times longer to initiate the strike, and the initial strike distance was one-third that of the sighted controls (Kardong and Smith 1991). Prey cues presented in concert are most effective in eliciting predatory appetitive behavior in the laboratory and capture success in traps in the field (Shivik 1998; Stark et al. 2002), with odor plus visual cues being twice as effective as either cue presented separately. When presented as a single stimulus, odor was slightly better than a visual cue alone.

Ultimately, for practical operational reasons (i.e., effectiveness as a lure and ease of maintenance), USDA settled on a live mouse lure system contained within a Wildlife Services Standard Trap design (Hall 1996). While effective at catching snakes, the expense of maintenance and operation is a major factor limiting the number of traps that can be deployed (Clark et al. 2012). For these reasons, efforts to replace the live lure system and exploit the natural prey preferences and sensory foraging modalities have been extensive (Savarie and Clark 2006).

While laboratory studies of alternative lures elicited interest from brown tree snakes, the rate of capture relative to the live mouse lure system was poor. The exception was the use of mouse carrion (Shivik and Clark 1997, 1999a,b; Shivik et al. 2000; DeVault and Krochmal 2002). As an aside, one interesting aspect about the attractiveness of dead neonatal mice (DNM), and as revealed by video analysis, traps with live mice attract more snakes, but are less efficient in their capture, whereas traps with DNM attract fewer snakes, but are more efficient in their capture (L. Clark, unpublished). This is a case of snakes exhibiting different foraging behaviors. For traps with live mice, snakes spend more time striking and are less likely to find the trap entrance (a one-way door), whereas snakes investigating DNM lures are more methodical in the investigatory behavior and find the one-way door without distraction. The appeal of DNM is that it could be used as both a lure (for trapping) and a bait (for toxicant delivery).

The attractiveness of DNM appears to be related to bacterial decomposition of the mouse skin (Jojola-Elverum et al. 2001). One- and two-day-old decomposed mouse skin yields optimal attractiveness to brown tree snakes. Other tissues (depelted mice; ground mice; other meats such as chicken, pork, and beef) all are less attractive than DNM (Savarie and Clark 2006; Savarie 2012).

Synthetic lures are desired because DNM have an effective usefulness of two days in the field and they are relatively expensive to obtain, ship, and store frozen. An improved lure/bait system would incorporate a synthetic lure that was inexpensively manufactured, shipped, stored, and deployed, and would be durable in hot, wet, humid tropical environs. Efforts to test the attractiveness of chemicals commonly associated with carrion yielded results that snakes were moderately attracted to a location, but could not hold the attention of foraging snakes sufficiently long enough to effect capture at traps or entice snakes to eat the bait at the levels observed for DNM (Savarie and Clark 2006; Kimball et al. 2016). It is presumed that a good synthetic lure can be incorporated into a matrix with controlled and timed release. Such a system would maintain effectiveness of traps while substantially reducing operating costs relative to traps with live mouse lures. Recently, Kimball et al. (2016) identified a promising system that uses a complex suite of compounds designed to more realistically mimic a two-day-old rotted mouse carcass. The delivery matrix identified (a commercial meat product) is also more amenable to retaining the synthetic lure for timed release and as a palatable bait that snakes accept at rates comparable to the DNM, thus it is suitable for toxicant delivery as well. From an operational perspective, the system is amenable for large-scale manufacture and production capacity that will be necessary if any large-area operational programs are to be successfully implemented in a cost-effective manner.

PHEROMONES

Use of pheromones is another lure-based strategy frequently used in the control and management of pest species (Howse et al. 2013; Pickett et al. 2014). For brown tree snake control, uses include luring snakes to traps or other control tools (Greene et al. 2001), reproductive inhibition through confusion or disruption of male snakes seeking female mates (Greene and Mason 2003), and early detection of nascent populations on islands at risk of snake invasion (Mathies et al. 2013).

Brown tree snakes do not demonstrate seasonal patterns of fertility or reproductive state on Guam (Savidge et al. 2007; Mathies et al. 2010). Yet, despite the continuous availability of reproductively receptive snakes at the population level, it also appears that the number of reproductively receptive brown tree snakes is low when compared to conspecifics in their native range, suggesting that overpopulation and competition for food resources are limiting reproductive opportunity (Moore et al. 2005). Male brown tree snakes readily follow the semiochemical trail of both male and female conspecifics (Greene et al. 2001). However, male courtship of females can be suppressed by cloacal secretions from females (Greene and Mason 2003). While this observation may have significance from an evolutionary signaling perspective, it is not year clear how this inhibitory mechanism could be adapted to a large-scale management scenario.

Using pheromones to attract animals to a trap is a more typical use pattern, that is to say, the lure and kill strategy. In laboratory studies, using a tongue flicking bioassay, the attractiveness of vitellogenic brown tree snake females to males is greater than nonvitellogenic females (Mathies et al. 2013). Exploiting this observation may also prove useful for the detection of reproductively active males on islands with low snake densities and where the attractiveness of food-based lures may not be sufficiently high (Mason et al. 2011). Regardless, more work is needed to identify the composition of the pheromone (Greene and Mason 1998) so that it could be synthetically produced at sufficient quantities, embedded in a sufficiently compatible matrix for distribution, and validated using trap capture success when used as the lure. Tongue flicking is a low threshold of success when compared to the sustained motivation and investigatory behaviors needed to capture a snake in a trap.

DEVICES AND OTHER STRATEGIES FOR BROWN TREE SNAKE CONTROL

TRAPS

Trapping is one of the most basic and universal forms of vertebrate pest control. Since the mid-1980s, numerous trap designs have been screened for their suitability for brown tree snake control (Rodda et al. 1999b). Incorporating preferred design components from these many years of testing by multiple agencies, and subsequent to rigorous testing (e.g., Linnell et al. 1998; Engeman and Vice 2000), USDA settled on the "Wildlife Services" Standard Trap (WSST) design, which employs components of a one-way door at the end of an inverted cone placed at both ends of a cylinder (Figure 7.5; Vice et al. 2005). The shape and orientation of the one-way door flap are such that gravity holds it closed until pushed open by an entering snake, with the flap then closing behind the snake and trapping it in the interior; this self-setting design allows for repeated captures of multiple snakes. Traps are typically suspended

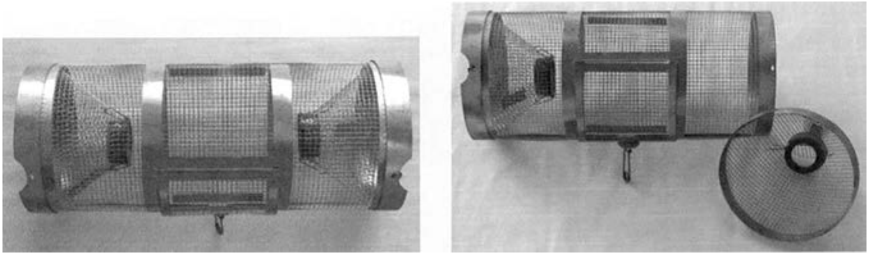

FIGURE 7.5 Wildlife Services Standard Trap design. The modified minnow trap used by the USDA Wildlife Services program, known as the Wildlife Service Standard Trap (WSST).

at approximately waist to chest height for ease of checking and maintenance. Snakes are drawn to, and into, the traps by a lure, typically and most effectively a live mouse lure, which is contained within a separate wire mesh chamber containing provisions for food and moisture, which is enclosed within the body of the trap, and protects the mouse from snake strikes. The top half of the trap is typically covered by an opaque plastic shield provided to afford protection from rainfall and direct sunlight.

When using the live mouse lure, most snakes captured by the WSST design are within the size range of 800 to 1100 mm SVL (Vice et al. 2005). Such traps, using live mouse lures, are only partially effective at capturing snakes 700–900 mm SVL, and not effective for smaller juvenile snakes (Rodda et al. 2007b; Tyrrell et al. 2009) due to a strong ontogenetic prey preference for small lizards and nonresponsiveness to rodent-based lures (Savidge 1988; Lardner et al. 2009a; Siers 2015). Efficacy of different lure systems and field operational evaluations are covered below.

PERIMETER TRAPPING

Costs, logistics, and time always constrain management and control programs. From an operational perspective, these tradeoffs influence the calculus of which method to use under any set of circumstances. The fragmented nature of the islands' forested habitats represents an opportunity for control efforts. Fragments are interspersed with roads and trails, presenting the opportunity to easily place and maintain snake traps along forest edges. Snakes of size classes vulnerable to trapping can effectively be controlled in habitat blocks of up to 18 ha using the WSST with a live mouse lure and a perimeter trapping scheme (Engeman and Linnell 1998; Engeman et al. 1998a,c, 2000). In a similar habitat, spacing traps at 20-, 30-, and 40-m intervals did not affect snake capture rates (Engeman and Linnell 2004).

BAIT TUBES

Compared to live mice, DNM represent a lower cost bait matrix to deliver toxins to brown tree snakes (Clark et al. 2012). A convenient way to deliver the baits is to place the toxicant-treated DNM inside a PVC pipe bait station, or "bait tube," suspended along perimeters of forested habitat. This presentation minimizes exposure of the toxic bait to nontarget organisms. Savarie et al. (2001) demonstrated that delivery of acetaminophen-treated DNM in bait tubes was sufficient to reduce the population of snakes vulnerable to rodent-based tools by 83% (based on pre- and posttreatment mark recapture estimates using live mouse lures). One concern about using DNM is that this prey base may be selective to only a fraction of the population, owing to ontogenetic prey preferences attributable to size of the foraging snake, its foraging history, and satiety, among other factors. Small snakes (<843 mm) did not eat DNM from tubes (Lardner et al. 2013). Disappearance of DNM from bait tubes is often considered one index of snake abundance or snake foraging activity. The use of bait tubes alone as a method for monitoring snake populations should be viewed with some caution. Removal of DNM baits may indicate presence of certain size classes of snakes for a given satiety level, but does not provide a reliable index of population numbers. Bait disappearance may also result from takes by nontarget organisms such as rats or crabs, though photo and video evidence indicates that such events are rare (USDA, unpublished data). Snake control through applications of toxic DNM baits in bait tubes has been demonstrated to be 1.67 times more cost effective than trapping with live mouse lures (Clark et al. 2012).

AERIAL APPLICATION OF TOXIC BAITS

Trapping over moderately sized areas (~17 ha) can reduce snake populations significantly, but is logistically time consuming, costly, and frequently impractical when large areas or rugged terrain need to be managed (Clark et al. 2012). A lower-cost alternative to trapping has been proposed that uses dead mice baits treated with acetaminophen (Savarie et al. 2001; Clark et al. 2012). USDA developed prototype delivery systems (Savarie et al. 2007) and demonstrated their aerial delivery feasibility and target specificity (Shivik et al. 2002). Subsequently, DNM treated with toxic doses of acetaminophen were aerially broadcast over 6 ha at an application rate of 37.5 baits/ha. Take of unadulterated DNM baits from bait tubes, as an index of snake activity, was reduced approximately 85% relative to pretreatment levels and to isolated untreated reference plots (Figure 7.6; Clark and Savarie 2012; Dorr et al. 2016), thus demonstrating proof of concept and feasibility of large-scale area suppression of brown tree snake populations. Larger-scale aerial applications are

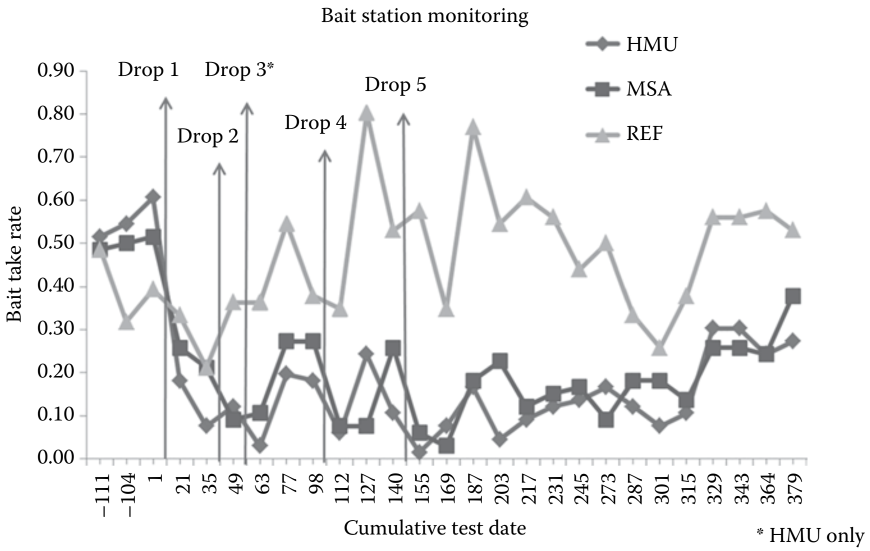

FIGURE 7.6 Reduction in snake activity following aerial application of baits. Reductions in brown tree snake activity, as indicated by takes of dead neonatal mouse baits from monitoring stations, following aerial application of acetaminophen-treated mice on Guam. (Data adapted from Dorr, B. S. et al. 2016. Aerial application of acetaminophen-treated baits for control of brown tree snakes [RC-200925; NWRC Study Number: QA-1828]. Final Report, U.S. Department of Defense ESTCP.)

planned by USDA that will incorporate automated bait packing and geospatially controlled delivery systems to further improve on the economics of large-area brown tree snake suppression.

Visual Detection, Spot Lighting, and Fence Line Removal

Fences are often associated with property boundary roads and serve as a first line of security for properties surrounding airports, housing areas, and ports. Because snakes readily travel along the length of fences, using spotlights provides a simple method for visual inspection and removal which has been exploited by operational personnel (Engeman et al. 1999). In comparing trapping and visual spotlighting methods and their placement along forest edges and fences, Engeman and Vice (2001) found that trapping success rates were similar on fences and forest edges, and both were four to seven times more successful than visually directed hand removal efforts. However, studies on effectiveness of trapping show an exponential decline in trap success as local populations of snakes are depleted (Engeman and Linnell 1998), while the removal rate for spotlighting and hand capture remains constant over time (Engeman and Vice 2001).

Systematically searching for brown tree snakes directly on vegetative substrates along forested perimeters or along transects in forest interiors has proved more problematic given their overall drab coloration and very subtle movements. Christy et al. (2010) demonstrated that probabilities of visual detection of individual snakes are very low and influenced by multiple factors such as snake sex, size, and body condition; observer effects; and environmental conditions. Optimization of the way lighting is applied and interpreted can help to increase the probability that a searcher will detect a snake that is within his or her field of vision. Searching efficiency might be improved by selection of headlamps with desirable beam characteristics (Lardner et al. 2007, 2009b). While contrasts in background versus snake reflectance might theoretically be exploited, early simple efforts in this area have not proved successful (Siers et al. 2013).

Though more costly than trapping, an advantage of visual detection is that all size classes are exposed to detection, while size distributions of snakes captured by rodent lure-based methods are more biased toward larger snakes (Rodda et al. 2007b). This may be important when comparing snake size distributions among sampling locations (e.g., Siers 2015) and particularly important in early detection and rapid response efforts, when all snakes, including larger snakes not adequately attracted to baits (e.g., when satiated or when alternative prey are abundant), must be exposed to opportunities for detection.

Barriers

Constructed barriers can be used to enclose or exclude snakes on a temporary or permanent basis. Barrier designs include temporary, bulge, masonry, and vinyl (Rodda et al. 2002). Temporary barriers are used for excluding snakes at cargo staging areas and are 93%–99% effective at restricting snake movement across the barrier (Perry et al. 1998). Bulge barriers consist of 1/4-in. mesh hardware cloth attached to chain-link fence. Near the top, a hardware cloth bulge is formed which prevents further climbing by the snake; as it leans back, it does not have sufficient purchase to retain contact with the fence. Vinyl barriers are made from commercial interlocking seawall panels and can be cut to shape. The smooth surface of the material prevents adequate climbing purchase by snakes. A variation is use of fly-ash-covered wall coatings which can be glued to existing vertical structures (Rodda et al. 2007a). Walls of prestressed concrete panels are the sturdiest of the barrier systems, capable of withstanding typhoon-force winds. Under experimental tests, all four designs were 99%–100% effective at preventing snake movement across the barrier (Perry et al. 1998). Finally, electrical barriers have been outfitted onto individual trees and power structures to protect nesting birds (Aguon et al. 2002).

"Area 50" on Guam was enclosed using a bulge barrier, with snakes removed by trapping for the protection of Guam rails (*Gallirallus owstoni*) (Beauprez and Brock 1999). While snake densities remained low, there was a failure to eliminate snakes from this area. Many reasons have been postulated, from inadequate trapping effort to leakage in the barrier system or snakes being refractory to traps (attributable to a variety of causes) (Rodda et al. 2002). Given that severe suppression or elimination of snakes in small plots is feasible (Campbell et al. 1999; Rodda et al. 1999a), leakage and maintenance of the barrier may be the most likely contributory cause of failure in this case, demonstrating the commitment a barrier system needs to succeed. With high levels of maintenance, a similar barrier around the USGS Closed Population (Northwest Field, Andersen Air Force Base) has exceeded longevity expectations and is now 12 years old.

Roads and paths are barriers to wildlife movement in general and snake movement in particular (Trombulak and Frissell 2000). Small-scale studies on snakes fitted with radio transmitters demonstrated over short time periods that brown tree snakes only move short distances, and roads or runways were a partially effective barrier to movement across those substrates (Tobin et al. 1999; Clark and Savarie 2012). A more extensive analysis showed that traffic volume, gap width, and surface type all were negatively related to the probability of a snake crossing a road, and those snakes that did cross tended to be larger. Proximity to traps along a perimeter also decreased the probability of a snake crossing a road (i.e., possible demonstration of an intercepting effect) (Siers et al. 2014, 2016).

DETECTOR DOGS

Working dogs have been employed to detect a variety of targets (e.g., game, drugs, pests, explosives, pathogens) throughout history (Henry 1977; Crooks et al. 1983; Gordon and Haider 2004). As part of an interdiction and control effort, USDA Wildlife Services has used detector dogs to find brown tree snakes in cargo since 1993 (Hall 1996; Engeman et al. 1998b, 2002). Since then, other government agencies have begun to evaluate the utility of dogs in early detection and rapid response activities on islands not yet impacted by snakes. However, improvements are needed for effective detection and recovery of snakes from forested habitats (Savidge et al. 2011).

As used by the USDA, the detector dog effort is generally the last line of defense for inspecting high-risk outward-bound cargo (Linnell and Pitzler 1996; Perry and Vice 2009). Estimates of detection success under operational conditions at cargo ports using blind test challenges of handler-dog teams are in the 70% range (Engeman et al. 1998c). Adverse climatic events such as typhoons seem to promote the movement of snakes; subsequent to storms, detector dogs are especially useful as a line of defensive containment and interdiction because other methods such as traps are generally pulled from service during such events to prevent damage to them (Vice and Engeman 2000). With support from the USFWS and OIA, the Commonwealth of the Northern Mariana Islands—at high risk of accidental importation of snakes from Guam—employs detector-dog teams for the inspection of inbound cargo. These teams are also included in rapid response activities when snake sightings are reported. This dual strategy, covering points of entrance and egress, provides an added measure of effectiveness for interdiction and control.

OTHER CONTROL METHODS

Biological Control

Introduction or augmentation of "natural enemies" (predators or parasites) to control invasive species has been effective against injurious or pest insect and plant systems, and has been considered as one avenue for brown tree snake control (Campbell et al. 1999). Engeman and Vice (2001) briefly review the limited potential and risks of biological control for management of brown tree snakes. Since that time, the potential of parasites for suppression of brown tree snakes has received further investigation—for example, Caudell et al. (2002) and surveys within the brown tree snake's native range for candidate pathogens or parasites (Richmond et al. 2012)—with no clear improvements in the prognosis for biological control. While theoretically holding the potential for a role in an Integrated Pest Management (IPM) program for brown tree snakes, this is currently not deemed likely by us to yield an effective control tool.

Harvest Incentives

Bounty systems have been used to promote conservation, damage management, and invasive species control (Parkes 1993; Pohja-Mykrä et al. 2005; Zabel and Roe 2009). A full discourse is beyond the scope of this review, however. Commercial markets for brown tree snake products are not feasible in that their skins do not have desirable characteristics for leather goods, and their lean bodies do not provide much meat (which is reported to be only marginally palatable). Bounties, or cash payments to individuals upon evidence of the collection of an organism, may be successful at recovering a large number of snakes, but to achieve effective control, a progressive bounty structure would be required to maintain participation when snakes become harder to obtain. At some point, the financial impetus to continue to produce snakes will create a "perverse incentive" to "cheat," for example, thru captive rearing or surreptitious importation to maintain this source of income; concern also exists that a ready revenue stream on Guam may incentivize the introduction of snakes to neighboring islands, for example, Saipan, Rota, or Tinian, in order to replicate this source of profit in these economically depressed markets. Ultimately, harvest incentives are incompatible with an eradication objective, as a program of harvest incentives is dependent upon a continued yield.

CONCLUSION

Great progress has been made in the understanding of brown tree snake biology and the development of control methods since the last formal synthesis by Rodda et al. (1999e). Control programs have been implemented and continue to undergo evaluation and adaptive management as new technologies develop. However, challenges still exist. Improvements in design and effectiveness are needed for existing technologies. Such improvements will be needed as operational considerations such as scalability (production and large-area implementation) become an issue under budgetary constraints. Efforts to monitor success and devise cost-effective strategies for monitoring and remedial treatments will also be needed. In short, formal systems analyses are needed for a variety of objectives: interdiction, containment, suppression, eradication, conservation, and ecosystem restoration. These analyses require better integration and communication among the various partners and will be critical for optimal resource allocation. The various working groups established by federal and state agencies are a good first step toward these goals.

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