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Title

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Journal

Proceedings of the Vertebrate Pest Conference, 29(29)

ISSN

0507-6773

Authors

Siers, Shane R.
Eisemann, John D.
Pitt, William C.
et al.

Publication Date

2020

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Automated Aerial Baiting for Invasive Brown Treesnake Control: System Overview and Program Status

Shane R. Siers, **John D. Eisemann**, **William C. Pitt**, and **Larry Clark**
USDA APHIS Wildlife Services, National Wildlife Research Center, Fort Collins, Colorado
Scott M. Goetz
USGS Fort Collins Science Center, Fort Collins, Colorado
Robert J. Gosnell and **Aaron F. Collins**
USDA APHIS, Wildlife Services, Guam State Office, Barrigada, Guam
Eric T. Hileman, **Melia G. Nafus**, and **Amy A. Yackel Adams**
USGS Fort Collins Science Center, Fort Collins, Colorado
Michael C. Messaros and **William G. N. Coon**
Applied Design Corporation, Boulder, Colorado

ABSTRACT: The economically and ecologically catastrophic introduction of invasive brown treesnakes to the Pacific Island of Guam has long served as a cautionary tale about the dangers of invasive species and the seeming impossibility of their management on a landscape scale. USDA Wildlife Services and federal and private partners have engineered a system for the automated manufacture and aerial delivery of toxic baits for landscape-scale suppression of brown treesnakes in large and remote forest plots. The helicopter-borne dispensing module can launch four bait cartridges per second, and a single payload of 3,600 cartridges can treat 30 ha of forest at 120 baits/ha in 15 to 30 minutes depending on flightpath efficiency. In this paper we recap the research, development, testing, and implementation of the system, including the procedures for monitoring biological responses to bait applications during an experimental suppression within a 55-ha forest plot surrounded by a snake-proof barrier.

KEY WORDS: aerial bait application, *Boiga irregularis*, brown treesnake, eradication, invasive species, landscape-scale suppression, technological innovation, vertebrate pesticide

Proceedings, 29th Vertebrate Pest Conference (D. M. Woods, Ed.)
Paper No. 46. Published November 30, 2020. 7 pp.

INTRODUCTION

The brown treesnake (*Boiga irregularis*; BTS) is a slender, arboreal, nocturnal, generalist predator native to tropical biomes in northern and eastern Australia and throughout most of the islands of Oceania, including New Guinea and the Solomon Islands. In the late 1940s or early 1950s, a small number of BTS were accidentally transported to the tropical Pacific island of Guam, an unincorporated U. S. territory, probably in shipments of military material staged near the jungles of Manus in the Admiralty Islands (Rodda et al. 1999a, Rodda and Savidge 2007, Richmond et al. 2015). Initially garnering little attention, an irrupting BTS population spread from the forest surrounding Naval Base Guam, the likely point of import, throughout the rest of the island, reaching the southern end of the island by 1968 and the northern limestone forests by 1982 (Savidge 1987). During the height of the irruption in the 1980s, BTS may have reached densities of up to 100 per hectare; estimates from the 1990s suggested that densities had subsided to approximately 25-50 per hectare, still far exceeding the highest known densities of any terrestrial non-aggregating snake (Rodda et al. 1999b).

Hyperabundant BTS populations caused several detrimental societal impacts such as damage to utility infrastructure from short-circuiting power lines, predation on poultry and pets, human bites (including a high incidence of infants being bitten while sleeping), loss of tourism revenues, and costs of inspecting outbound cargo to prevent further spread to other islands in the Pacific (reviewed in Rodda and Savidge 2007). The ecological toll of the BTS invasion of Guam has long served as a textbook case of the dangers of species invasion. All native vertebrate taxa have been negatively impacted by BTS predation including fruit bats and lizards (Wiles 1987, Rodda and Fritts 1992, Fritts and Rodda 1998, Campbell et al. 2012). However, the most profound effects have been on the native birds of Guam. Bird populations on Guam crashed in a wave coincident with the spread of BTS across the island, leading to the extirpation of the entire forest avifauna and extinctions of some species and subspecies (Savidge 1987, Wiles et al. 2003). This extraordinary loss of birds has led to cascading ecological consequences such as disruptions to natural processes of seed dispersal, arthropod regulation, mutualistic interactions, and forest regeneration (Perry and Morton 1999, Rogers et al. 2012, Caves et al. 2013, Rogers et al. 2017, Freedman et al. 2018). The sum of impacts following its invasion of Guam has earned the BTS a place on the list of the world's worst invasive species (Global Invasive Species Database 2020).

An immediate priority was to prevent further spread to other islands in the Pacific, such as the Commonwealth of the Northern Mariana Islands and the Hawaiian Archipelago, to prevent additional negative effects. With funding from the U.S. Department of the Interior and Department of Defense (DOD) agencies, USDA Wildlife Services (WS) implemented a full interdiction program (BTS Technical Working Group; BTSTWG), including trapping and spotlighting of BTS around cargo facilities and inspections of outbound aircraft and cargo by trained snake detection dogs (Engeman and Linnell 1998, Engeman et al. 1999, Clark et al. 2018, Engeman et al. 2018). Since the program's inception in 1993, there have been no live BTS found in inbound cargo to Hawaii or other islands (BTSTWG 2015); this constitutes a tremendous conservation victory considering the dire impacts predicted if the BTS invasion was to spread elsewhere in the Pacific. Subsequent to preventing the escape of BTS from Guam to other islands, additional priorities of the multi-agency Brown Treesnake Technical Working Group include development and implementation of BTS suppression on a landscape scale, reduced ecological effects, ecosystem restoration, and evaluation of the potential for eradication of BTS from the island of Guam (BTSTWG 2015). Guam's native birds will not recover without large-scale reduction of BTS predation.

Landscape-scale Control

Objectives for landscape-scale suppression of BTS abundance include: 1) reduced incidence of damage (e.g., predation events, power infrastructure damage, etc.); 2) enhanced protection against spread outside Guam through BTS population reduction, and 3) facilitating conditions for recovery of native species and ecosystem function. A successful program for landscape-scale suppression faces many challenges. Although Guam is relatively small (520 km^2), it consists of a mosaic of multiple land cover types across topographically complex and rugged terrain. BTS occur in all terrestrial environments on Guam including limestone, scrub, strand, and ravine forests, savannas, and industrial and residential urban areas (Siers et al. 2017c). BTS are cryptic in behavior and appearance, being nocturnal, arboreal, and having coloration and body shape that are difficult to distinguish from vegetation and difficult to access in the canopy; furthermore, BTS detectability, invasion risk, negative impacts, and susceptibility to control tools all vary by size within the species (Tyrrell et al. 2009, Christy et al. 2010, Siers et al. 2017b). Conversely, a few advantages accrue to our benefit: unlike many snakes, BTS are willing to feed on carrion (dead animals); with respect to risks posed by BTS control activities, Guam has relatively few nontarget species of concern; and, provided that interdiction efforts remain effective, Guam is surrounded by the impassible barrier posed by the Pacific Ocean.

Alongside the interdiction efforts of the WS operational program (WS-Ops), scientists at the WS National Wildlife Research Center (WS-NWRC) have been conducting research on the biology, ecology, and behavior of BTS to guide testing, development, and evaluation of traditional and novel means of animal damage prevention since the early 1990s (reviewed in Clark et al. 2018). Inspired by remarkably successful programs for island rodent eradication using aerially-applied rodenticides (Howald et al. 2007, Russell and Holmes 2015), WS sought to develop a program for aerial baiting of BTS in the forests of Guam. Significant developments toward a program for landscape-scale suppression of BTS include:

- Identification of acetaminophen as a relatively safe and humane toxicant (Savarie and Bruggers 1999, Savarie et al. 2000) which is particularly effective for snakes (van den Hurk and Kerkkamp 2019);
- Identification of dead newborn mouse (DNM) as the best available bait matrix (Shivik and Clark 1997, Shivik and Clark 1999, Savarie and Clark 2006);
- Demonstration that hand-placement of acetaminophen mouse baits (AMB) in bait stations can reduce BTS numbers on a landscape scale (Savarie et al. 2001);
- Comparisons of multiple methods for suspending AMB in forest canopy (Savarie and Tope 2004, Savarie et al. 2007);
- Small-scale tests of efficacy of BTS suppression by aerial baiting (Shivik et al. 2002, Clark and Savarie 2012);
- Environmental and nontarget risk assessment for a program of acetaminophen baiting for BTS control (Johnston et al. 2002); and
- EPA registration of 80-mg acetaminophen tablets as a pesticide for BTS control (EPA Registration No. 56228-34) by WS.

The first large-scale and repeated test of BTS suppression by aerial baiting was performed by WS in 2013-2014 (Dorr et al. 2016). They applied eight treatments of 36 baits per hectare to a 55-ha Habitat Management Unit (HMU; see description below) surrounded by a snake-proof barrier and seven treatments in an adjacent 55-ha unbound plot. Baits were manually assembled by inserting an 80-mg acetaminophen tablet into a DNM bait via the oral cavity and using hot-melt glue to adhere a hind foot of the DNM to one of the cardboard squares comprising the ends of a crepe-paper streamer used as flaggers by crop-dusting aircraft. These baits were then manually broadcasted individually by WS personnel within a helicopter, timed to throw one flagger bait every 36 m on helicopter flight paths spaced 36 m apart. BTS reduction was evaluated by comparing rates at which unadulterated DNM were removed from bait stations before and after toxicant treatments, and among treatment plots and an adjacent untreated control plot. Bait take rates were significantly suppressed in both treatment plots, and the results were interpreted as proof of concept of an aerial baiting program for BTS suppression at the landscape scale. However, they concluded that manual bait preparation and application would be cost-prohibitive for a large-scale aerial baiting program.

Automated Bait Production and Aerial Delivery

Contemporaneous with the Dorr et al. study, WS was experimenting with means for automated aerial bait application. With WS funding administered through a cooperative research agreement, and working with WS scientists, a small, woman-owned private engineering company, Applied Design Corporation (ADC; Boulder, CO), conceptualized a bait cartridge that would lend itself to high volume automated manufacture and be rapidly dispensable from an aircraft-mounted module. Prototype bait cartridges along with their associated manufacturing and dispensing systems were built with further funding from the Department of the Interior's Office of Insular Affairs (OIA).

The core technology of the system is a patented bait cartridge (Figure 1) (Messaros et al. 2017). Within the automated bait manufacturing system (ABMS): an 80-mg acetaminophen tablet is hot-melt glued to the abdomen of a DNM; the DNM is partially glued into a bamboo bagasse capsule; the capsule halves are folded over the DNM; one end of a ribbon is glued to the top of the capsule, the ribbon is wound barber-pole fashion along the capsule, and the tail end of the ribbon is glued to a bagasse end cap; an outer cardboard tube is sleeved over the wound capsule, to form a completed bait cartridge (80 mm long by 25 mm in diameter). Completed cartridges are packed into cases of 900 for freezing.

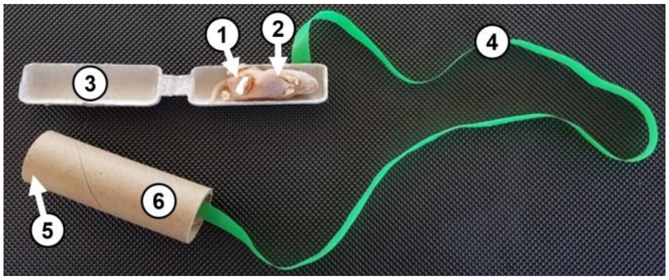

Figure 1. Components of an aerial delivery system (ADS) bait cartridge: 80-mg acetaminophen tablet (1) adhered to a dead newborn mouse bait (2) that is partially glued into the bait capsule (3); the capsule is folded around the bait and wound with a ribbon (4) which is attached to an end cap (5, not seen); the outer tube (6) is fitted over the wound capsule and end cap, for a completed bait cartridge. All components are biodegradable (patent: Messaros et al. 2017)**.**

Figure 2. Automated dispensing module (ADM) comprised of four magazines carrying 900 bait cartridges each. Mounted in Wildlife Services Hughes OH-6 helicopter.

The helicopter mounted automated dispensing module (ADM) is comprised of a frame, battery, GPS-enabled computer module, four magazine bays, and a series of four solenoid-driven firing units and ejection ports. The ADM is secured in the rear bay of a helicopter (Figure 2) and operated from a laptop computer by a payload manager in the co-pilot seat of the helicopter using payload management software. A 'fly-to-line' heads-up monitor indicates the aircraft position with respect to the programmed flight path, assisting the pilot in maintaining proper flight path spacing. Each of four magazines hold one case of 900 cartridges, for a payload of 3,600 cartridges. Flying at ground speeds of 50 to 70 knots, the ADM can eject up to four cartridges per second. Upon ejection, the inner capsule is jarred from the outer tube, the ribbon unfurls, the capsule opens exposing the DNM and tablet, and the assembly tangles in the forest canopy where the bait is available to arboreally-foraging BTS. Deployed baits remain viable for 48 to 96 hours. Most BTS expire within 48 hours of consuming a bait (Savarie et al. 2000, Mathies and Mauldin 2020). All cartridge components are biodegradable and rapidly deteriorate in Guam's hot, wet climate.

Together, the ABMS and the ADM comprise the aerial delivery system (ADS) for landscape-scale BTS suppression. The first *in situ* test of the ADM and bait cartridges occurred over 110 ha of secondary forest on Guam in July of 2016 (Siers et al. 2019a). Despite technical difficulties with the prototype system, primarily associated with jamming of the firing mechanisms and failure of many of the bait capsules to properly deploy from the outer tube, the bait application resulted in an immediate >40% decrease in nontoxic bait take rates, no decrease in surrounding untreated forest, and a BTS suppression effect apparent nearly a year after baiting (Siers et al. 2019b). After this qualified success, engineering advancements improved bait cartridge ejection and deployment reliability, and significant financial investments were made by OIA and DOD to upgrade ADM and ABMS prototypes into operational-grade equipment. Subsequently, the ADS has transitioned from a WS-NWRC research and development program to a WS operational program capacity.

Operational Implementation in the HMU

Situated on Andersen Air Force Base, Guam, the HMU comprises 55 ha of native limestone forest heavily invaded by nonnative vegetation, primarily *Vitex parviflora* which dominates the canopy. The HMU was established as a dedicated conservation area and location for biological resource studies under various legal drivers (reviewed in Siers et al. 2017a). The site is within forest that has been designated as survival and recovery habitat for the conservation of Guam Micronesian kingfisher (*Todiramphus cinnamominus*; DON and USFWS 2015). The HMU is surrounded by a chain-link fence clad on the outer surface with a 6.35-mm galvanized mesh hardware cloth. At 1.2 m above ground level, the mesh is formed into a bulge; snakes scaling the mesh vertically lose purchase when trying to pass the bulge. Hence, the fence serves as a one-way snake barrier, allowing snake inside the HMU to climb out over the chain-link face of the fence but preventing in-migration of snakes from surrounding habitat. Barrier construction was completed in 2010. The HMU serves as a test case for drastic suppression and trial eradication of BTS, evaluation of the ADS and other control tools, low snake density research, and other restoration experiments (Siers et al. 2017a, Boback et al. 2020, Nafus et al. 2020).

In Fiscal Year 2019 (FY19), WS was contracted by DOD to apply ADS treatments in the HMU at the maximum allowed rate of 120 baits per ha and nine applications per year (≥1,080/ha/yr), as the first operational implementation of the ADS. In support of the ADS program, WS Aviation Safety, Training, and Operations Center assigned a Hughes OH-6 Cayuse light helicopter to Guam. The nine applications were scheduled to occur over three treatment periods, each composed of three applications at least three days apart, with treatment periods from 27 September to 4 October 2018; 9 to 15 March 2019; and 7 to 14 June 2019.

During the initial application on 27 September 2018, magazine feeding failures resulted in frequent irrecoverable magazine feed impediments and ejection port jams, forcing the day's operation to be cancelled. In the intervening days, engineers were able to make system adjustments to alleviate the mechanical difficulties and complete the 1 and 4 October applications. Further system refinements were conducted prior to the second and third treatment periods, and the system performed nearly flawlessly during all subsequent applications, applying all 6,600 baits per application within less than 90 minutes of helicopter time, inclusive of refueling and magazine reloading operations. In total, >52,000 baits were applied to the HMU in FY19. WS has subsequently been contracted to complete another nine ADS bait applications in FY20.

Biological Response Monitoring

Efficacy of aerial baiting and demographic effects on suppressed BTS populations are being evaluated by four methods: 1) monitoring of nontoxic bait take rates from bait stations (as previously described) as an index of BTS foraging activity and proxy for BTS abundance; 2) known-fate telemetry, directly assessing survival or mortality of known individual snakes implanted with VHF radio transmitters; 3) visual survey, detection, hand capture, passive integrated transponder (PIT) tagging, morphometry, and re-release of snakes in the HMU (*sensu* Christy et al. 2010); and 4) trapping, PIT tagging, morphometry, and release (*sensu* Tyrrell et al. 2009). These evaluation methods will continue through subsequent ADS treatments. As BTS abundance approaches zero, additional surveillance will include infrared game cameras on live lures to evaluate residual BTS predation threat to species considered for recovery.

Monitoring results of treatments will be reported in subsequent peer reviewed publications. Preliminary data indicate: an 80% decline in nontoxic bait take rates following the first year of treatments (S. Goetz and S. Siers, unpubl. data); 37% mortality of radio-tagged snakes released before the third treatment (E. Hileman and S. Goetz, unpubl. data); and a 64% decrease in snake captures per unit effort following the first year of treatments with an associated decrease in mean size of visually detected and trapped snakes (A. Y. Adams, unpubl. data).

DISCUSSION

These preliminary results indicate that snake abundance and foraging activity can be reduced with sustained aerial baiting. The following biological and behavioral characteristics of BTS should be considered when contemplating sustained large-scale control or eradication programs.

Juvenile BTS are gecko specialists (Lardner et al. 2009, Siers 2015) and therefore relatively less vulnerable to rodent-based control tools (Rodda and Reed 2007, Tyrrell et al. 2009, Lardner et al. 2013, Siers et al. 2017b). However, BTS begin to respond to rodent baits at approximately 700 mm snout-vent length (SVL) but do not begin to be reproductively mature until approximately 910 mm (females) or 940 mm (males) (Savidge et al. 2007, Siers et al. 2017b); if all reproductive-aged females can be removed, and all BTS maturing into rodent-feeding size classes can be effectively targeted before reaching reproductive age, potential exists for eradication with aerially-delivered DNM baits (Lardner et al. 2019).

Unlike high-metabolism rodents, which have been successfully eradicated from small islands with only one or a few aerial bait applications, snakes are adapted to long intervals between prey encounters and often exhibit periods where they cease to forage, particularly after feeding (Siers et al. 2018). This slower pace of feeding and lower metabolic demand, coupled with our inability to reliably target juvenile snakes, dictates that any attempts at aerial eradication with existing tools will be a protracted effort with a low probability of success. Optimism for future native bird recovery hinges partially on the concept that there may be some currently unknown threshold of BTS abundance at which experimentally-reintroduced bird populations may be sustained or increase (Yackel Adams et al. 2019). Because snake-proof enclosures are expensive to build and maintain, and limited in size, recovery of birds on a landscape scale may rely on an ability to drastically reduce and maintain very low snake numbers in the core of a very large unbounded (fenceless) treatment area, with in-migrating snakes removed by subsequent treatments. This concept remains unproven, and has been designated as a priority of the Research Committee of the BTS Technical Working Group.

Finally, ADS applications are very expensive, with bait cartridges constituting the primary cost. Current demand for bait cartridges is low, with only 55 ha of habitat in treatment; at this level, economies of scale are not achieved. It has been projected that the cost per bait could be reduced by 60-70% when demand reaches approximately one million baits per year, which is estimated will provide BTS control over an area ranging in size from 1,000 to 3,000 ha depending on recommendations for long-term baiting intensity. Price per cartridge may also be reduced by replacing the DNM with a less expensive bait; research and development of an artificial bait is already underway (Kimball et al. 2016). Baiting at the maximum rate allowed by the EPA may not be optimal, as there may be some threshold of bait density beyond which the potential effect is saturated and additional baits are not cost-effective. For example, an intensive suppression phase may be followed by a maintenance phase with lower-intensity baiting (Lardner et al. 2019). These and other questions about the frequency and intensity of baiting are currently unanswered. Cost reduction remains a high priority for further refinement of the system and strategies for its application.

CONCLUSIONS

Through collaboration and technological innovation, USDA now has a tool to reduce invasive BTS abundance on a landscape scale. For the first time, natural resources managers can significantly reduce BTS abundance in the most remote and rugged forests on Guam, stoking cautious optimism for a future that might see native species reintroductions and restoration of ecosystem function. Future challenges include improved targeting of all snake size classes, scaling up to landscapes large enough to support populations of reintroduced native flora and fauna, evaluating what level of suppression is required, containing costs, and cultivating and sustaining public and political will to commit to indefinite suppression, at least until such time as unforeseen new technologies make island-wide eradication possible.

ACKNOWLEDGMENTS

The achievements of this program have been made possible by the contributions of a legion of cooperating scientists, technicians, engineers, resource managers, and funders too numerous to name individually. We thank all contributing WS operational program personnel, WS-NWRC scientists and technicians, the WS-NWRC Registration and Technology Transfer Unit, USGS biologists, Applied Design Corporation engineers, DOD funders and natural resources managers, and DOI funders and advisors. This work was supported in part by the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government.

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