

**Risk Assessment****Can we prove that an undetected species is absent? Evaluating whether brown treesnakes are established on the island of Saipan using surveillance and expert opinion**Amy A. Yackel Adams<sup>1,\*</sup>, Patrick D. Barnhart<sup>1</sup>, Gordon H. Rodda<sup>1,2</sup>, Eric T. Hileman<sup>1,3</sup>, Melia G. Nafus<sup>1</sup> and Robert N. Reed<sup>1,4</sup><sup>1</sup>U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Ave, Bldg C, Fort Collins, Colorado 80526, USA<sup>2</sup>Present address: 404 Adobe Drive, Hesperus, Colorado, USA<sup>3</sup>Mississippi State University, Department of Wildlife, Fisheries and Aquaculture, Starkville, MS, 39762, USA<sup>4</sup>U.S. Geological Survey, Pacific Island Ecosystems Research Center, Hawai'i Volcanoes National Park, Hawaii 96718, USA

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**Citation:** Yackel Adams AA, Barnhart PD, Rodda GH, Hileman ET, Nafus MG, Reed RN (2021) Can we prove that an undetected species is absent? Evaluating whether brown treesnakes are established on the island of Saipan using surveillance and expert opinion. *Management of Biological Invasions* 12(4): 901–926, <https://doi.org/10.3391/mbi.2021.12.4.09>

**Received:** 4 February 2021**Accepted:** 14 July 2021**Published:** 8 October 2021**Handling editor:** Shane R. Siers**Thematic editor:** Catherine Jarnevig**Copyright:** © Yackel Adams et al.

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**OPEN ACCESS****Abstract**

Detection of invasive species and decisions centered around early detection and rapid response (EDRR) are notorious challenges for decision makers. Detection probability is low for cryptic species, resources are limited, and ecological harm (especially for island ecosystems) can result from failure to remove invasive species due to inadequate or delayed surveillance efforts. Due to the proximity to the U.S. territory of Guam and inter-island traffic, the Commonwealth of the Northern Mariana Islands (CNMI) is at high risk of colonization by the invasive and cryptic brown treesnake (*Boiga irregularis*; BTS). There have been numerous reports of snakes and 7 confirmed specimens secured at ports of entry on the island of Saipan in the CNMI over the last four decades, raising the possibility that a population might be established. Establishment of BTS on Saipan is a major concern, as evidenced by the ecological and economic disruption that occurred on Guam. We evaluated the possibility of a small localized population on Saipan using evidence from surveillance efforts in 1999, 2007, 2009, 2016, and 2018, and from results of expert assessment of the credibility of non-confirmed reports of snakes for the period 1982–2013. For active surveillance efforts, we use a Poisson-based model to estimate the 95% probability of at least one snake being detected at a stated density given the level of sampling effort and detection probability. Based on this collective evidence we conclude there is a low probability that Saipan currently has an incipient population of BTS. However, with the continued presence of BTS on Guam, continuing commercial and military transportation in the region, and relief shipments responding to increased storm intensity, Saipan remains highly vulnerable to accidental introductions. Effective surveillance remains a crucial element for detection of any species, but this may be particularly true for a cryptic snake that is difficult to control once established.

**Key words:** biosurveillance, *Boiga irregularis*, expert knowledge, incipient population, early detection and rapid response, propagule pressure

**Introduction**

Proving that a species is present is conceptually easy: find an individual! Proving absence of a species, however, is comparatively difficult and the subject of much recent research (Rout et al. 2011; Russell et al. 2017; Bonneau et al. 2018; Yackel Adams et al. 2018; Baker and Bode 2020). Typically, the



**Figure 1.** Brown treesnake (*Boiga irregularis*) on Guam. Photo credit: Björn Lardner.

best metric available to managers is to demonstrate that absence is probable at a stated confidence level (Kéry 2002; Durso et al. 2011; Russell et al. 2016; Yackel Adams et al. 2018). Thus, the short answer is, “No, we cannot prove absence”. Because eradication is more likely at early stages of the invasion when the population is small (Simberloff 2009) and we cannot prove absence, managers face complex decisions related to resource allocation for invasive species management (Moore et al. 2010; Baker and Bode 2020). Often the importance and difficulty of detecting small populations and concluding absence justifies both active surveillance and subsequently critical evaluations of surveillance techniques, as well as efforts to integrate and synthesize various efforts into comprehensive assessments.

Small populations of cryptic species are a more problematic challenge relative to many invasive species. One such species, the brown treesnake (*Boiga irregularis*; BTS; Figure 1) is an invasive species on Guam notorious for extirpating most vertebrate populations on the island (birds: Savidge 1987, mammals (bats): Wiles 1987, and lizards: Rodda and Fritts 1992). Elimination of native wildlife by the snake has been so complete on Guam that one can visit many forests where only lizards are found; native birds and mammals are absent (Savidge 1987; Jaffe 1994). Declines and reductions of Guam’s bird populations are likely responsible for major ecological changes to forest structure and composition (Rogers et al. 2017). For more comprehensive discussions of Guam’s extinction event and the influence of BTS, see Savidge (1987), Fritts and Rodda (1998), Rodda et al. (1999a), and Rodda and Savidge (2007). It is of note, however, that it took 30 years after the accidental introduction of BTS for resource managers to realize consequential impacts had occurred.

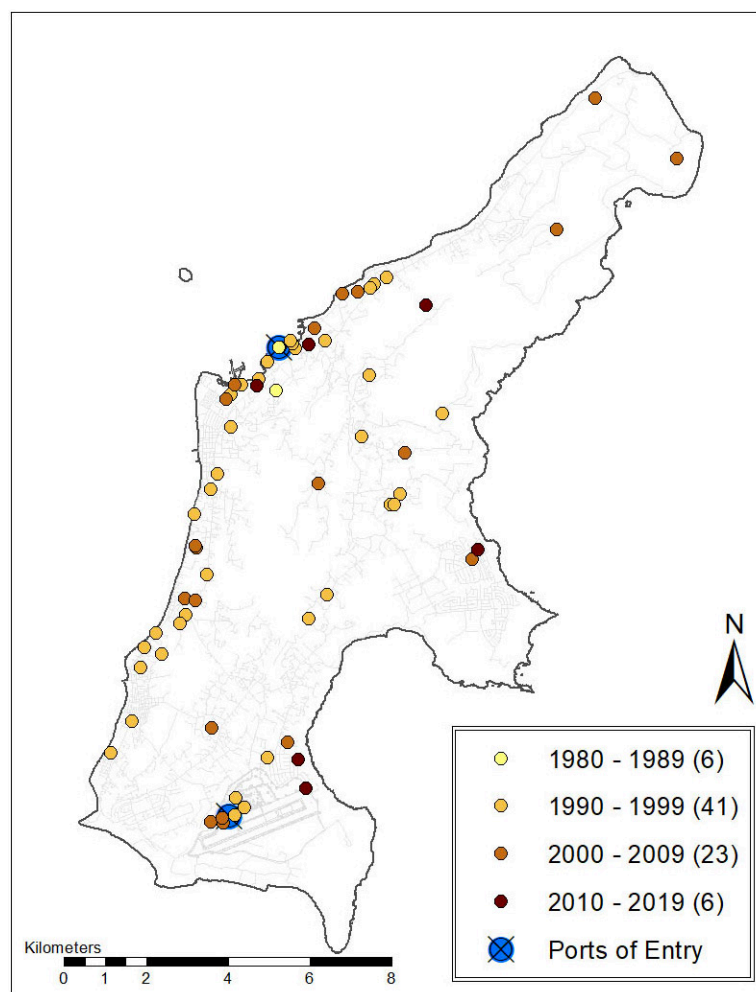
Beyond causing an acute biodiversity contraction, the introduction of BTS to Guam adversely affected human society more directly (Burnett et

al. 2006; Shwiff et al. 2010). The arboreal nature and climbing abilities of BTS cause frequent and expensive power outages (Fritts et al. 1987; Fritts and Chiszar 1999; Fritts 2002). BTS consume chicks and eggs (Fritts and McCoid 1991), yielding economic impacts to poultry production. BTS indirectly reduce regeneration of socially valued plants by consuming important avian seed dispersers (Perry and Morton 1999; Egerer et al. 2018). BTS also bite human infants, injecting them with a mildly neurotoxic and myonecrotic venom (Fritts et al. 1994; Fritts and McCoid 1999; Mackessy et al. 2006). These effects are equally likely to occur on any island upon which BTS become established.

To prevent colonization by the snake, the Commonwealth of the Northern Mariana Islands (CNMI) initiated a BTS interdiction program to inspect cargo coming from Guam (Perry and Vice 2009). The CNMI is an island territory of the United States adjacent to Guam. To spread awareness of the risks posed by BTS to the CNMI, some islands have publicity campaigns to encourage the prompt reporting of snake sightings (Hawley 2007; Martin 2007). With the exception of the blind snake (*Indotyphlops braminus*), the Mariana Islands are naturally snake-free so detection of any snake warrants investigation.

To help prevent accidental spread, the U.S. Department of Agriculture's Wildlife Services (USDA-WS) conducts control of BTS near Guam's cargo and ports with trapping, toxicants, and spotlighting, and inspection of outbound cargo with snake detection dogs (Vice and Pitzler 2002). The program has been a tremendous success, as the number of BTS reported outside of Guam plummeted after initiation of the federal program (Stanford and Rodda 2007). The broader interdiction program designed to prevent species spread also supports secondary canine inspections on Saipan for incoming cargo and early-detection traps around ports and airports, operated by the CNMI Division of Fish and Wildlife (DFW).

Most reports of snakes outside of Guam have occurred on Saipan (1980–2019,  $n = 128$ ; (Figure 2, see also Stanford and Rodda 2007). Saipan (120 km<sup>2</sup>) is only 184 km north of Guam and imported cargo is usually routed through Guam. Planes flying to Saipan do not cruise at altitude, eliminating the possibility of freezing accidental stowaways in wheel-wells and cargo holds (Perry 2002; Christy et al. 2007). After typhoons, relief deliveries are made to Saipan, increasing inter-island traffic when BTS interdiction protocols are likely to be impaired or abrogated. For these reasons, Saipan is at high risk of accidental translocations of BTS from Guam. Biodiversity loss of the largest island in the CNMI would amplify the conservation tragedy in the Mariana Islands, partly because Saipan and neighboring islands serve as ecological models and source populations for possible restoration of some species to Guam.



**Figure 2.** Temporal distribution of historic brown treesnake reports during four decadal periods on the island of Saipan, Commonwealth of the Northern Mariana Islands ( $n = 76$  [location verified using GPS coordinates] of 128 reports). Snake reports are still regular occurrences on Saipan, but are usually determined to be flowerpot snakes (*Indotyphlops braminus*), monitor lizards (*Varanus tsukamotoi*; Weijola et al. 2020), or another non-snake species. Vectorized shoreline of Saipan, Commonwealth of the Northern Mariana Islands (used in Figures 2, 4, and 7), derived from IKONOS imagery (2002, 1:24,000) published by National Oceanic and Atmospheric Administration Ocean Service (Coastal Services Center).

Multiple records of confirmed snakes at ports of entry (McCoid and Stinson 1991) and unconfirmed snake sightings on Saipan have generated speculation that the BTS is established on the island (Colvin et al. 2005; Zug 2013). A single non-reproducing snake is not a threat, whereas an incipient population (new, small, and localized but growing) will likely erupt unless detected and removed (Simberloff 2009). In order to better quantify the speculative statements, we provide an analysis using assessments of the credibility of sighting reports and data available from expert snake-searching surveys on Saipan.

To date, BTS surveillance on Saipan has consisted of passive surveillance (snake sightings reported by the public) and active surveillance (periodic searches by trained biologists). We assess the probability of an incipient population existing on Saipan in the light of multiple lines of evidence obtained from these surveillance efforts and expert elicitation. We interpret

our findings within the context of the current risk of BTS establishment on Saipan due to ongoing propagule pressure (Simberloff 2009). This paper aspires to quantify the probability that an incipient population of BTS is present on Saipan and provides a framework that managers can use for resource allocation within early detection and rapid response (EDRR).

### **Methods for passive and active surveillance**

Our evaluation of the possibility of an incipient BTS population on Saipan used evidence from (1) passive surveillance (public reporting) and expert panel assessment of those reports, and (2) active surveillance using varied detection tools for deployment efforts conducted in 1999, 2007, 2009, 2016, and 2018.

#### *Brown Treesnake Rapid Response Team (RRT)*

In 2002, the multi-agency RRT was established to assist with early detection, incipient population evaluation, and capture of BTS on recipient islands (Stanford and Rodda 2007). USGS-Fort Collins Science Center leads this team with Office of Insular Affairs funding. The team integrates personnel from multiple agencies and organizations including: USGS, US Fish and Wildlife Service (USFWS), the CNMI Division of Forestry and Wildlife (CNMI-DFW), Guam Department of Agriculture, Division of Aquatic and Wildlife Resources (DAWR), Hawaii Invasive Species Councils, Hawaii Department of Agriculture, Government of the RMI (Marshall Islands), Government of the FSM (Federated States of Micronesia), Government of Palau, Department of Defense, Office of Insular Affairs, Colorado State University, and University of Guam. The RRT conducts annual trainings on and off Guam, maintains communication networks with partners and permanent RRT personnel located on at-risk islands, conducts public outreach across the region, refines detection tools, and maintains deployment capabilities. As a multi-agency group, the RRT uses an incident command structure (Stanford and Rodda 2007) when responding to credible snake sightings (or captures) for efficient coordination of all response efforts. In addition to trained personnel, auxiliary observers from partner agencies often assist with searches.

To evaluate the presence of an incipient population, the RRT implements two forms of active surveillance when deployed, representing the two components of EDRR: preemptively (to investigate areas that produce multiple reports over a long period or in random locations: early detection) and immediately (within two days of a credible report of BTS: rapid response). When local members of the RRT alert the coordinator on Guam of a reported sighting, an interview is conducted with the person reporting the sighting. This standardized interview (Stanford and Rodda 2007; Appendix A) gathers detailed information about the sighting and the exact location to obtain geographic coordinates. This information is then evaluated along



with information on other factors such as incidents increasing the likelihood of snake transportation (recent natural disasters, emergencies, and military operations), to arrive at an appraisal of sighting credibility. If deemed at least a moderately credible BTS sighting, local RRT members begin nocturnal visual surveys along habitat edges in the vicinity of the sighting and may also set traps. Very credible sightings initiate deployment of a core group of highly experienced BTS biologists based on Guam to the location of the sighting within 24–48 hours. Detection tools (nocturnal visual surveys, traps, surveillance cameras, and detector dogs) are deployed at mapped positions along georeferenced transects. Each USGS-led deployment of the RRT is a multi-agency decision, with consent of the island's government and the primary federal agency responsible for funding the program (Office of Insular Affairs).

### *Passive Surveillance Reports*

Since 2004, CNMI residents have been implored by radio jingles, posters, and trucks with prominent signage to immediately report sightings of snakes. The islands have a BTS Hotline with a memorable number (28-SNAKE) to facilitate reporting. Following initiation of the publicity campaign, average program response times declined from 126 hours to 1 hour 42 minutes (Hawley 2007).

### *Expert Elicitation*

In 2013, authors AAYA and RNR convened a panel of nine BTS experts (current and former personnel from USGS, USFWS, and US Department of Agriculture, including several individuals who worked as BTS biologists on Saipan), to assess the credibility of 100 snake reports from Saipan. Experts conducted their rankings without knowledge of other assessors' rankings and participation. Experts received the compiled spreadsheet containing all information from interviews and scanned copies of all original notes for each sighting. In Step 1, these experts assigned BTS credibility scores of 1–5 for each report (5 = completely credible). In Step 2, assessors selected a reason from a previously established multiple-choice list (Table 1). After ranking and providing reasons for all reports, each assessor gave a summary yes/no assessment of whether BTS were likely established on Saipan.

### *Active Surveillance detection tools and associated detection probabilities*

BTS detection methods have been extensively tested on Guam (Rodda et al. 2007; Tyrrell et al. 2009; Christy et al. 2010; Lardner et al. 2009, 2019a, b; Yackel Adams et al. 2019), where both high snake density and low prey availability are favorable for detections and methodological evaluation. An incipient population on Saipan might experience higher prey densities, especially for larger snakes, which could reduce foraging activity or predatory

**Table 1.** Two-step approach used by experts to evaluate the credibility of each snake report ( $n = 100$ ). In Step 1, experts assigned credibility scores of 1–5 for each report. In Step 2, experts provided their main reason for assigning the credibility score. If an expert scored a report in the range 1–3, they were asked to select the main reason from a list of 5 pre-defined options associated with that credibility score range. However, if an expert scored a report 4–5, they were asked to select the main reason for the score from another list of 5 pre-defined options associated with that credibility score range. Additional comments were allowed.

Step 1: Assign a credibility score to each potential Brown Treesnake snake report
1 = Not credible
2 = Slightly credible
3 = Moderately credible
4 = Very credible
5 = Completely credible
Step 2: Provide reason for credibility score used in Step 1
Main Reason for selecting a credibility score of 1–3
Insufficient evidence
Report is internally inconsistent
Observer lacks credibility
Physical description suggests some other species
Narrative conflicts with known brown treesnake behavior
Main Reason for selecting a credibility score of 4–5
Strong Evidence
Report is internally consistent
Observer appears to be credible
Physical description matches brown treesnake
Narrative consistent with known brown treesnake behavior

motivation and thereby potentially reduce visual and trap detections (Gragg et al. 2007; Christy et al. 2017; Siers et al. 2018). Although we lack precision in predicting detection rates for an incipient population, we can safely assume that snake density will be low and prey density high on previously uninvaded islands (Wiewel et al. 2009).

### Nocturnal Visual Surveys

Nocturnal visual surveys are known to detect BTS of all sizes (Christy et al. 2010) and are the primary detection tool used by the RRT. During RRT deployments, visual surveys occur along forest edges, roadsides, and forest interior (via measured and flagged transects). Observers use headlamps (see Lardner et al. 2019a) to search for snakes in the vegetation or on the ground. Survey transects are sized so that observers can complete one transect per hour (ca. 450 m/hr) and capped at four transects per searcher per night to avoid searcher fatigue (Lardner et al. 2019a). Observers record start and end times, total actual search time, all vertebrates detected (to gain baseline knowledge of snake prey abundance), and distance traversed. Surveys begin 30 minutes after sunset. Transects are usually searched once or twice on a given night, rarely more. Repeated surveys on the same night are completed by different people and separated by at least a 1-hr interval. Under average conditions on Guam, detection probability ( $p$ ; the likelihood that an average snake present in a survey area will be detected at least once during a survey period) is about 0.07 per mid-sized snake (ca. 900 mm snout-vent length) per search occasion along forested transects (Christy et al. 2010).

## Trapping

Trapping snakes requires less labor than visual surveys while still providing evidence of snake presence or absence. The RRT uses a modified minnow trap as a BTS trap (Rodda et al. 1999a). Traps are suspended horizontally from natural vegetation or fences 1–1.5 m off the ground. Within each trap, a chamber houses and protects a live attractant mouse. Traps are checked each morning, and the grain mix and potatoes providing food and water for lure mice are replenished as needed. Dead mice are replaced immediately when possible, or within two days; dead mice have been shown to be roughly as attractive as live mice for the first 2–3 days (Shivik and Clark 1997, 1999). Traps are deployed along transects—which may be the same transects where nocturnal visual surveys occur—and are spaced roughly 20–40 m apart. Spacing varies depending on recency of the sighting, number of traps available, and the terrain where traps are set. Traps have been extensively tested and shown highly effective for medium-sized BTS, but not effective for BTS smaller than about 700 mm snout-vent length snakes (Rodda et al. 2007; Gragg et al. 2007; Tyrrell et al. 2009). If BTS exist on Saipan, we have no information on their size distribution. Prior work suggests that smaller individuals are more likely to be translocated (Vice and Vice 2004), while early evidence from an incipient population of BTS on Cocos Island, Guam, indicates a size distribution skewed to large individuals (Barnhart et al. 2021). However, the goal of the RRT is to identify and locate incipient populations which itself implies reproductive individuals are present. BTS achieve reproductive sizes > 900 mm snout-vent length (SVL) and we therefore assume that at least some of the snakes from an incipient population would be of a trappable size. If the conditions observed by Tyrrell et al. (2009) apply ( $p = 0.14$ ), we would expect each occasion (one night for a trap array) to yield a capture probability per trappable-sized snake present within the array that was at least 65% less than that documented in a prey-rich area (Gragg et al. 2007) ( $p = 0.14 \times 0.35 = 0.05$ ).

The use of trail cameras in monitoring efforts has increased in recent years as camera costs decline and technology and statistical methods improve (Royle and Gardner 2011; Amburgey et al. 2021). Yackel Adams et al. (2019) documented that BTS images are digitally captured by cameras with time-lapse settings using live lures (snakes do not reliably trigger motion detectors); some snakes have been recorded investigating a trap entrance for hours ( $n = 122$  BTS), without entering the trap. Since 2016 the RRT positions cameras approximately 2 m from BTS traps with the trap in full view on a small subset of traps adjacent to the credible BTS sighting. RRT cameras are set to take time lapse and motion detection photos and enhance detection (close to 100%) but not capture of BTS.



### Detector Dogs

Since 1993, detector dogs have inspected high-risk cargo leaving Guam for BTS. Detection rates averaged 62% for snakes in escape-proof containers planted in cargo without the knowledge of the dog handlers (Engeman et al. 2002). Dog detection of BTS in the wild is less effective because the environment presents unique challenges compared to cargo inspections, such as distraction by non-target animals and scents, poisoning by toad ingestion, and searching in a highly complex habitat off leash under windy conditions. If dogs alert, then techniques are needed to help dog handlers find the snake inside dense vegetation. Savidge et al. (2011) tested BTS search dogs and found that the average detection rate of two tested dogs was about 35% for 2-hr searches in the wild. If such dog searches were conducted twenty times, and if the detection probabilities were independent from occasion to occasion, the likelihood of failure to detect after 20 occasions would be about  $0.65^{20}$  or 0.0002, a very low probability of a missed detection. However, dog detection does not translate into BTS capture rate if the handler cannot find the detected snake. While an attractive tool, its use is cost-prohibitive for RRT deployments and thus dogs have only been used twice in surveillance efforts.

### *Rapid Response Team Deployments*

There have been 13 RRT deployments on Saipan in response to a credible sighting since the team formed in 2002. There was at least one deployment each year between 2003 and 2008: three in 2003, two in 2004, one in 2005, one in 2006, two in 2007, and two in 2008. Two deployments occurred in 2016 in response to four reports that were considered credible. The searches of 2003 to 2008 ranged from a few days to two weeks. The 2016 searches were each about one month long.

We also conducted 4 preemptive deployments in 1999, 2007, 2009, and 2018. Ports of entry have had multiple credible reports and have been the focus of these preemptive searches, with secondary effort in surrounding areas and more distant locations where a credible report occurred. The 2018 surveillance was uniquely conducted in conjunction with nocturnal lizard surveys (Hileman et al. 2020) that had been designed to sample native vertebrate species, primarily in areas where no snake reports had occurred. The preemptive searches differed in duration, spatial extent, tools used, and number of observers used. Along with the two intensive 2016 searches, these four preemptive searches compose most of the active surveillance evidence to evaluate if Saipan likely has an incipient BTS population. All available information on the 4 preemptive deployments was assembled and summarized below:

### 1999

Trapping was conducted by USGS, Colorado State University, and CNMI-DFW at 14 sites on Saipan between 06 March–18 October 1999. Site selection

was based on potential BTS habitat, historic snake sighting reports, and confirmed snake captures at commercial ports of entry. Traps were placed along existing forest edge to facilitate deployment, monitoring, and maintenance. The number of functioning traps may be underestimated: traps were checked 1 to 2 times per week and recorded as nonfunctional for all days since the previous check when nonfunctional on the day of the check. A missing live-lure mouse was the leading reason for a trap being categorized as nonfunctional. Nocturnal visual surveys were conducted by paired observers, searching along opposite sides of the roads where traps were placed.

#### 2007 and 2009

The RRT deployed to the vicinity of the Saipan International Airport in 2007 and 2009 because 4 of the 7 confirmed BTS captured on Saipan were at the airport facility. In addition, it is surrounded by forest that is easily accessed by observers, there are extensive chain-link fences around the airport that are easily surveyed for climbing snakes, and the airport vicinity has many areas suitable for dog-aided surveys. Surveys were completed over a 21-day period during February and March in 2007. A second 5-day survey effort was undertaken in the same area during April 2009.

Both efforts included intensive nocturnal visual surveys of a core forest block (10 ha) located next to the airport cargo facilities (hereafter focal area), composed of secondary forest and several ruined structures including defensive fortifications from WWII. Although the focal area received the most intensive search effort, we searched a larger surrounding area at lower intensity. Apart from nocturnal visual surveys, we also deployed snake detection dog teams (4 teams in 2007, 1 in 2009) and spotlight surveys from vehicles along some transects, fence lines, and tree lines around the airport complex. Survey efforts were undertaken by 18 (2009) and 19 (2007) RRT members who had completed Team training as well as by 20 (2009) and 30 (2007) auxiliary observers from partner agencies.

#### 2016

Super Typhoon Soudelor passed directly over Saipan on 02 August 2015, and single reports of snakes occurred in mid-December 2015, 02 January 2016, and 01 March 2016. This prompted a full RRT deployment (hereafter Response 1). Another report on 01 April 2016 occurred near the commercial seaport and prompted a deployment (hereafter Response 2). Efforts to address these 4 snake reports consisted of visual surveys, trapping, and camera surveillance monitoring around the area of the reported snake sighting.

#### 2018

From 09 July–12 August 2018, island-wide nocturnal herpetofauna surveys were conducted on a subset of avian transects used by the CNMI-DFW

(Hileman et al. 2020). Methods employed include visual surveys with two teams of two biologists (members of the RRT) visually surveying two adjacent 50-m transects each night, totaling 0.8 km surveyed each night. For the first 50 m of each 100 m transect, biologists looked for BTS and lizards; for the next 50 m they focused only on BTS. Each 100 m transect was surveyed twice per night, with at least 30 minutes between surveys and biologists switching sides for the second survey. Each night there were four biologists surveying 1.6 km for BTS, with 0.8 km of BTS surveys occurring along the same transects used for lizard surveys.

### *Poisson-based Model*

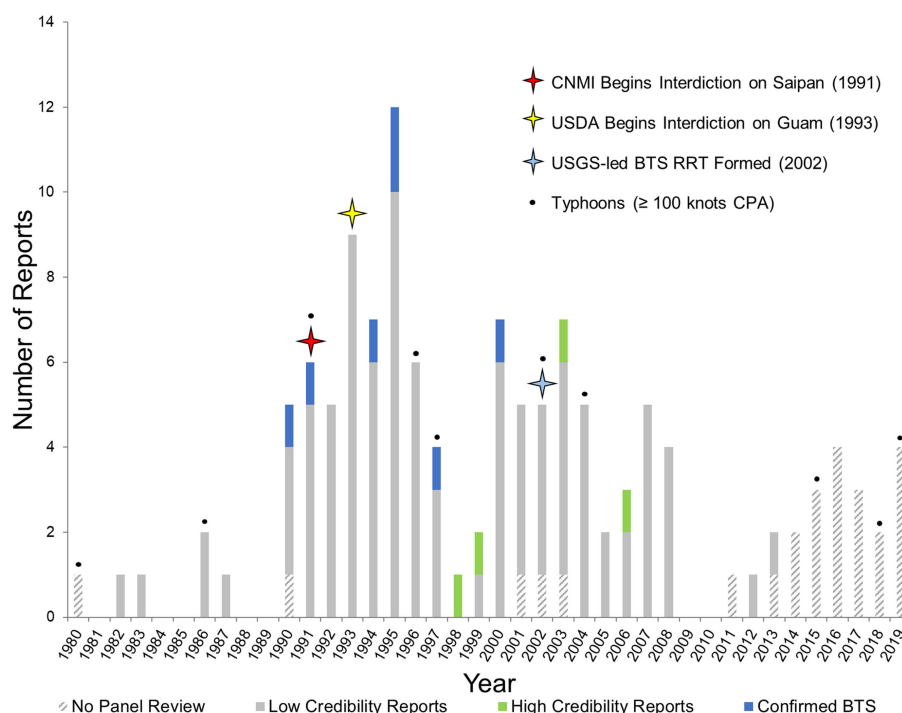
We used the Poisson-based model developed by Yackel Adams et al. (2018) to assess the probability that snakes would have been found during surveys should a snake population be present in the focal area. The model assumes the search effort occurs where an incipient population is thought to be, and inferences are limited to that search area. This model uses effort-linked detection probabilities from a censused BTS population on Guam to calculate the probability that the finite rapid response effort would have revealed any snake at a stated snake density given assumed detection estimates. We assumed a 50 percent reduction in snake detection probabilities ( $p = 0.035$ ) for visual estimates (*sensu* Yackel Adams et al. 2018) because well-fed snakes are more frequently inactive (Christy et al. 2017; Siers et al. 2018). To address the greater uncertainty of BTS trap capture on the prey rich island of Saipan, we present a range of capture probabilities ranging from best-case to worse-case scenarios (0.05–0.01). Justification for the best-case scenario is outlined in Yackel Adams et al. (2018; see Supplement 1). We set the desired level of confidence about BTS absence at 0.95 because of the high stakes of an incorrect determination. Surveillance efforts yielding no snakes and density estimates  $> 2$  BTS/ha (at 95% certainty) provide limited support for determining the absence of an incipient population.

## **Results**

### *Passive Surveillance*

#### Reports

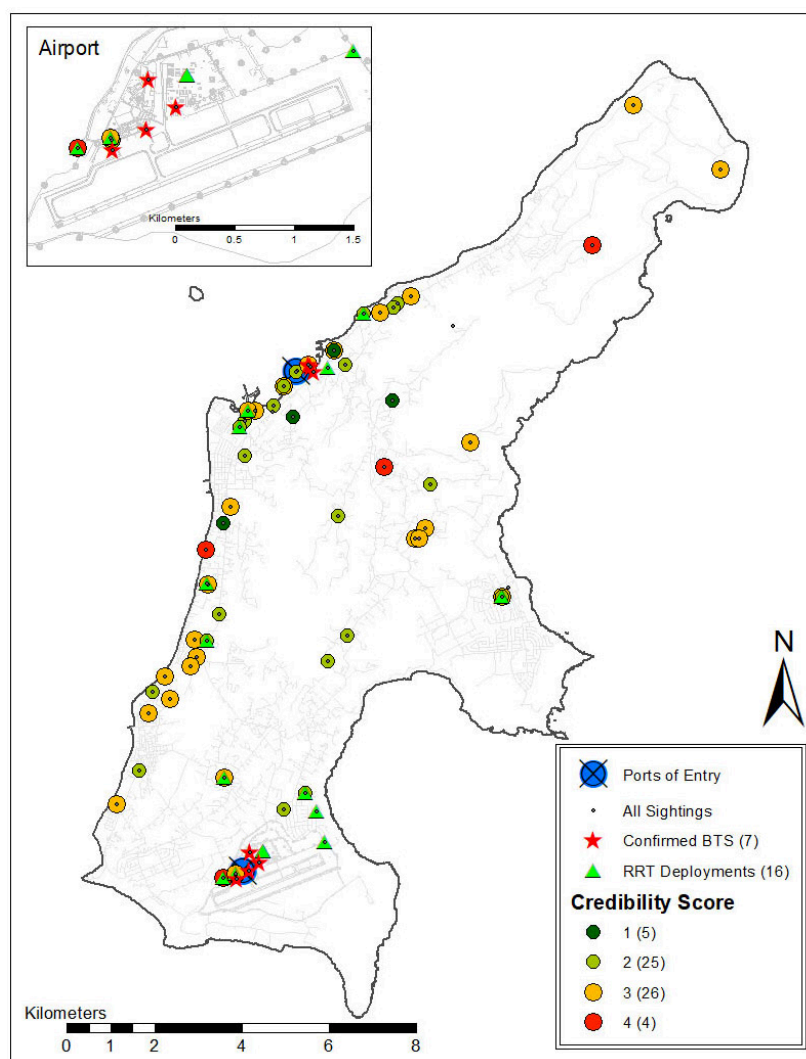
Reports of possible snake sightings on Saipan date back to 1980 (Figures 2 and 3). From 1990 to 2008, the number of reports intensified, with a peak of 12 snake reports in 1995 (Figure 3). Seven BTS were captured (5 alive, 2 dead) on Saipan from 1990–2000 (Figure 3, blue bars; Figure 4, red stars) at ports of entry or on ships docked at the seaport. Prior to 2002 reports were not standardized and frequently contained only parts of the information that now are regularly recorded during the formal interview process (see Appendix A in Stanford and Rodda 2007).



**Figure 3.** All known brown treesnake (BTS) sighting reports from Saipan, Commonwealth of the Northern Mariana Islands ( $n = 128$ ) in the context of significant management and storm events. Reports from 1982–2013 ( $n = 100$ ; solid gray, green, and blue bars) were evaluated for low and high credibility based on expert panel evaluation. Panelists gave low credibility sightings (solid gray) a score of 1–3 and high credibility sightings (green) a score of 4 or 5 (see Table 1 for definitions). Confirmed BTS ( $n = 7$ ; blue bars) were secured dead (2) or alive (5) and found at port of entry facilities, positively identified, and preserved as museum specimens ( $n = 4$ ). Reports denoted with gray hatched bars were not evaluated by panelists because records were either (1) not known at the time, (2) confirmed as a species other than BTS, or (3) occurred after the panel evaluation. However, these reports were evaluated by members of the RRT at the time of the sighting. As extralimital sightings of BTS increased in the Commonwealth of the Northern Mariana Islands (CNMI) interdiction efforts were initiated on Saipan in 1991 (red star) and the U.S. Department of Agriculture (USDA) initiated interdiction efforts on Guam in 1993 (yellow star). The multi-agency RRT was formed in 2002 (light blue star). Interdiction efforts have changed over time and now consist of cargo inspections with and without trained canines and live mouse-baited snake traps hung at ports of entry. Since 2013 there have been 21 (as of 2019) additional sighting reports on Saipan and only two were deemed to be of high enough credibility to warrant a rapid response deployment (2016). Black dots above columns represent years with major storm events (recorded at  $\geq 185$  kph [100 knots]) at the closest point of approach (CPA) to Saipan; National Weather Service, (<https://www.weather.gov>)).

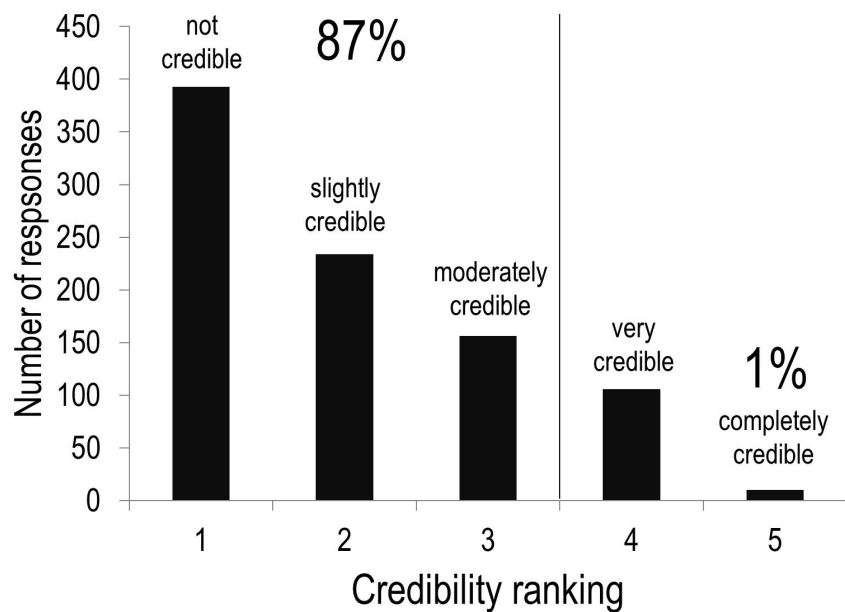
### Expert Opinion on Passive Surveillance Reports

Each expert evaluated 100 passive surveillance reports that occurred from 1982–2013 across Saipan (Figure 4; colored circles) excluding confirmed BTS captures (Figure 4; red stars). They considered almost half of the reports (44%) not credible (score of 1; Figure 5). The primary reasons given for assigning low-credibility scores (1–3) to reports were insufficient evidence (57%) and physical descriptions suggesting some other species (25%). Over half the primary reasons given for assigning high-credibility scores were narratives consistent with BTS biology (28%) and physical descriptions of sighted animals that matched that of BTS (26%). As a group, experts were consistent in ranking individual reports (Figure 6). Eight of the nine experts concluded that BTS were likely not established on Saipan based on these

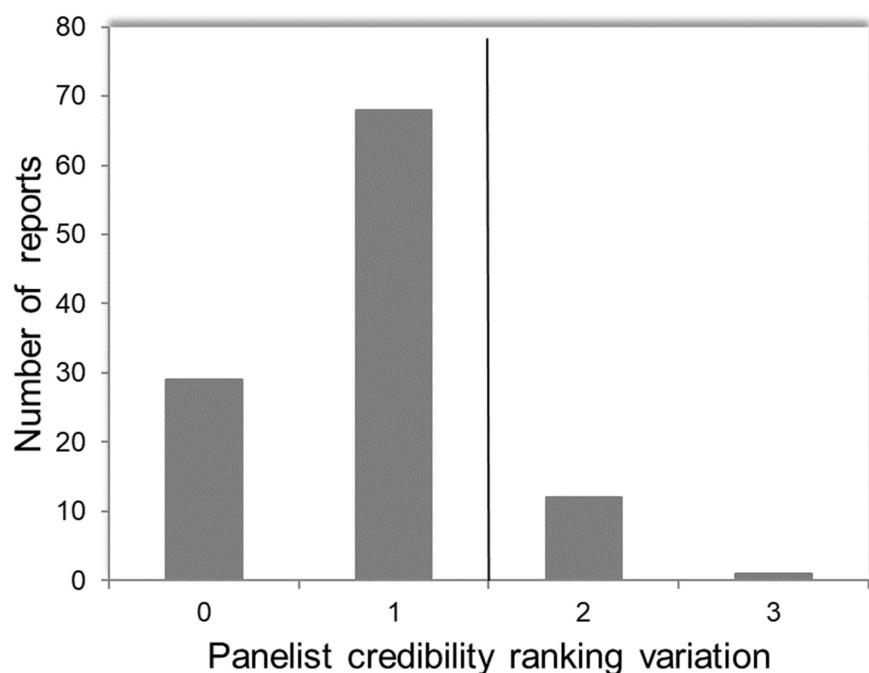


**Figure 4.** Distribution of historic reports of brown treesnake (BTS) sightings between 1980 – 2019 ( $n = 76$  [location verified using GPS coordinates] of 128 reports; denoted by small black dot) on Saipan, Commonwealth of the Northern Mariana Islands. Reports of snake sightings have occurred throughout the island with concentrations at ports of entry (airport in the south and seaport on the west coast) and adjacent areas where seven reports were of confirmed BTS (red stars). Sixteen reports elicited an immediate Rapid Response Team deployment (green triangles). Criteria for deployments were fewer in the early years of the RRT (est. 2002) which resulted in precautionary deployment in response to less credible reports. None of those efforts detected BTS. In 2013, a subset of all sighting reports ( $n = 60$  with GPS coordinates, 100 total reports) were assigned credibility scores (1–5, low to high credibility) derived from expert panel elicitation (see methods). Parenthetical numbers denote the count of sighting records receiving that credibility score averaged across nine panelists. Average credibility scores with spatial data are depicted with color circles; no sighting was assigned an average credibility score of 5.

reports. Snake reports not included in the panel assessment are depicted in Figure 3 with hatched bars. Nineteen reports have been added since 2013. Of these, only 4 were considered credible (based on review by 5 individuals with BTS expertise using panel instructions, Table 1). These 4 consisted of 1 report in late 2015 and 3 reports in early 2016, resulting in two RRT deployments in 2016. The remaining 15 reports were of low credibility, primarily due to the physical description suggesting some other species (i.e., lizard) or an inanimate object.



**Figure 5.** Credibility scores assigned by 9 panelists from reviewing 100 snake sighting reports on Saipan, Commonwealth of the Northern Mariana Islands from 1982–2013. Almost all reports (87%) were ranked as no to low credibility (credibility score of 1–3). Only 1% of reports evaluated by panelists were ranked as completely credible (credibility score of 5); when scores were averaged across panelists, no sighting received a score of 5.



**Figure 6.** Variation in credibility ranking of reports of brown treesnake (BTS) sightings among the panelists for a given report (estimated by maximum rank score listed for a report minus average rank score from the panelists for the same report). Almost all reports (88%) were similar in panelist ranking of credibility scores (values 0–1) and increases our confidence in credibility scores in Figure 5.

### Active surveillance

#### 1999

This island-wide trapping effort resulted in 58,637 functional trap nights (Table 2, Figure 7 yellow squares). Over the entire survey period, an average



**Table 2.** Major active surveillance activities for brown treesnakes (*Boiga irregularis*; BTS) on the island of Saipan, Commonwealth of the Northern Mariana Islands. First BTS trap assessment in areas of previous snake reports occurred in 1999. Efforts in 2007 and 2009 were Rapid Response Team (RRT) preemptive surveillance based on historic sightings around the Saipan International Airport. RRT deployments in 2016 were immediate deployments (within 24–48 hrs) based on credible reports near the Saipan International Airport and the Saipan Commercial Sea Port (Lower Base Area). The effort in 2018 was RRT preemptive surveillance in association with island-wide nocturnal herpetofauna surveys. None of these surveillance efforts detected BTS. NA = data were not collected.

Metrics	1999	2007	2009	2016 <sup>1</sup>	2018 <sup>2</sup>
Duration of Effort (nights)	226	21	5	54	34
Total Number of Visual Observers	Unknown	49	38	29	12
Total Number of Trained Visual Observers	Unknown	19	18	24	12
Estimated Total Visual Search Effort (hrs)	Unknown	1,660	267	1,972.2	189.5
Estimated Total Distance of Visual Search Effort (km)	24.6	333	52	998.8	56
Number of Canine Teams	0	4	1	0	0
Estimated Total Canine Search Effort (hrs)	0	105	5	0	0
Number of Live-Lure Mouse Traps Deployed <sup>3</sup>	260 <sup>4</sup>	285	0	133	0
Number of Trap Nights	58,637	5,775	0	5,309	0
Number of Prey Observations	1,125 <sup>5</sup>	13,865	1,704	50,298	1,246 <sup>6</sup>
Density of BTS/ha Poisson estimate for visual surveys <sup>7</sup>	4.24	0.38	2.00	0.14/0.44	1.86
Density of BTS/ha (best-worst) Poisson estimate trapping <sup>7</sup>	0.04–0.18	0.36–1.80	NA	0.43–2.15 <sup>8</sup>	NA
Number of BTS detected	0	0	0	0	0

<sup>1</sup> Two separate RRT deployments (2 January to 14 March and 1–22 April) reported here as a total effort unless annotated otherwise.

<sup>2</sup> Additional sampling details provided in Hileman et al. (2020).

<sup>3</sup> Live-mouse lure traps; subset of traps with cameras ( $n = 16$ ) used in 2016.

<sup>4</sup> Average number of traps active each night over duration of effort. Peak daily count was 356.

<sup>5</sup> Potential snake prey caught in traps (rats, mice, skinks, geckos), prey seen during visual surveys not recorded in 1999. Prey observations from 2007, 2009, and 2016 combined prey observed in traps and along visual survey transects.

<sup>6</sup> Number of snake prey visually detected from first 50 m of transect, see Hileman et al. (2020).

<sup>7</sup> Density of snakes/ha that would have been detected given a specified detection probability and the amount of sampling effort expended based on a Poisson distribution model (see text) assuming a desired level of 95% certainty. Visual surveys density estimates based on detection probability of 0.035. Trapping density estimates use capture probabilities ranging from best-case ( $p = 0.05$ ) to worst-case ( $p = 0.01$ ) capture scenarios.

<sup>8</sup> Best-worst density estimates for response 1 trap effort ( $n = 4,841$  trap nights) are listed. Response 2 trap effort ( $n = 474$  trap nights) density estimates required for 95% confidence that BTS were absent were much higher: 4.38–21.9; a range more indicative of a well-established versus incipient population.

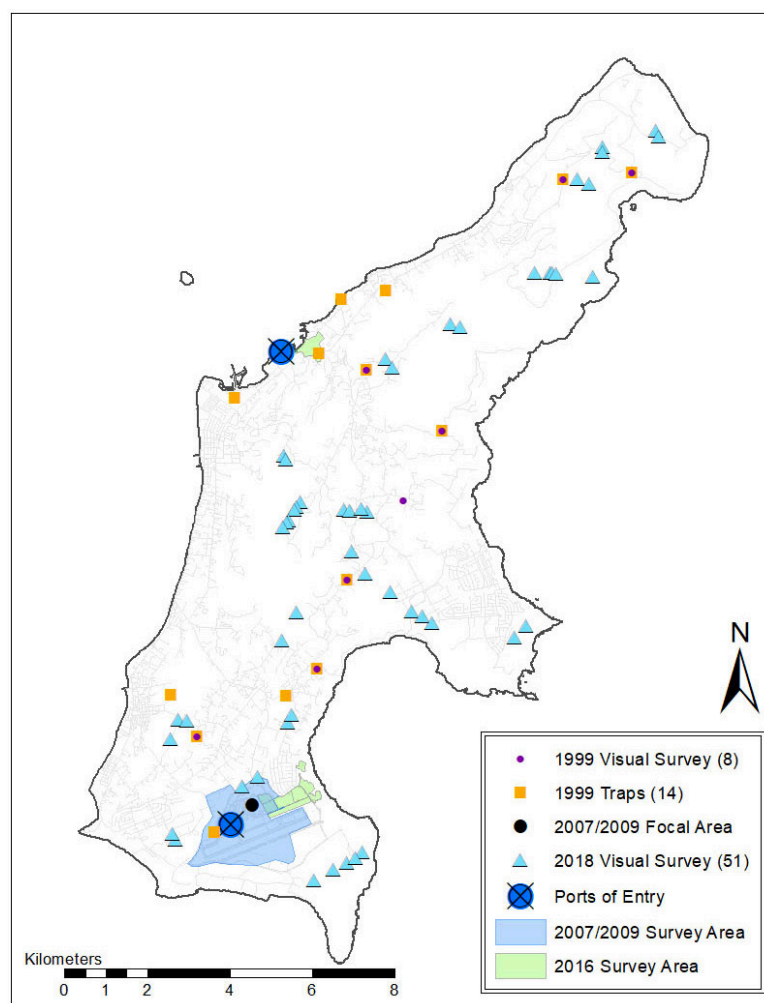
of 260 traps were active and functional each night. Despite the intensive trapping effort, no snakes were captured. Given this level of trap effort, we predict with 95% certainty that biologists would have trapped at least one snake if the population density was 0.18 snakes/ha or higher (Table 2) assuming a worst-case capture probability of 0.01.

Nocturnal visual surveys were conducted over 9 nights along a subset of the trapping transects plus one additional site (Figure 7, purple dots), resulting in 24.6 km of visually searched habitat. Given this level of effort, at  $p = 0.035$  we would expect with 95% certainty that observers would have detected at least one snake if the population density was  $\geq 4.24$  snakes/ha.

### 2007 and 2009

The 2007 effort included a trapping effort ( $n = 285$  traps; 5,775 trap nights) that did not occur in 2009 (Table 2, Figure 7). No BTS were trapped. Given this level of trap effort, based on a presumed worst-case capture probability of 0.01 we would expect with 95% certainty that biologists would have trapped at least one snake if the population density was  $\geq 1.80$  snakes/ha.

In 2007 (February–March) observers visually surveyed 333 km of transects without BTS detection (Table 2, Figure 7). Given this level of effort, at  $p = 0.035$



**Figure 7.** Distribution of active surveillance locations for brown treesnakes on the island of Saipan, Commonwealth of Northern Mariana Islands conducted in 1999, 2007, 2009, 2016, and 2018. In 2007/2009, visual surveys were conducted throughout the blue shaded area, but most surveys were conducted in a single core forest area (focal area), represented by a black dot on the map. Numbers in parentheses in the legend represent the number of sites where snake trapping or visual surveys were conducted.

we would expect with 95% certainty that observers would have encountered at least one snake if the population density was  $\geq 0.38$  snakes/hectare. In 2009, observers visually surveyed 51 km of transects without BTS detection (Table 2, Figure 7). As would be expected with reduced surveillance effort, we expected with 95% certainty that observers would have encountered at least one snake if the population density were  $\geq 2$  snakes/ha.

In addition to visual surveys and trapping we used detector dogs for a total of 110 search hours (105 hrs in 2007 and 5 hrs in 2009) over the two surveillance efforts (Table 2). Dogs failed to alert on any BTS during their Saipan searches. Dividing the 105 total search hours conducted in 2007 into 2-hr blocks we obtain approximately 52 search occasions in the focal area (Figure 7). Using the assumption that detection probabilities were independent from occasion to occasion the likelihood of failure to detect after 52 search occasions would be about  $0.65^{52}$  or almost zero for the areas searched using canine teams.

## 2016

Response 1 occurred between 04 January and 14 March 2016 in a constrained area around the airport (Figure 7, southern green survey area). Visual occurred from 06 January to 25 January and from 21 February to 13 March; trapping and trail camera monitoring occurred from 06 January through 11 March. The RRT and partners visually searched 759.6 km and conducted 4,841 trap nights (Table 2). We set 16 cameras for the entire deployment duration on individual traps. Traps were set at 40 m spacing. No snakes were detected by the RRT efforts (visual surveys, trapping, or camera surveillance) during this deployment to Saipan. Given this level of effort we conclude with 95% certainty that visual observers would have encountered at least one snake had the population density been 0.14 snakes/hectare or higher. Based on the trapping effort, and assuming the worst-case capture probabilities we estimate with 95% certainty that we would have trapped at least one snake had the population density of trappable snakes been  $\geq 2.15$  snakes/ha (Table 2).

Response 2 occurred between 01 April and 22 April 2016 with nightly visual surveys around the seaport (Figure 7, northern green survey area). Trail camera monitoring occurred from 09 April to 17 April 2016 on six traps; trapping took place from 04 April through 22 April 2016. Traps were set 20 or 40 m spacing. The RRT and partners visually searched 239.2 km and conducted 474 trap nights (Table 2). No snakes were detected as a result of these efforts, and we conclude with 95%-certainty that the observers during Response 2 would have encountered at least one snake had the population density been 0.44 snakes/ha or higher. Based on the limited trapping effort, and assuming the worst-case capture probability there is a 95% certainty that the RRT would have trapped at least one snake had the population density of trappable snakes been  $\geq 21.91$  snakes/ha (Table 2).

## 2018

Hileman et al. (2020) conducted island-wide nocturnal herpetofauna surveys over 34 nights, repeatedly searching 51 km of unique transects (Table 2, Figure 7; blue triangles). No snakes were detected during these surveys. Given this collective level of visual survey effort we would expect with 95% certainty that one snake would have been observed along the transects if the BTS population density was  $\geq 1.86$  snakes/ha. No BTS snake traps were set in 2018.

## **Discussion**

Despite Saipan's biosecurity plans and significant interdiction efforts on Guam, there have been 128 snake reports on Saipan between 1980–2021. Of these reports, only 21 were deemed “very credible” by the RRT leadership and expert panelists ( $n = 100$  records evaluated), with the oldest

dating back to 1990. Seven BTS specimens have been collected on Saipan, all at port of entry facilities (Figure 4, red stars), not fully in the wild. As of May 2021, 13 RRT deployments have occurred on Saipan, resulting in no BTS detections despite an effective RRT implementing surveillance effort of long enough duration to ensure incipient population detection. After examining all available evidence from these reports, searches, and expert elicitation, we conclude that Saipan has a very low probability of an incipient population of BTS. That does not mean that biosecurity efforts ought to be relaxed. Indeed, current interdiction efforts appear to have been effective at reducing BTS propagule pressure, as supported by reduced sighting reports through time. Increased storm activity in the region and increased disaster emergency efforts after storms, as well as military relocation and training in the region (Department of Defense 2015) and continued movement of people and cargo through Guam, will continue to present a threat to recipient islands as long as BTS propagule pressure persists on Guam. Given Saipan's vulnerability it is prudent to ensure a strong passive surveillance network, schedule strategic preemptive surveillance efforts in areas around ports of entry, and enhance collaboration with other wildlife survey efforts for BTS detection as was done with lizard surveys in 2018 (Hileman et al. 2020).

While a population can be established by unreported snakes, there are only two likely ways Saipan could have a BTS population founded by a reported snake: (A) the population is founded by BTS individuals reported prior to 2016 or (B) the population is founded by one of the four reported in 2016. If founded by (A), then the population could date back to 1990 when the first individual was reported with a credibility rank of "very credible." In the subsequent decades, that population would have grown sufficiently for at least one individual to be detected during the island-wide search of 2018 or port of entry searches in 2016 during which no individuals were detected. Hence, (A) is unlikely and has quantitative justification for dismissal. Regarding (B), four snake sightings were reported in 2016, of which three were at the airport and one at the seaport. If those snakes were founders, the population may have been too small for the 2018 search to detect an individual. Moreover, the 2018 search did not concentrate in areas around the ports; rather, that search was island wide. Such a dispersed search could have failed to detect evidence of a population founded possibly in 2016.

There have been no highly credible reports since 2016. Given that both ports use interdiction measures, the probability of snakes arriving since 2016 through the ports is low. However, inter-island boat traffic bringing snakes to Saipan's coastline beyond the ports may be possible. Still, the four individuals from 2016 could have founded a population that by now would be of a size detectable by a concentrated RRT search in the areas of the two ports. Preemptive deployment of the RRT at set intervals with search effort duration informed by the Poisson model would maintain critical early detection capabilities for incipient populations.

A second reason for a preemptive search is that typhoons occur in Saipan (e.g., 2018 and 2019). Typhoons are followed by increased cargo traffic to Saipan. During increased traffic, interdiction measures can be overwhelmed, increasing the probability that a snake eludes detection. Thus, even if the 2016 snakes failed to establish a population, there is a remote chance that snakes introduced in the aftermath of those two typhoons and could have founded one. In preparation for a preemptive RRT effort, CNMI-DFW staff currently stationed on Saipan could justify periodic preemptive searches in the areas of both ports to further enhance early detection of the species.

Biosecurity measures can be impaired or eliminated by structural damage caused by severe storm events, and protocols may be impaired by decisions to relax biosecurity to expedite relief efforts. In 2015, Saipan's inspection and quarantine infrastructure experienced storm damage and cement snake barriers were not repaired for many months because higher priority was given to speeding importation of cargo. After the 2015 typhoon, the four credible 2016 reports of BTS on Saipan (Figures 3 and 7) were located near ports of entry, where un-quarantined construction supplies were offloaded.

Tropical typhoon intensity in this region is predicted to increase (Webster et al. 2005; Grecni et al. 2020) and relief efforts after damaging storm events have been associated with accidental introduction of invasive species elsewhere in the world (van den Burg 2019). BTS are known to stowaway in small, dark spaces which are often abundant in cargo. The four credible reports of BTS on Saipan followed the 2015 storm. Subsequent failure of the RRT to detect any snakes may be attributable to several factors. Because more people were outside cleaning up storm damage, the number of engaged observers increased, as did the chance of false reports. While the four reports were deemed "credible", the sightings could have been of another reptile species, as the interview process is not infallible. If the reports were accurate, however, the two 2016 RRT search efforts would likely have detected at least one snake had there been a population; no snake was detected. A preemptive search as discussed above can enhance our confidence that undetected snakes did not establish a population.

Given the increased threat of incursion following high-severity typhoons, it would be wise after such storms to increase public awareness and to decrease credibility standards for RRT deployment (as occurred in 2016). Maintaining and enhancing passive surveillance remains the most cost-effective tool for detecting BTS in the CNMI. While not addressed in this research, Perry et al. (2020) highlight the importance of assessing existing policy, governance, and management implementation should a population ever become established.

In decades of preventing BTS spread from Guam, there have been only two cases of live BTS captured in the wild in locations other than Saipan. In 2014, a snake was captured in an interdiction trap in the seaport of Rota (the island between Guam and Saipan), prompting a deployment resulting

in 640 km of visual surveys and 9,661 trap nights over 79 days without finding a snake (Yackel Adams et al. 2018). The second case is more recent. In October 2020, the RRT deployed to the previously snake-free 33.6-ha island of Cocos, 2.4 km south of Guam, following several credible snake reports and documented the presence of a breeding BTS population via visual surveys (U.S. Geological Survey 2020; Barnhart et al. 2021). This late-stage detection of an established population in the process of irruption on Cocos Island supports the need for the RRT to integrate active surveillance by trained personnel.

### *Passive surveillance*

Citizen observers are the basis of many early detection and rapid response programs (Cacho et al. 2010; Hester and Cacho 2017; Lehtiniemi et al. 2020) for the obvious reason that active surveillance by paid field staff is expensive and occurs only in discrete periods. Saipan is an island of 12,290 ha; help from the populace (ca. 52,000 people) is vital for reporting invasive species over such a large area. Encouraging people to report snake sightings is relatively inexpensive. Awareness-raising tools (signage, radio jingles, etc.) can be reused indefinitely and modified easily as communication technologies change. Moreover, with a continuous program across years, the significance of each new report increases, as there is an increasing baseline of data (spatial and temporal) with which to provide context for the new report.

Periodic evaluation of the public-outreach program in the CNMI is essential for maintaining its integrity. We are aware of only two such in-depth evaluations for Saipan (Colvin et al. 2005; Hawley 2007) but both were conducted well over a decade ago and may signal a need for a new assessment. For many invasive species surveillance programs, managers rely on citizen reports for detecting spatial and temporal trends; hence, maintaining such programs at levels as high or higher than in previous years is critically important. If surveillance programs are not maintained, the significance of a lack of reports becomes ambiguous, implying either there are no snakes to sight or there are no citizens engaged sufficiently to report snakes. Since 1995 the number of BTS reports on Saipan has declined. Because outreach efforts have not declined, nor have reporting methods changed, we would expect the number of reports to have risen if Saipan was hosting an incipient BTS population. The reporting decline is consistent with our assessment that Saipan has a very low probability of currently hosting an incipient population.

### *Expert Elicitation*

Expert elicitation, the formalized process to obtain expert opinion for many conservation problems (i.e., address data gaps; Martin et al. 2012; Converse et al. 2013; Johnson et al. 2017), was essential for assessing the accumulated records of snake reports on Saipan. Two key findings from



the panelists support our overall assessment that it is unlikely that BTS are established on Saipan: 1) they found only 13% of 100 reports evaluated to be highly credible and 2) the experts were consistent in their evaluation of credibility scores for a given record as most scores either matched or differed by only one point. Quantifying the diversity of opinions represents the actual state of knowledge, such that lower diversity indicates greater accuracy (Morgan 2014) for the metric assessed. The low diversity of panelists' scores per report provides strong evidence that the panelists' BTS assessments were accurate and would be repeatable.

Eight of the nine panelists answered "No" to the likelihood of an incipient BTS population on Saipan. The one dissenting expert answered "Yes" given there were 13 "highly credible" reports. This dissent, however, raises an important distinction between individual snakes and an incipient population of snakes. While there likely have been BTS on Saipan at various times, a few dispersed snakes does not constitute a population. Dispersed individuals likely die without encountering a receptive member of the opposite sex. However, had they reproduced and established a population, subsequent RRT deployments would likely have detected at least one snake; they did not.

#### *Active surveillance and the Poisson Model*

To date no snakes or notable prey reduction have been detected by the RRT on Saipan despite substantial surveillance efforts over years (Table 2). Modeling efforts based on surveillance activities after 2007 indicate that if BTS were present they would be at very low densities (ca.  $\leq 1$  BTS/ha). For comparative purposes, BTS density found in Guam's forests is estimated to be around 23 snakes/ha (Rodda et al. 1999b; Tyrrell et al. 2009; Christy et al. 2010; Amburgey et al. 2021). Detecting snakes at low density (e.g.,  $\leq 1$  BTS/ha) requires a substantial investment of time and resources. The Poisson model shows that to infer with 95% certainty that BTS are  $\leq 1$ –2 snakes/ha the sampling effort must be greater than was previously thought for cryptic species (Kéry 2002; Hartel et al. 2009; Durso et al. 2011). Beginning in 2014, the RRT adjusted their sampling effort accordingly, shifting surveillance efforts from  $\leq 2$  weeks to 6–8 weeks to ensure a 95% probability that BTS are  $\leq 1$ –2 snakes/ha. This decision is a tradeoff between the risk of declaring that no incipient population exists when one does and the risk of continuing to search when there is no incipient population to find.

Additionally, surveillance decisions would benefit from defining incipient population criteria (e.g.,  $\leq 1$  BTS/ha at 95% certainty) in conjunction with spatial configuration of expansion and spread of BTS. For instance, if populations establish at low densities and then spread quickly, surveillance efforts would need to provide high confidence at very low densities over a large area (an assumption consistent with island-wide 2018 surveillance

effort if BTS had been introduced in the 1990 or early 2000s). Alternatively, if species population dynamics yield saturated areas prior to their spread (Rodda et al. 2008) then high confidence in a very small search area with high densities would be adequate (an assumption consistent with the 2016 surveillance effort at the seaport; high certainty and  $> 2$  BTS/ha). Each of these hypothetical scenarios inform the optimal surveillance strategy for an area. However, very little is known about movement ecology of snakes in the early stages of invasion because most invasive snake populations are not typically detected until they are well established (Savidge 1987).

Furthermore, if the intrinsic rate of growth in an incipient population of a focal species is known or can reasonably be inferred, and if one uses the current population density (based on RRT surveillance effort) and assumes a given population size distribution, then the growth of a suspected population could be modeled. Knowing the intrinsic rate of growth would allow estimation of higher probability of detecting any population during repeated surveillance at a later point in time. This would lower labor costs but entails the risk that BTS could gain an even stronger foothold. Local eradication for this species is in experimental phases on Guam (Nafus et al. 2020; Siers et al. 2020, Goetz et al. 2021) within barriers (Perry et al. 1998; Hileman et al. 2021); data collected thus far indicate that eradication of an established population over even medium geographic scales will be very costly and time consuming.

## Acknowledgements

We thank the Department of Interior Office of Insular Affairs for funding support and the numerous agencies who were involved in planning and/or whose staffs participated in these efforts. E. Campbell and K. Buermyer of the USFWS deserve special mention for their assistance. L. Bonewell provided program assistance. D. Cruz (CNMI Department of Land and Natural Resources, DLNR), R. Seman (CNMI Division of Fish and Wildlife, DFW), and S. Igisomar (CNMI DFW / USFWS) provided extensive support and made sure that local resource personnel were available to conduct much of the survey work. We are indebted to the many members of the CNMI DFW and DLNR from Saipan, Tinian, and Rota who spent many long hours in the field searching for snakes. This work would not have been possible without their efforts. We thank the members of the response team and other local, territorial, state, and federal employees as well as local community members who participated in the field work. Thanks to all those involved with large field efforts in 1999, 2007, 2009, 2016, and 2018. Participating observers were: J. Ada, M. Aldan, Anne, J. Babauta, P. Barnhart (author), L. Blas, L. Bonewell, D. Bradke, A. Cabrera, B. Cabrera, C. Calastro, J. Camacho, E. Campbell, M. Capone, T. Castro, B. Cepeda, P. Chee, A. Collins, D. Cravalho, M. Christy, Chris E., J. Cruz, Diego, W. Emul, F. Erickson, J. Furey, J. Gonzales, GP, G. Haddock, A. Hambrick, R. Hansen, N. Hawley, M. Hayes, E. Hileman (author), T. Hinkle, M. Hogan, E. Holldorf, S. Igisomar, T. Iguel, E. Jackson, KB, K. Kabat, A. Kapileo, J. Kapileo, J. Kaseman, A. Knox, J. Kohl, F. Kraft, B. Lardner, E. Limes, J. Limes, J. Lizama, P. Lisua, M. Manglona, T. Mareham, Marilyn, S. Mullin, A. Narzynski, J. Omar, M. Onni, B. Palacios, A. Pangelinan, P. Perez, P. Petkovich, C. Qualls, Randy, R. Reed (author), L. Reyes, P. Reyes, P. Reynolds, C. Robinson, H. Rogers, J. Salas, C. Sanchez, M. Saures, J. Savidge, J. Selbert, I. Seman, S. Siers, J. Stanford, S. Taisacan, P. Teigita, P. Tomkane, Tovi, A. Tuggle, N. Van Ee, D. Vice, M. Wilkinson, T. Wilsey, K. Winford, E. Wostl, P. Xiong, A. Yackel Adams (author), D. Young, L. Zarones, and the many college students and volunteers involved over the years. F. Kraus provided valuable guidance for panel evaluation. We thank M. Pangelinan for facilitating the 2018 sampling effort. We thank D. Cravalho, M. Hall, N. Hawley, G. Perry, R. Phillips, R. Reed, R. Rozar, J. Stanford, and A. Yackel Adams for serving as panelists. R. Adams was instrumental in organizing and drafting the manuscript at all stages. M. Mazurek, S. Mullin, and anonymous reviewers improved earlier drafts. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Data analyzed in this study are available as a USGS data release (Yackel Adams et al. 2021).

## Funding declaration

H. McCoy, T. Taylor, and F. Kraft of the Office of Insular Affairs played pivotal roles in funding these efforts. These funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. U.S. Geological Survey Fort Collins Science Center provided support for AAY during manuscript preparation.

## Authors' contribution

Research conceptualization (AAY, RNR); sample design and methodology (AAY, GHR, and RNR); investigation and data collection (AAY, PDB, RNR, ETH [2018]); data analysis and interpretation (AAY and PDB); ethic approval (none); funding provision (AAY and RNR); and writing original draft (AAY and PDB) and reviewing and editing (all authors).

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