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Brown tree snake (*Boiga irregularis*) population density and carcass locations following exposure to acetaminophen

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Abstract Mass aerial delivery of dead mouse baits treated with acetaminophen has been evaluated as a means to reduce brown tree snake (*Boiga irregularis*) populations over large areas, increasing the likelihood of wide-scale eradication on Guam. Given the high density of snakes in some areas of their invasive range, eradication efforts could result in a resource pulse that may influence food web dynamics and the indirect transport of acetaminophen among trophic levels. We evaluated abundance, habitat type, and snake size (i.e., age) within two study sites on Guam, a secondary limestone forest (upland) and an abandoned coconut plantation (coastal), to determine how experimentally dosing snakes with acetaminophen is likely to influence carrion availability. We found snakes trapped in 3.24 ha plots occurred in greater abundance (population size = 72.5 snakes; SE = 8.8) and were significantly larger (978.6 mm, SE = 14.9) in the coastal than in the upland site (population size = 26.9, SE = 21.5; length = 903.0 mm, SE = 15.9). Despite these differences, carcasses of snakes that died after consuming acetaminophen-laced mice (80 mg) were recovered in consistent locations between sites, with 92 % located on the ground, 4 % in trees, and 4 % found in rock cavities at both sites. Given that most snakes were found on the ground rather than in the tree canopy, our results suggest that many poisoned snake carcasses will be accessible to a wide range of potential scavengers, possibly influencing food web dynamics and potentially contributing to indirect toxicant transfer within affected ecosystems.

Keywords Acetaminophen · Carcass location · Brown tree snake · Indirect toxicant transfer · Scavenging

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Introduction

Brown tree snakes (BTS; *Boiga irregularis*) were inadvertently introduced to Guam sometime during, or shortly after, World War II (Savidge 1987) and have negatively impacted both the economy (Fritts et al. 1987) and native fauna of this small Pacific island (Savidge 1987; Rodda and Fritts 1992). BTS have been especially problematic given their propensity to survive in close proximity to human development, highly varied diet (Savidge 1987), and ability to seek shelter in cargo or transport vessels (Fritts et al. 1999). These characteristics, in conjunction with Guam's strategic position as a focal point for commercial and military shipments, present a significant threat of BTS dispersal to other areas. Current control efforts for BTS on Guam are focused on area-specific population reduction to minimize impacts to native wildlife restoration projects, electrical infrastructure, and to prevent their spread (Rodda et al. 1998), rather than island-wide eradication (Vice and Pitzler 2000). Primary methods of control include trapping, barriers, fence line searches, canine inspections, bait tubes, and prey-base control around cargo facilities by employing rodenticides (Vice and Pitzler 2000). Direct estimates for managing this invasive species were approximately $10 million in 2004 (Brown Tree Snake Working Group 2004), and do not reflect increased shipping costs (Rodda and Savidge 2007), damages from power outages (Fritts 2002), or depredation of livestock (e.g., poultry; Fritts and McCoid 1991).

High cost and the logistical challenges of reducing BTS over large areas has led to calls for more cost-effective eradication alternatives (Savarie et al. 2001b; Clark et al. 2012). Taking advantage of the scavenging behavior observed in many snake species (Shivik and Clark 1997; DeVault and Krochmal 2002), bait tubes using acetaminophen-laced dead mice have been used operationally and require less maintenance than traditional traps with live mice; however, this approach is primarily limited to roads or easily accessible areas. Recently, mass aerial delivery of dead mice baits treated with acetaminophen (80 mg/bait) has been proposed for cost-effective reduction of BTS populations over larger areas (Clark and Savarie 2012). Given this technique's initial effectiveness at reducing BTS activity (80–85 % reductions; Clark and Savarie 2012), and its potential to reduce snake populations over larger areas, there exists a greater likelihood of large-scale eradication programs on Guam.

Savarie et al. (2001a) documented 100 % mortality in captive BTS (47–300 g) fed acetaminophen at 40-mg ($n=10$) and 80-mg ($n=29$) doses; 67 % mortality with 20-mg ($n=9$) doses; and 0 % mortality with 10-mg ($n=8$) doses. Additionally, Johnston et al. (2002) estimated acetaminophen concentrations of 881 µg/g in snakes at day 0 following dosing (80 mg), and a decay rate of 9.5 % per day out to four days (Johnston et al. 2002). Based on a daily diet containing acetaminophen concentrations of 881 µg/g, Johnston et al. (2002) concluded an acceptable level of risk for potential scavengers, although the potential for bioaccumulation was not explored. Currently acetaminophen is primarily only used operationally on Guam to control BTS, although it has been proposed for control of two other reptiles in Florida; Nile monitors (*Varanus niloticus;* $LD_{100} = 522–2438$ mg/kg) and Burmese pythons (*Python bivittatus*; $LD_{100} = 263–703$ mg/kg; Mauldin and Savarie 2010).

In light of the high density of snakes that has been reported in some areas of Guam (50 snakes/ha; Rodda et al. 1992), wide-scale reductions of BTS could result in resource pulses (Yang et al. 2008) of nutrient-rich carrion that may influence soils (Bump et al. 2009), microbes (Yang 2004), plants (Towne 2000), animals (DeVault et al. 2003; Wilson and Wolkovich 2011), and ultimately alter nutrient cycling and species diversity across the island (Hocking and Reynolds 2011; Beasley et al. 2012). In recent years there has been an increased recognition that carcass size, habitat type, and environmental variability influence scavenging and ultimately food web dynamics (DeVault et al. 2004; Pereira et al. 2014). Yet, relatively little consideration has been given to spatial heterogeneity of carrion (i.e., where an animal dies) within systems, especially with regards to decomposition and scavenging dynamics within three-dimensional space (Beasley et al. 2012). For example, rodents succumbing to poisons die in the open on the forest floor as well as in underground burrows (Howald et al. 1999), where the decomposition process can vary considerably between these two microsites (Parmenter and MacMahon 2009). Similarly, given the arboreal nature of BTS (Fritts 1998; Tobin et al. 1999), we hypothesize that they may be more likely to die in the forest canopy. Shalaby et al. (2000) found a carcass that was in contact with the ground had higher internal temperatures and a larger number of arthropods than a hanging carcass, which ultimately led to slower rates of biomass removal. Such spatial variation will ultimately determine the number and types of scavengers that have access to carrion, and represent a potential source for the transfer of toxicants (e.g., acetaminophen) among trophic levels.

Despite intensive measures currently being employed to control BTS on Guam, the potential for population establishment to other locations remains (Fritts et al. 1999). Range expansion of this invasive species would likely result in significant ecological and economic damage (Shwiff et al. 2010). Although the use of toxic baits to control invasive species has been carried out in numerous localities (e.g., Pott et al. 2015), deployment of baits in forest canopy targeting a primarily arboreal species is less common. Consequently, understanding the spatial variation of snake carcasses post-dosing is beneficial for estimating potential exposure to non-target scavengers in other areas, especially if they contained threatened or endangered indigenous wildlife. Thus, our objective was to determine the location of BTS carcasses following ingestion of acetaminophen to help elucidate how carcass location may influence food web dynamics and the indirect transport of acetaminophen among trophic levels within the Guam ecosystem.

Methods

Study site

Guam is located in the western Pacific Ocean, and at 540 km^2 is the largest of the Marianas Islands. The climate is tropical with little seasonal variation in temperature (24–30 °C). Our study was conducted during the wet season (July to November) at two 3.24 ha sites (upland and coastal) on Andersen Air Force Base at the north end of Guam.

Total precipitation in July and August 2015 was 105 cm (Weather Underground 2015). The coastal site was located in a historical coconut (*Cocos nucifera*) plantation dominated by coconut palms in the overstory with minimal understory vegetation. Elevation ranged from 22–41 m above mean sea level (msl). The upland site occurred at a higher elevation (150–158 m above msl) in a secondary mixed limestone forest–plateau (Engineering-environmental Management, Inc 2008). This area was dominated by relatively short stature woody species resulting in a fairly open canopy that allowed abundant undergrowth. Common plant species present in the dense undergrowth were *Vitex parviflora*, *Ficus prolixa*, *Guamia mariannae*, and *Aglaia mariannensis* (Engineering-environmental Management, Inc 2008).

Potential scavengers of BTS carcasses present on Guam include wild pig (*Sus scrofa*), domestic dog (*Canis familiaris*), domestic cat (*Felis catus*), mangrove monitor (*Varanus indicus*), cane toad (*Bufo marinus*), black drongo (*Dicrurus macrocercus*), domestic chicken (*Gallus domesticus*), coconut crab (*Birgus latro*), rat (*Rattus sp.*), mouse (*Mus spp.*), as well as other BTS. Estimated LD_{50} (mg/kg) from acetaminophen for mouse, rat, domestic dog, domestic cat, and wild pig was 338, 1944, >2000, 361, and >1000 respectively (Johnston et al. 2002).

Sampling regime

We estimated snake abundance over approximately 3.24 ha of each study site by placing 50 U.S. Department of Agriculture, Wildlife Services' (WS) standard BTS traps (Vice et al. 2005) 25–35 m apart in a loose grid. We suspended traps about 1.5 m high from vegetation and baited them with a live adult mouse (*Mus musculus*) contained in an inner cage within the trap. Mice were provided a food block and potato for a source of water. Due to low capture probabilities during the first two weeks (Otis et al. 1978), we checked traps daily for 21 days from 15 July to 4 August 2015. We measured tail length, length from snout to vent (SVL), and probed for hemipenes to determine sex (Jordan and Rodda 1994) for all captured snakes. We used SVL measurements to estimate weight of male (Log_e of weight = 3.227*Log_e of SVL—10.078) and female (Log_e of weight = 3.002*Log_e of SVL—9.057) snakes based on formulas derived by Savidge (2001). We classified snakes as adult (>980 mm) or juveniles (≤980 mm) based on SVL (Rodda et al. 1998). We then marked BTS by inserting HPT12 PIT tags (Biomark Inc, Boise, ID, USA) subcutaneously and gave them unique scute clips (Brown and Parker 1976) for a secondary mark to ensure no snakes were misidentified. The standard WS traps we deployed are biased towards capturing snakes >700 mm SVL (Rodda et al. 2007). As a result, our density estimates likely reflect only this segment of the population.

To avoid influencing BTS availability during population estimation, we began dosing trials of snakes captured in the same area one day after completing mark–recapture trapping. We secured 0.90 g BD-2 transmitters (162–164 MHz; Holohil Systems Ltd., Carp, Ontario, CA) measuring 15 × 7 × 3.5 mm with a 16 cm whip antennae to the ventral side of all subsequently captured snakes ($n = 53$) with a thin piece of camouflage duct tape (Wylie et al. 2011). Transmitter length, not including whip antennae, ranged from 1 % to 2 % of total body length and from 0.6 % to 2.3 % of total body weight. We then fed transmittered snakes mouse baits containing 80 mg of acetaminophen as this is the labeled application rate for BTS control on Guam (Savarie et al. 2001b), and released them at the capture site. Dosing estimates ranged from 2062–510 mg/kg of body weight. We initially placed transmitters roughly three-quarters of the distance from the snout to the vent ($n = 12$) as recommended by Wylie et al. (2011). However, after obtaining an observation on one snake 24 h after dosing, it appeared the mouse carcass was not able to pass the duct tape. Following this observation we began mounting transmitters just forward of the vent on the ventral side ($n = 41$) and observed no further issues with digestion. We attempted to observe dosed snakes daily by homing in on their location using a receiver (158–170 MHz; Communications Specialists Inc., Orange, CA, USA) and hand-held directional antenna (Telonics Inc., Mesa, AZ, USA). If we could determine that the snake was dead, we marked the location with a hand-held GPSMAP 64 s global positioning device (GPS [+/−3.7 m]; Garmin Inc., Olathe, KS, USA) and recorded whether the carcass was located in a tree, burrow, or on the ground. If we determined the snake was not dead, or we could not obtain a visual (e.g., the animal was in a tree), we recorded an approximate location, noted the specific habitat of the location (i.e., tree, ground, or burrow), and returned on subsequent days to ensure the animal was dead. If the animal failed to move after 3 days we assumed the animal was dead. All procedures were approved by the University of Georgia Animal Care and Use Committee (Approval number A2014 10-010-R1).

Data analysis

To estimate abundance and determine factors influencing probability of capture, we used a closed capture model (Otis et al. 1978) in Program MARK (White and Burnham 1999) with the logit-link function to compare an a priori set of 10 candidate models. We considered each day of the 3-week trapping session as an occasion. Due to low capture probabilities, we did not attempt to estimate differences in probability of first capture (p) versus probability of recapture (c). Initially, we evaluated 5 models that allowed detection probabilities to vary as a function of (1) group (g), indicating there was a difference between study sites, (2) time (t), in which each day had a unique probability, (3) precipitation (*precip*), consisting of days where precipitation was greater than 5 mm, (4) precipitation plus a one day lag effect (*precip* + *lag*), in which days with >5 mm precipitation plus the following day were different, and (5) constant (.), indicating detection probabilities were constant throughout the trapping period. Precipitation values were based on data collected at Andersen Air Force Base (Weather Underground 2015). We then reevaluated these 5 models, allowing them to vary based on the assumption that abundance (N) was different for each study site (g) or was constant (.). We based model construction on variables we considered biologically meaningful and used Akaike's Information Criterion corrected for small sample size (AIC_c) to select models that best described the data (Burnham and Anderson 2002). We compared AIC_c values to select the most parsimonious model and considered models differing by ≤ 2 ΔAIC_c from the selected model as reasonable alternatives (Burnham and Anderson 2002). We used Akaike's weights (w_i) as an indication of support for each model. For dosing trials, we tested for differences in size (SVL) between snakes caught in the upland and coastal sites using a t-test assuming equal variances. Additionally, as actual dosage in terms of mg/kg of body weight varied, we used an analysis of variance to test for differences in dispersal distance from dosing site to mortality site based on age class (adult vs. juvenile) and between sites. All analysis were performed in program R (R Development Core Team 2014).

Results

Over the 3 week trapping session we captured 18 unique individuals in the upland site and 48 in the coastal site. Our best approximating model ($w_i = 0.71$) was $\{p = c(precip)\ N(g)\}$ indicating capture probabilities varied as a function of precipitation and abundance varied by study site (Table 1). Specifically, we found capture probabilities increased from 0.03 to 0.08 on days with >5 mm of precipitation (Table 2), a result which suggests that aerial baiting programs for BTS might target bait drops after rain events. We also found support for a difference in population size of BTS between the upland (26.9; SE = 4.5) and coastal (72.5; SE = 8.8) sites (Table 2).

From 5 August to 16 August 2015 we dosed 53 BTS (coastal = 28, upland = 25) with mice containing 80-mg of acetaminophen. Dosed snakes in the upland site were smaller ($t_{50} = 3.474$, $p = 0.001$; SVL = 903.0 mm, SE = 15.9) and contained a higher proportion of juveniles (88 %) than in the coastal site (SVL = 978.6 mm, SE = 14.9; juveniles = 39 %). Approximately 50 % of snakes were dead within 24 h of dosing and 96 % were dead within 72 h. We obtained daily locations for ≥7 days on 2 snakes in the coastal site post-dosing, as well as several visual observations; however, based on their movements it did not appear they were affected by the acetaminophen, potentially due to regurgitation of the mouse bait. Consequently, we obtained carcass locations for 26 of 28 BTS in the coastal site. We retrieved all carcasses and transmitters from the coastal site and all but one (96 %) from the upland site. One carcass in the upland site was located on 3 consecutive days in a rock cavity, but due to digging restrictions on Department of Defense property in Guam we were unable to retrieve the carcass. Locations of deceased BTS were identical between sites with 92 % located on the ground, 4 % in trees, and 4 % found in rock cavities at both sites. Distance from dosing site to mortality site ranged from 7.9 m to 120.2 m, although

Table 1 Closed capture model selection results for brown tree snakes (BTS) on Guam, Jul to Aug 2015

Model[a]	AICc	ΔAIC_c	w_i[b]	K[c]	Deviance
$p = c(precip)\ N(g)$	330.285	0	0.709	4	273.299
$p = c(precip)\ N(.)$	333.043	2.758	0.179	3	278.068
$p = c(precip + lag)\ N(g)$	335.391	5.106	0.055	4	278.405
$p = c(t)\ N(g)$	336.319	6.034	0.035	23	240.551
$p = c(precip + lag)\ N(.)$	338.243	7.958	0.013	3	283.268
$p = c(t)\ N(.)$	338.944	8.659	0.009	22	245.244
$p = c(.)\ N(g)$	347.956	17.671	0.000	3	292.981
$p = c(g)\ N(.)$	349.399	19.114	0.000	3	294.424
$p = c(g)\ N(g)$	349.922	19.637	0.000	4	292.936
$p = c(.)\ N(.)$	350.943	20.658	0.000	2	297.977

[a] $p = c$ indicates initial capture probabilities (p) equals probability of subsequent recaptures (c), (g) = variable varied as a function of study site (upland vs. coastal), (.) = variable was constant, (*precip*) = days where precipitation totaled >5 mm, (*precip*` + *lag*) = days with >5 mm precipitation + the following day, (t) = capture probabilities varied each day

[b] Difference in AIC_c relative to min AIC_c

[c] K = number of parameters

Table 2 Parameter estimates from top model (Table 1) for brown tree snakes (BTS) on Guam, Jul to Aug 2015

Parameter	Estimates	SE	lower	upper
Capture probabilities				
Wet	0.077	0.013	0.055	0.107
Dry	0.033	0.006	0.023	0.047
Population size[a]				
Coastal	72.50	8.82	60.36	96.57
Upland	26.87	4.46	21.50	40.48

[a] Population estimates based on a trapping grid of 3.24 ha

we found no difference in dispersal distance (site: $F_{1,49} = 0.000$, $P = 0.996$; age class: $F_{1,49} = 1.455$, $P = 0.233$) based on study site (upland = 43.1 m; SE = 5.6 m; coastal = 43.0 m, SE = 4.1 m) or age class (adult = 48.3 m, SE = 4.8 m; juvenile = 39.9 m, SE = 4.6 m).

Discussion

Despite differences in habitat, snake size (age), and population abundance we found location of mortality for snakes succumbing to the effects of acetaminophen to be the same between study sites. We initially hypothesized that a greater number of snake carcasses would ultimately reside in the forest canopy given this animal's association with dense arboreal foliage (Fritts 1998; Tobin et al. 1999). For example, from May to August Tobin et al. (1999) found 93 % of subadult and 68 % of adult daytime sightings were in trees. Contrary to these previous findings and our initial hypothesis, the majority of carcasses (96 %) we located were on the forest floor. Over 70 % of carcasses located on the ground were only partially covered or in completely open areas, indicating some of these snakes may have died in trees and simply fallen to the ground. Furthermore, we routinely found snakes resting in trees on days after dosing before mortality occurred, but on subsequent visits to the site the carcass was located just below the tree. Regardless of how carcasses come to rest (e.g., whether they die on the ground or fall there) their availability to ground-based scavengers would be similar.

Our study was intended to mimic the expected response of BTS to large-scale delivery of acetaminophen baits over a broad area. Our methodology differs in several ways from the expected uptake of baits, yet we believe the patterns we observed reflect what would be expected with this management activity. For example, we handled snakes prior to offering or force-feeding them dosed mice, whereas they would need to naturally take baits with aerial delivery. Although we did not offer any free-ranging snakes baits, Lardner et al. (2014) found no difference in snake activity between individuals force-fed a transmitter and those that were offered a gecko bait containing a transmitter. Second, we released all snakes on the ground near traps where they were captured, while the current delivery system for aerial baits is designed to entangle in vegetation (Savarie et al. 2007). This could be a potential source of bias with our data; however, we routinely observed snakes immediately move into trees or shrubs after we released them, and several snakes were located >100 m from their release site, providing ample opportunity to move into any habitat strata they chose. We also found no difference in distance traveled between dosing and mortality sites between adult and juvenile BTS indicating snakes had ample opportunity to recover a normal activity after release regardless of actual dose of acetaminophen each snake received in terms mg/kg. Furthermore, Lardner et al. (2014) found juvenile BTS traveled 38 m between successive daytime refugia, which was close to the 40 m we observed for juvenile BTS fed acetaminophen-laced mouse baits. Lastly, we dosed all snakes during daylight hours, whereas most snakes would, presumably, take aerial baits at night (Lardner et al. 2014). Snakes that succumb to acetaminophen during the day would be more likely to be located in some refugia (i.e., burrow or tree), and possibly less likely to fall postmortem, while snakes actively hunting or moving at night may be less ensconced and more likely to end up on the ground. Based on our observations, it appears mortality post ingestion can occur within 24 h but take as long as 72 h, giving snakes ample access to trees or other locations. Given the time to mortality and the variation we observed for a large sample size of snakes, it seems unlikely that time of day at which dosing occurs is likely to influence where a carcass ends up on the landscape.

Dead or dying BTS would represent a potential route through which other wildlife could be exposed to acetaminophen. The magnitude of this risk would be contingent on both the concentration of acetaminophen in the snake carcass as well as the accessibility of the carcass to facultative scavengers (Johnston et al. 2002). Although acetaminophen concentrations in individual snake carcasses occur at acceptable levels for daily consumption by non-target animals (Johnston et al. 2002), our results suggest that subsequent to large-scale eradication events, many snake carcasses may be found on the ground and ultimately be available to a wider range of potential mammalian and invertebrate scavengers than would be likely in the tree canopy. Additionally, although the density of BTS we observed (8.3–22.4 snakes/ha) was lower than the 50 snakes/ha reported by Rodda et al. (1992), it is still virtually unprecedented even for an introduced snake species. For example, density of the introduced Burmese python in Everglades National Park in Florida, USA, was conservatively estimated at 0.2 snakes/ha in 2007 (Snow et al. 2007) which would range from 0.7 % to 1.9 % of the densities we observed. This number of snakes, coupled with the increase in accessibility, could increase the probability of individual scavengers consuming many snakes over a short period of time potentially increasing exposure to acetaminophen, particularly during an eradication. Researchers obtaining information on exact animal locations following exposure to toxins should consider reporting these data to better quantify the spatial variation of carrion availability. Unfortunately, the efficiency of the scavenging community on Guam is not well understood, so many knowledge gaps exist in understanding the flow of energy through this and other Pacific Island food webs. Future research assessing the diversity and efficiency of the scavenging communities in these areas would help elucidate the flow of toxicants as well as energy dynamics associated with large-scale eradications, such as BTS, on these islands.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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