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AN EVALUATION OF PASSIVE THERMAL FUMIGATION FOR BROWN TREESNAKE CONTROL IN SURFACE TRANSPORTATION FROM GUAM

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Abstract: The brown treesnake (BTS) has been on Guam for about 50 years and in this period has caused extensive ecological, economic, and social damage. It has also repeatedly dispersed from Guam via the transportation network, arriving at numerous locations. However, the conditions snakes face in surface shipping are unknown, making assessment of the risk of snake survival impossible. To address this, we recorded thermal conditions in surface shipments leaving Guam and identified factors that determine these conditions. We monitored 16 shipments to locations in Micronesia and the United States mainland and conducted a series of intensive studies at the Naval dock facility, using up to 29 containers at a time. Maximum temperatures recorded while containers were in transit were likely too low to consistently kill snakes. Empty exhibited uniformly high temperatures, but filled containers did not heat as much, nor as evenly. Maximum temperatures inside boxes and furniture are even lower, though often still exceed 40° C. Exposed containers reached high temperatures, but shading by other containers greatly decreased the maximum temperature reached inside.

Key Words: *Boiga irregularis*, brown treesnake, dispersal, Guam, invasive species, passive thermal, fumigation, surface shipping.

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INTRODUCTION

The brown treesnake (BTS, *Boiga irregularis*) arrived on Guam in the late 1940s as a stowaway in military cargo. By the early 1980s the snake inhabited the entire island and caused one of the most extensive ecological upheavals due to a single introduced species (Fritts and Rodda 1998, Perry and Morton 1999). Other problems are economic, primarily resulting from frequent and costly snake-caused power outages, and sociological, resulting from human bites and indirect cultural impacts (Rodda et al. 1997, Fritts and Rodda 1998). As dire as this problem has become on Guam, the risk of its further spread is even more alarming. Brown treesnakes have been found on ships and aircraft leaving Guam and at many destinations served from the island, some as far away as Spain (Fritts et al. 1999). Sanitizing the transportation network has repeatedly been identified as a high priority (Brown Tree Snake Control Committee 1996). Despite a substantial annual budget, the agencies conducting interdiction efforts on Guam and elsewhere lack the funding, authority, outside cooperation, and tools to achieve total success. As a result, snakes still leave Guam, although at a reduced rate, via the extensive commercial and military transportation network (Vice et al. 2004).

Currently, the primary control tools used for snake interdiction are traps, night-time visual searches, and dog searches (Vice and Pitzler 2002). However, these methods are expensive, time-consuming, and not completely effective (Vice and Vice 2004). This has led to attempts to develop additional tools for this task, including various methods for cargo fumigation using chemicals (Savarie and Bruggers 1999). A second type of fumigation, thermal fumigation, involves exposing high-risk cargo to thermal conditions that would lead to snake mortality (Christy et al. 2007). Since they lack the ability to physiologically control their body temperature, exposure of reptiles to either cold or heat can be fatal. Operationally, this means that temperatures in airplane wheel wells might drop low enough during a flight that snakes would freeze to death (Perry 2002). Thermal fumigation can be passive, relying on available conditions and not requiring additional technology, or active, depending upon special equipment for forced delivery (Zeichner et al. 1998). Thermal fumigation, and especially passive thermal fumigation, has several

advantages over chemical fumigation. Among them are lack of human health hazards, lower cost, and greater environmental acceptability. However, conditions in containers leaving Guam have not previously been assessed, and the utility of thermal fumigation for BTS control is unknown. Here we address this gap through both experimental manipulations of containers waiting to be loaded and observation of conditions in containers being shipped to multiple off-island locations. In conjunction with data on BTS thermal biology (Christy et al. 2007), we then assess the utility of thermal fumigation for BTS control in the Guam transportation network.

METHODS

Guam's Transportation Network

We obtained information on the procedures containers are exposed to in both civilian and military operations from written material (Vice et al. 2004), the shipping companies, port operations personnel, USDA Wildlife Services specialists tasked with inspecting cargo, and site visits. In addition to understanding standard procedures, we looked for opportunities to expose occupied shipping containers to intense solar radiation while minimizing the negative impact on shipping operations.

Conditions In Containers

We used three approaches to document temperatures inside containers. First, we measured temperatures in shipments made between 1996 and 1999. In each shipment, we installed temperature-sensitive dataloggers (Hobo loggers, Onset Computer, Pocassett, Massachusetts) set to sample at 5-20 minute intervals, depending on the study. Our study encompassed goods traveling to the United States (US) mainland (14 dataloggers retrieved from 7 shipments) and all three major islands in the Commonwealth of the Northern Mariana Islands (CNMI): Rota (8 dataloggers retrieved from two shipments), Saipan (6 dataloggers retrieved from three shipments), and Tinian (5 dataloggers retrieved from 3 shipments). Cargo utilized varied to the extent possible, and included both commercial shipments and household goods. This procedure provided information on conditions in transit, which typically took a month or more. However, in most cases we had to rely on the good will of shippers for both placement and retrieval. This resulted in a small sample size and allowed little control of logger placement within a container and of container placement on the ship. Additionally, it allowed for little replication within a shipment. Given the limitations of the initial study, we also conducted studies of conditions in shipping containers in route to the CNMI. In one container in route to Saipan and one heading to Tinian, we were able to precisely place a large number of loggers inside the cargo and document the placement of the container on the ship.

To experimentally examine the effects of specific operational procedures on temperatures inside containers, we conducted studies simulating dock-side conditions at the US Navy yard on Guam. In single-container studies we used both empty and full 20-ft containers placed on the dock. Initially, we only used an empty container in which we placed eighteen dataloggers, set to record every 5 minutes before it was sealed for 3 days. Although most containers leaving Guam are empty, the greatest risk of snake incursion is likely posed by containers packed on Guam. We therefore also simulated the dockside leg of the process of shipping containerized goods. We used two 20-ft containers, one containing goods and one, serving as a control, that was left empty. In the first phase of the study, we simulated shipping of a vehicle by enclosing a van in the container for 10 days. A second set of dataloggers was installed within and about the vehicle. In the second phase, we removed the van and filled the cargo container with wooden shipping pallets, also containing dataloggers.

In operational use, containers are typically stacked, usually two-high, in order to save space. Their spatial arrangement tends to be aggregated, in dense rows. As a result, some containers are exposed to sunlight from above and all four sides, others get sun only from above and perhaps from their ends, and some get little or no direct sunlight. In a final container study we used 29 empty 20-ft shipping containers and a design which allowed us to sample containers differing in contents, dock tenure, and location within the cargo yard. The containers were arrayed in three rows, some of them stacked. We placed a single logger, set to sample every 5 minutes, in each of 17 accessible containers. All loggers were placed in the same relative position within the container: on the floor, in the middle, 3 ft from the door. Containers were then sealed for one month.

RESULTS

Guam's Transportation Network

Much of the cargo shipped from Guam is first handled in a multitude of privately owned and operated warehouses located in the Harmon industrial area. Empty containers are stored nearby or delivered as needed, often having been placed in high snake density areas for protracted periods. Some outbound material is kept outdoors for prolonged periods, usually in an un-containerized state highly susceptible to snake incursion. Normally, however, outbound materials are kept indoors (exceptions include private vehicles, a large number of which are shipped off island every year). Typically, they are only placed in reliably snake-resistant containers shortly before they are taken to the port. The normal procedure used at these facilities, therefore, does not provide an opportunity for lengthy exposure to sunlight. Further, most packing installations lack the space for storing sealed containers outside for any length of time. In contrast, containerized and breakbulk (non-standard goods, such as pipes, that cannot fit inside a container) cargo on Guam often spend several days at the port. Although some containers are stuffed at the last minute and loaded directly from the truck onto the ship, cargo (including all containers and most breakbulk) is typically stored uncovered at the port. This occurs while it is waiting to be loaded onto the ship, or after unloading and before pickup by the consignee. During sunny periods, these containers are often exposed to strong sunlight, but snakes are free to enter or leave breakbulk throughout this period.

After staging, containers are stacked onto ships. At this stage, there is a large difference between some of the small barges, which typically serve short-range destinations such as the CNMI, and the larger ships serving more distant locations. Barges typically store containers in a single layer, all on deck, whereas larger ships store containers in multiple layers, many of them under the deck and completely isolated from sunlight. Thus, the dock stage appears to be the most promising and least disruptive part of the process for the purpose of passive thermal fumigation.

Conditions In Containers

About ten percent of the loggers installed in shipments were not recovered. A typical profile obtained from a shipment of household goods from Andersen Air Force Base to the mainland US can be divided into 6 periods (Figure 1). Initially (A), goods and loggers are inside the temperature-controlled house. They are then crated, and for a period (B) await loading on the dock, inside metal containers. This is when temperatures reach their highest levels. The container is then loaded onto a large ship, typically (but not always) below deck, and remains there throughout its travel to its destination (C). Temperatures can be quite low during parts of this phase. Upon arrival, the goods are transferred to storage (D), where they await delivery to the owner. Finally, they are unpacked inside a temperature-controlled-house (E). The final section (F) represents temperatures recorded as the logger was being shipped back to Guam. Overall, recorded temperatures were mostly moderate. High temperatures were recorded, if at all, when the cargo was on the dock. Of all crossings documented (N = 33 loggers in 15 shipments), the highest temperature recorded was 52.9^{o} C and the lowest maximal temperature recorded was 29.8 ^{o}C (mean maximum temperature and SD = 40.0 $\pm$ 6.99). The lowest temperature recorded was –12.8^{o} C and the highest minimum temperature seen was 29.1 ^{o}C (Mean and SD: 15.3 ± 13.26).

A somewhat different pattern was found in cargo shipped to the CNMI, although the distinction between temperatures recorded on the dock and on the ship was retained. Temperatures measured in the pallet kept within the warehouse until shipping (Figure 2A) were considerably lower than those seen in the pallet left outside (Figure 2B). However, both pallets reached similar temperatures during the latter part of the process, including time on the dock on Guam, in transit, and on the dock on Rota. This is because shipments to the CNMI were carried by open barges which typically stored containers in a single layer on an open deck.

Shipments to the mainland experienced significantly lower maximum (Mainland: 36.7 ± 6.39 ^{o}C, Saipan: 47.8 ± 2.78 ^{o}C, Rota: 45.5 ± 8.17 ^{o}C, Tinian: 39.1 ± 2.25 ^{o}C; $F_{1,7.95} = 8.7$, $p = 0.0185$) and minimum (Mainland: 1.8 ± 7.70 ^{o}C, Saipan: 25.2 ± 0.88 ^{o}C, Rota: 26.2 ± 1.74 ^{o}C, Tinian: 24.6 ± 2.06 ^{o}C; $F_{1,9.77} = 30.87$, $p = 0.0003$) temperatures. The average high temperature measured for all shipments to the CNMI was 42.4 ^{o}C (range: 31.1-52.9) and the average low temperature was 25.6 ^{o}C (range: 22.1-29.1).

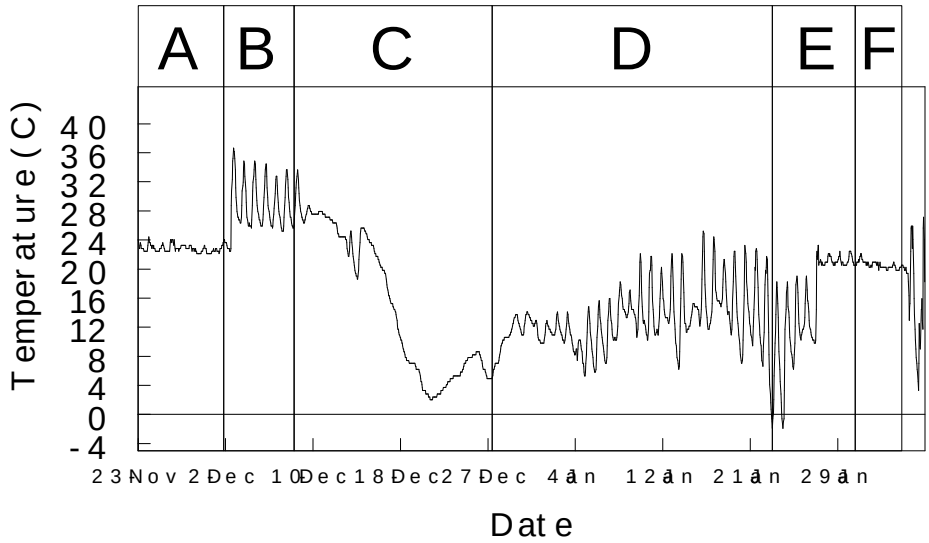

Figure 1. Temperatures recorded inside household goods shipped from Guam to the mainland US. A: goods are inside the home. B: crated and containerized goods await loading on the dock. C: the container is on board a large ship. D: following arrival at the destination, goods are in storage. E: goods are inside the destination house. F: temperatures recorded as the logger was being shipped back to Guam.

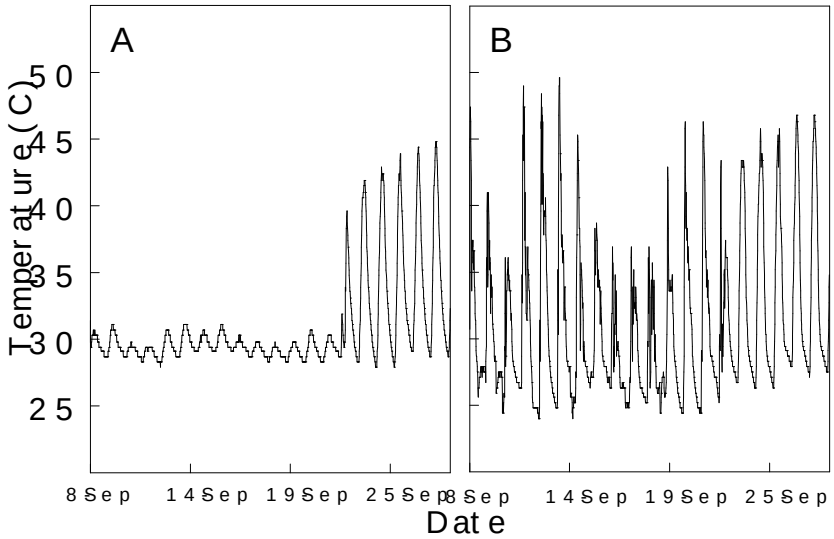

Figure 2. Temperatures recorded inside two pallets of fencing materials shipped from Guam to Rota, Commonwealth of the Northern Mariana Islands: (A) a pallet was warehoused until ready to be loaded onto the ship, (B) a pallet left exposed to ambient conditions outside of the warehouse.

We did not detect side or depth effects on mean or maximum temperature measured within a container shipped to Saipan, but logger height had a highly significant effect (Mean: $F_{2,12} = 20.06$, $p < 0.001$; Maximum: $F_{2,12} = 4.06$, $p = 0.045$). We also identified significant differences in maximum temperatures measured inside and outside boxes, as well as those placed within a shipped van ($F_{2,27} = 9.09$, $p = 0.001$). The highest values were measured in the container at large (Mean and SD = 51.5 ± 7.30 °C, range = 39.7-62.7 °C, n = 16), the lowest were inside the van (Mean and SD = 41.1 ± 3.20 °C, range = 35.3-44.9 °C, n = 8), and intermediate values were obtained in boxes placed outside of the van (Meanand SD = 44.5 ± 3.80 °C, range = 40.1-49.0 °C, n = 6). Qualitatively similar results were obtained from the Tinian shipment, with temperatures inside cargo (Mean and SD = 41.3 ± 2.65 °C, range = 38.3-45.4 °C, n = 10) significantly lower than those in the container at large (Mean and SD = 46.0 ± 3.64 °C, range = 40.1-52.4 °C, n = 14; $F_{1,16} = 10.50$, $p = 0.005$). All other single factor effects were also significant ($p < 0.031$ in all cases), with the highest values obtained at the top portion of the middle section of the container.

Mean temperatures recorded within the empty container were near 32 ^{o}C, and maximum values ranged from 44.4-50.1 ^{o}C (Table 1). Figure 3 presents typical temperature profiles for a variety of locations inside the container. The temperatures measured are summarized below according to logger location. As expected from the similarity of profiles, there was no significant effects due to logger position within the container (for height, $F_{2,11} = 1.68$, $p = 0.230$; for container side, $F_{2,11} = 0.25$, $p = 0.786$; for container end, $F_{2,11} = 2.61$, $p = 0.118$). This indicates no significant stratification occurs within empty containers, with similar temperatures prevailing throughout.

Temperatures were highest in the empty container and lowest inside the van enclosed in the filled container (Figure 4, Table 2). The difference between the two containers was significant ($F_{1,7} = 31.97$, $p = 0.002$), as was the difference between temperatures measured inside the van and in the rest of the experimental container ($t = 2.32$, $df = 16$, $p = 0.034$). Thus, an empty container will heat more, and show less thermal stratification, than a container holding even some goods. Location within the container exerted a significant effect on maximum temperature measured. Temperatures were higher as elevation within the container increased ($F_{2,7} = 92.27$, $p < 0.0001$), were higher at the middle of each container ($F_{2,7} = 7.86$, $p = 0.004$), and were highest on the side most exposed to direct sunlight ($F_{2,7} = 7.98$, $p = 0.004$).

Table 1. Summary of maximum daily temperatures obtained inside a single empty 20-ft container. Min is the lowest maximum temperature recorded; Max the highest. Sample size is the number of loggers used.

			Max temperature (°C)	
Hobo Location	**Sample Size**	**Mean (SD)**	**Min**	**Max**
Height				
Top	6	47.7 (2.86)	44.9	52.9
Middle	5	47.4 (2.38)	44.9	50.1
Bottom	7	45.6 (1.44)	44.4	48.5
Length				
Front	5	48.0 (0.98)	46.4	49.0
Center	8	45.5 (1.27)	44.4	48.0
Back	5	47.6 (3.67)	44.9	52.9
Width				
Left	7	46.3 (1.78)	44.4	48.5
Middle	4	47.4 (2.59)	44.9	50.1
Right	7	47.0 (2.88)	44.4	52.9

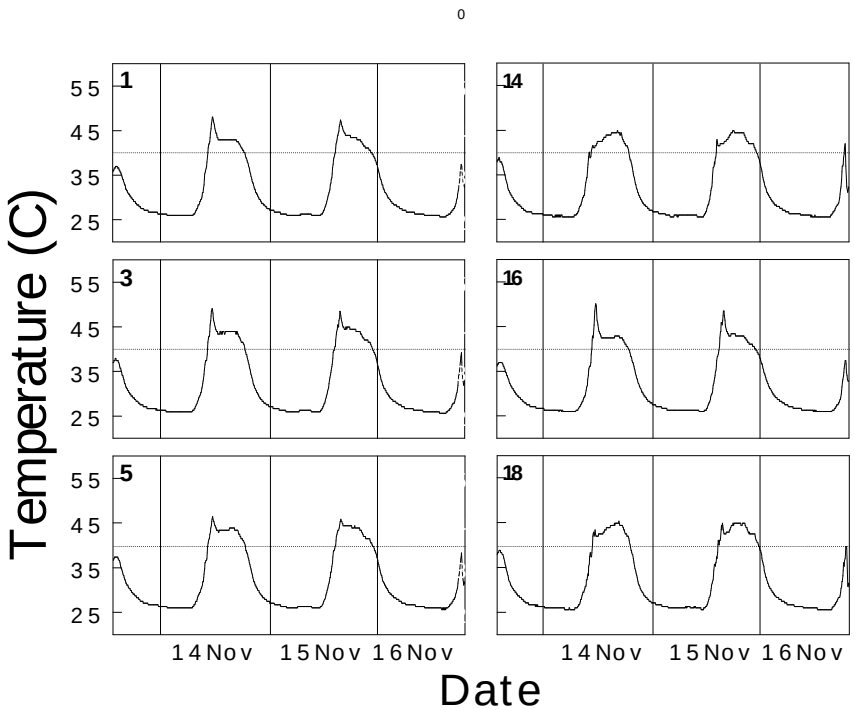

Figure 3. Temperatures recorded inside an empty 20-ft container. The dotted line represents 40 °C, presumed harmful to snakes.

We found a similar pattern when the van was replaced with pallets, which do not hold enclosed spaces and allow more air circulation. However, although maximum temperatures were highest in the empty container and lowest inside the pallets, the difference was small and not statistically significant ($F_{1,17} = 1.64$, $p = 0.248$). The difference between temperatures measured in the pile of pallets and in the rest of the experimental container were also not significantly different ($t = 1.14$, $df = 16$, $p = 0.269$). Similarly, although we detected a significant height effect ($F_{2,17} = 5.59$, $p = 0.043$), we found no side effect ($F_{2,17} = 0.31$, $p = 0.746$).

Temperature profiles obtained in multi-container studies were similar in shape to those obtained before (Figure 5). However, overall values obtained were lower than in single-container studies. Mean temperatures were about 30 ^{o}C (range: 28.1-30.7). The highest maximum hourly temperature measured was 43.9 ^{o}C, and the lowest maximum temperature we measured was 30.7 ^{o}C. Containers placed on the top row reached significantly warmer temperatures than those in lower ones ($F_{1,8} = 200.84$, $p < 0.001$, Table 3). However, temperatures typically exceeded 40 °C for less than one hour at a time. Thus, although containers placed on top do reach considerably higher temperatures, this only happens for relatively short periods of time. Repeating the same analysis with data that better represent overall patterns (Table 3) showed no significant effects due to stacking height and location within row (for height $F_{1,8} = 0.02$, $p = 0.891$; for location within the row $F_{1,8} = 0.61$, $p = 0.459$). However, internal rows showed higher temperatures than those measured in external row containers ($F_{1,8} = 10.43$, $p = 0.012$), perhaps because of reflected radiation from adjacent containers.

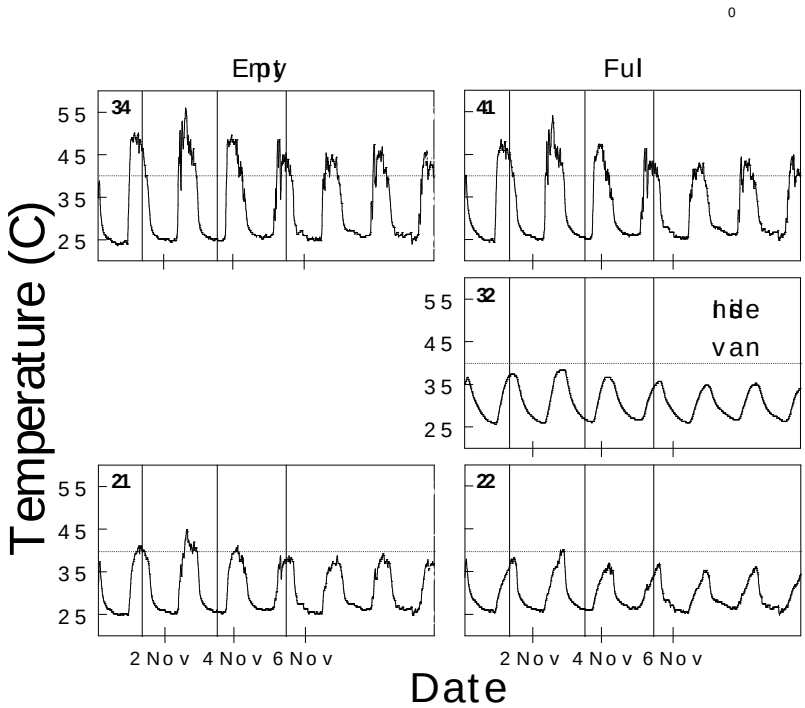

Figure 4. Temperatures recorded inside an empty 20-ft container (left) and one containing an experimental load. The dotted line represents 40 ^{o}C, presumed harmful to snakes.

Table 2. Temperatures measured inside control (empty) and experimental (containing van) 20-ft containers and inside the vehicle enclosed within the experimental container. The first four columns present container mean temperatures, whereas the next two provide the highest (Max) and lowest (Min) temperatures. N is the number of dataloggers used.

	Temperature (means, °C)			Maximum temperatures (°C)		
Location	Mean (SD)	Min	Max	Lowest	Highest	N
Control	31.1 (0.77)	24.2	50.3	43.4	56.0	13
Experimental	30.9 (1.04)	24.4	47.9	37.9	52.5	13
Van	30.9 (0.93)	25.6	41.6	37.4	49.6	5

DISCUSSION

Maximal temperatures reached inside containers leaving Guam were highly variable, ranging from relatively low (about 35 °C) to very high (near 60 °C). Given that shippers and cargo-handlers alike wish to minimize the time they must be responsible for cargo, the optimal timing for passive thermal fumigation to occur would be during periods when the cargo is on board a ship and en route to its destination. Unfortunately, our data conclusively show that this is not a viable option. Typical temperatures during the shipping process were well below the levels that might be useful for snake control. One consistent pattern, however, was that temperatures in containers bound for the CNMI were higher than those measured in US mainland-bound cargo,

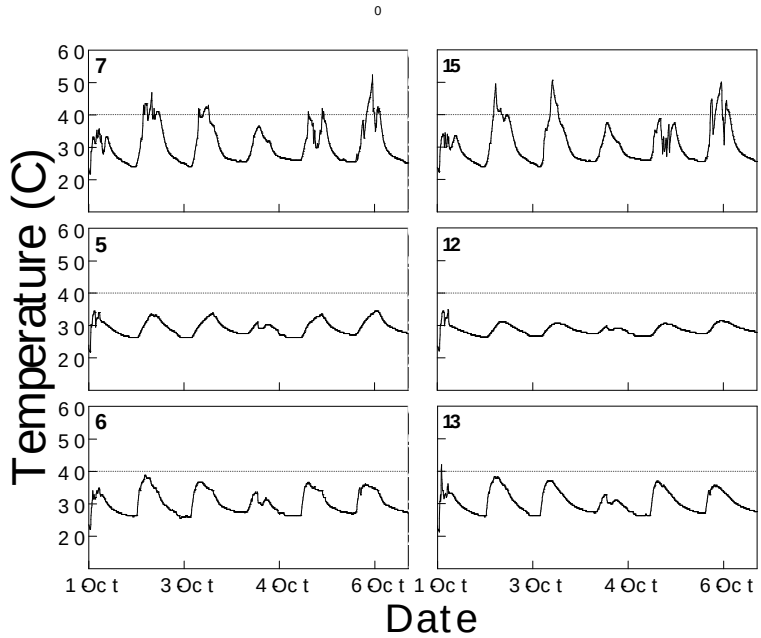

Figure 5. Temperatures recorded inside 20-ft containers stacked on the dock on Guam. The dotted lines represents 40 °C, presumed harmful to snakes.

Table 3. Summary of maximum daily temperatures obtained in the multi-container study. N is the number of containers in each category that were sampled. Min is the lowest maximum temperature recorded; Max the highest.

		Maximum temperature (°C)					
		Hourly			Overall		
Location	N	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Stacking height							
Top	5	37.5 (5.60)	31.1	43.9	62.5 (2.06)	59.2	64.2
Bottom	11	36.5 (4.46)	30.7	42.9	36.5 (3.73)	31.9	43.9
Row							
External	10	34.8 (3.84)	30.7	41.1	44.4 (12.61)	33.2	64.2
Internal	6	40.2 (4.12)	33.2	43.9	45.0 (14.44)	31.9	64.2
Location within row							
Corner	6	38.5 (5.95)	30.7	43.9	46.5 (11.53)	33.2	62.0
Internal	10	35.9 (3.75)	31.4	42.5	43.5 (14.04)	31.9	64.2

presumably because the latter are stowed below-deck and the former are often above-deck and exposed to additional solar radiation. When the cargo is waiting on the dock, maximum temperatures occasionally exceeded 60 °C, and often surpassed 40 °C, a temperature identified by Christy et al. (2007) as lethal to BTS after moderate exposure. Thus, if passive thermal fumigation is to be useful, it will have to occur during the dock phase of the process.

About 75 percent of the containers leaving Guam are empty. Temperatures inside empty containers are typically high, and may effectively kill or harm snakes trapped inside. This suggests

that air movement inside the containers is considerable and allows temperatures to equalize throughout. However, empty containers in good condition (i.e., lacking holes) pose a relatively low risk of snake incursion when their doors are closed. Stuffed containers are more risky, both because they have to be kept open during the loading process and because the cargo may have been invaded by a snake before being loaded. Full containers consistently showed a significantly different thermal profile than empty ones. They did not heat to the same extent, and loggers placed inside boxes and other cargo reached even lower maximum temperatures. Tightly-packed containers will allow less air circulation than ones left partly empty. As a result, containers packed full of boxes will provide more hospitable hiding places for snakes than ones that are half-packed with contents allowing easy air circulation, as in our pallet study. A snake loose within a container will be free to seek the least stressful environment it can find. Unfortunately, temperatures inside containers full of actual cargo were significantly stratified. The maximal temperatures measured near the bottom of the container or inside cargo did not typically reach 40 °C, possibly providing a refuge which could allow a snake to survive through the relatively brief periods of high ambient temperature elsewhere in the container.

When sunlight is abundant, maximal temperatures are reached inside sealed containers quite rapidly. This suggests that, when ambient conditions are right, only a relatively short period would be needed for passive thermal fumigation to reach its maximum possible efficacy. Conveniently, containers often stay on the dock in Guam for at least two days before being loaded, and two full sunny days should be considered the minimum amount of time allotted for this process. Importantly, four half-sunny days are not equivalent to two sunny days. Containers protected from direct sunlight do not typically reach high temperatures, and even those exposed to direct sunlight do not exceed 40 °C for very long. Thus, to receive any benefits from thermal fumigation, containers should not be stacked. Moreover, spacing between them must be great enough to minimize shading and maximize exposure to direct sun. During particularly cloudy periods, which are especially common during the rainy season, this may not be logistically possible, given shipping schedules, and alternative methods would then have to be applied.

Under the right conditions, passive thermal fumigation offers an economically attractive tool for limiting BTS excursion from Guam. Moreover, receiving destinations in the Pacific (e.g., CNMI and the Federated States of Micronesia) can use passive thermal fumigation, in combination with barrier technology (Perry et al. 1998, 2004; Rodda et al. 1998), to improve the chances that any snakes arriving in cargo will be dead before the container is opened. However, it is important to recognize the limitations of this method. Although likely to sometimes be effective, passive thermal fumigation is not a reliable tool unless used conscientiously, consistently, and intelligently. Sunny days cannot always be guaranteed, and container contents and packing will have a major effect on conditions inside. As a result, identical containers placed in the same location on consecutive days might reach greatly different internal temperatures. Similarly, different containers experiencing the same conditions may reach different internal temperatures. This level of complication is unlikely to present an appealing and effective operational solution under conditions prevalent in the Pacific, which unfortunately makes passive thermal fumigation not a “silver bullet” solution. Other methods of sanitizing cargo will be necessary, and passive thermal fumigation will be especially useful if used in conjunction with means for isolating and interdicting cargo, such as snake barriers and active thermal fumigation.

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