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Control of subterranean termite populations at San Cristóbal and El Morro, San Juan National Historic Site

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Abstract

Populations of *Coptotermes havilandi* and *Heterotermes* sp. were detected in soil and structures of San Cristóbal and El Morro of the San Juan National Historic Site. This was the first record of *C. havilandi* in Puerto Rico. Baits containing a chitin synthesis inhibitor, hexaflumuron, were applied using in-ground and aboveground bait stations. It took 2 - 8 months to eliminate 3 populations of *C. havilandi*, but 13 - 15 months were required to eliminate 4 populations of *Heterotermes* sp. Because of the vast area of the San Juan National Historic Site, there are probably many more unseen populations of subterranean termites. There is a need for a routine monitoring program for early detection of subterranean termite infestations so that baits can be applied to eliminate detectable populations before severe and irreversible damage occurs to this historic site.

Keywords: subterranean termites; *Coptotermes havilandi*; *Heterotermes* sp.; hexaflumuron; Sentricon

1. Introduction

1.1. San Juan National Historic Site

San Juan was one of the key harbors in the Caribbean for Spain to safeguard her trade monopoly after the establishment of the vast New World empire in the 16th century. The Caribbean Sea was a vital passageway for armed convoys carrying precious treasures acquired from the conquered New World to Spain. Although Puerto Rico was not a major link in the convoy system, fortification of San Juan was needed to keep the port and the island from becoming threats against Spanish settlements and trade. The strategical importance of San Juan harbor was so critical that King Philip II (1556-1598) called it "the key to the Indies."

The first defense structure on the island was a turret tower, built in 1539 at the western tip of the islet of Old San Juan, that oversaw the harbor entrance. During the following 250 years, the small tower evolved into the present form of El Morro which is a massive fortress made of six-tiered pile of sandstones. While El Morro was built to defend the passage into San Juan Bay, San Cristóbal on the eastern end of the islet was constructed between 1634 and the 1780s to protect the land approaches to San Juan from the east. Rising nearly 50 m above sea level, San Cristóbal contains a network of interdependent fortifications covering 27 acres, and is the largest fortress built by the Spanish empire in the Western Hemisphere [1]. A 1.3-km long fortified wall facing the Atlantic Ocean connects El Morro and San Cristóbal. These Spanish engineering features demonstrate state-of-the-art military construction techniques between 1533 and 1898, and are designated as a World Heritage Site by the United Nations. The San Juan National Historic Site has the best-preserved city wall system in the Americas, and is the only walled city defense system within the United States National Park System.

1.2. Termites of Puerto Rico

Termites are abundant in tropical Puerto Rico. Arboreal nests of *Nasutitermes costalis* (Holmgren), for example, are found on native vegetation and structures throughout the island. Drywood termite species such as *Cryptotermes brevis* (Walker) and *Incisitermes incisus* (Silverstri) are common pests in

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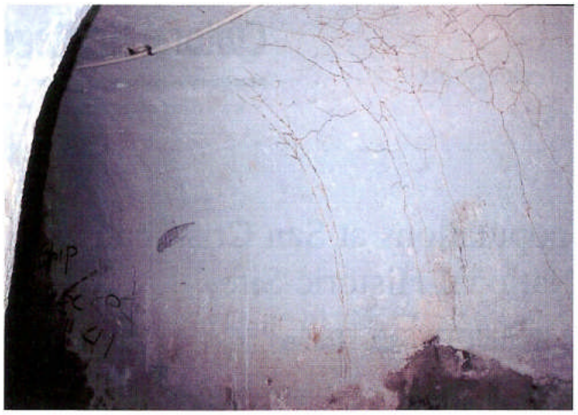


Figure 1: Old and hardened foraging tubes of *Heterotermes* sp. were found on the walls of underground tunnels in San Cristóbal, and are indicative of a long presence of this endemic species within the fortress.

wooden furniture and structures [2]. Literatures indicate 2 endemic species of *Heterotermes*, *H. convexinotatus* Snyder, and *H. tenuis* (Hagen), are present throughout the West Indies, but thus far they are morphologically indistinguishable [2], and are referred to as the *Heterotermes* sp., in this article. *Heterotermes* sp. is a pest found throughout the West Indies including Puerto Rico and the Virgin Islands. It forms relatively uniform and narrow foraging tubes that often suspend vertically from the ceiling. *Heterotermes* sp. is endemic and was present around this fortress since the earliest days of construction. During our site survey, for example, old foraging tubes of *Heterotermes* sp. that hardened after absorbing minerals from ground water over a long period were found on the walls of underground tunnels in San Cristóbal (Fig. 1), and graffiti dating from the early 1800s were painted over these tubes.

1.3. Termite damage to historic structures and control

Although El Morro and San Cristóbal were built primarily with mortar and sandstone, they are nonetheless vulnerable to termite damage given the traditional use of wood as a building material. As with other historic buildings, termite damage is both costly and irreversible and can diminish the historic significance of the structure through the loss of original building fabric. Subterranean termites are especially damaging because of their ability in causing fast and severe damage, and because of their cryptic nature. Conventional methods for the control of subterranean termite infestations rely heavily on the use of organic insecticides to provide a barrier for the exclusion of soil-borne termites from a structure. Typically, large volumes of liquid insecticide are applied to the soil beneath and surrounding an infested building. Due to its close proximity to the ocean, poisoning the soil in the San Juan Historic Site was not an option, and such an approach was probably not altogether effective considering the massive walls – some filled with rubble. Creating an uninterrupted barrier of treated soil beneath an existing structure is extremely difficult and gaps in the barrier invariably allow access to the structure. Because the soil treatment only deters termite attack, the vast majority of subterranean termites are unaffected. Conventional soil treatments may also result in physical damage to the structure. Soil treatments often require drilling of the foundation floor before liquid insecticides are injected into the subfoundation soil, and the injection holes may be disfiguring, unsightly, and irreversibly damaging to historic relics.

In 1995, bait containing an insect growth regulator, hexaflumuron, was commercialized in the United States under the trade name of Sentricon® Termite Colony Elimination System (Dow AgroSciences, Indianapolis, IN) for subterranean termite control. Hexaflumuron inhibits the synthesis of chitin that is essential for the formation of insect exoskeleton, but is virtually harmless to vertebrates. Using a monitoring-baiting procedure, hexaflumuron is delivered by foraging termites to eliminate entire colony populations of up to several million individuals [3]. The procedure has been used successfully to control the eastern subterranean termite, *Reticulitermes flavipes* (Kollar), in the Statue of Liberty National Monument [4], the Formosan subterranean termite, *Coptotermes formosanus* Shiraki, in the Cabildo complex, New Orleans, Louisiana [5], and the European subterranean termite, *R. lucifugus* (Rossi) in the church of Santa Maria della Sanità in Naples, Italy [6]. In late 1996, we were informed of the termite infestations at the San Juan National Historic Site by the Unite States National Park Service, and were asked to control the termite populations with the least-invasive measures. Because the Sentricon® system was not commercially available in Puerto Rico at the time, we developed suitable techniques for use at this site. This paper reports the results of the project to control termite infestations at the San Juan National Historic Site.

2. Materials and Methods

2.1. Termite infestations

2.1.1. Living Quarters, San Cristóbal

The initial termite survey was conducted January 1997 when the National Park Service personnel discovered termite foraging tubes on the walls of their living quarters outside the south walls of San

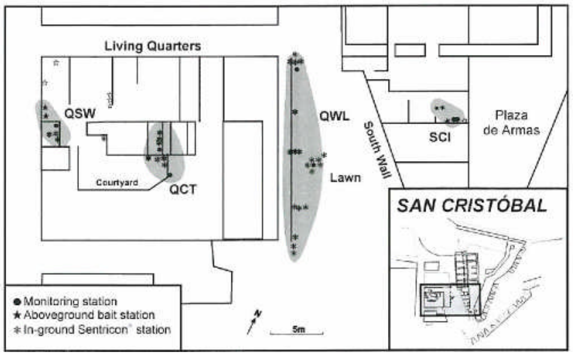


Figure 2: Three colonies of *Heterotermes* sp. (QSW, QCT, and QWL) were detected in the living quarters, and one colony of *C. havilandi* (SCI) was found in utility room facing the Plaza de Armas of San Cristóbal. Solid symbols denote stations with termite activity at least once during the testing period, while open symbols denote stations that were not infested with termites.

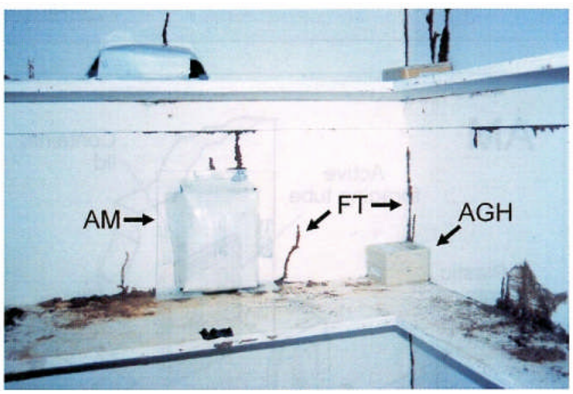


Figure 3: Wooden shelves of the utility room facing the plaza of San Cristóbal were heavily damaged by *C. havilandi*, with many foraging tubes (FT) extending to the walls. This is the first record of *C. havilandi* in Puerto Rico. Aboveground monitoring stations (AM) were placed over active infestation to measure termite activity, while hard-style aboveground bait stations (AGH) were used to deliver hexaflumuron baits to the target colony.

Cristóbal (Fig. 2). No live termites were found in the foraging tubes of *Heterotermes* sp., but these were apparently "live tubes" because when removed, new tubes would appear the following day, according to the occupants. Live workers and soldiers of *Heterotermes* sp. were found in wood pieces on the ground in the courtyards of the living quarters.

2.1.2. Utility room of Plaza de Armas, San Cristóbal

Extensive foraging tubes were found on the walls in a utility room at the southwest corner of Plaza de Armas of San Cristóbal (Fig. 2, SCI). Wooden shelves in the room were heavily damaged and infested with foraging tubes (Fig. 3) containing large numbers of the subterranean termite, *Coptotermes havilandi* (Holmgren). This is the first record of *C. havilandi* in Puerto Rico. *Coptotermes havilandi* is one of the most destructive termite

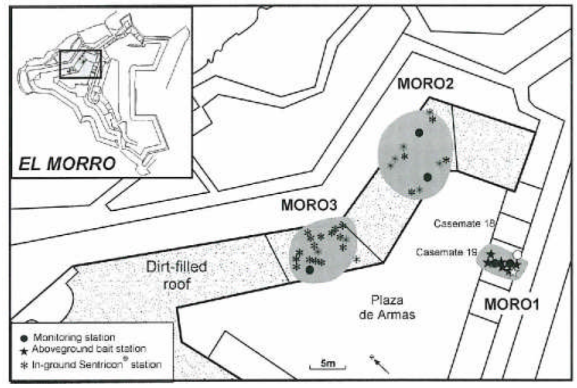


Figure 4: One cluster of *C. havilandi* activity (MORO1) was found on the walls and floor of Casemate 19, while another cluster of *C. havilandi* activity (MORO2) was detected in the dirt-filled roofs of the rooms across the plaza from Casemate 19 of El Morro. Although the mark-recapture procedure did not connect MORO1 and MORO2, data suggested they could be interlinked near the cistern beneath the plaza. A stake survey also detected a population of *Heterotermes* sp. (MORO3) in the dirt-filled roof west of MORO2. Solid symbols denote stations with termite activity at least once during the testing period, while open symbols denote stations that were not infested with termites.

Figure 5: Extensive foraging tubes of *C. havilandi* were found on the walls and floors of Casemate 19 facing the Plaza de Armas in El Morro.

species wherever it occurs and is found primarily in tropical regions, including the Southeast Asia, Central, and South America, and the West Indies such as Antigua, Barbados, Jamaica, Cuba, Turks and Caicos, and Little Cayman [2]. In 1996, *C. havilandi* was found in the continental United States for the first time [7]. Its foraging tubes are less uniform, wider and tend to form more branches than those of *Heterotermes* sp.

2.1.3. El Morro

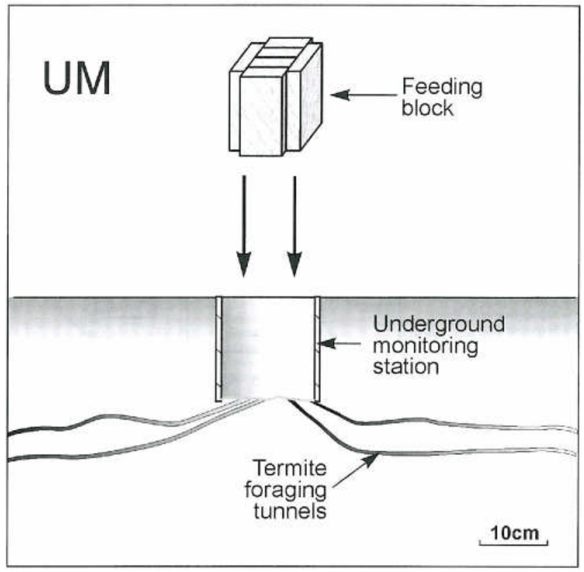
Beneath the stone floor of the Plaza de Armas in El Morro was a cistern that could hold 830 kl of rain water to provide a year's supply if the garrison were under siege (Fig. 4). The vaulted rooms surrounding the Plaza are called casemates that served as living

Figure 6: Roofs of the rooms (casemates) on the north edge of the Plaza de Armas in El Morro were filled with dirt to provide protection against shell bombardments from enemy ships approaching from the Atlantic Ocean. Several pieces of wood with apparent termite damage were found on top of the roofs, and activity of *C. havilandi* (MORO2) and *Heterotermes* sp. (MORO3) were detected by stake survey.

quarters for officers and soldiers, food storages, powder magazines, prison cells, and cannon firing positions. Extensive foraging tubes of *C. havilandi* were found on the floor and walls (Fig. 5) in the third room (Casemate 19) at the southeast corner of the Plaza (Fig. 4). The cistern is accessible through an entrance on the floor of Casemate 19, and wooden frames of the entrance were visibly infested by *C. havilandi,* with foraging tubes extending from the wooden frames down to the cistern beneath. According to the park personnel, all foraging tubes in Casemate 19 were removed two weeks prior to our visit, but were re-built within days and contained live termite. A few *C. havilandi* foraging tubes were also found on the eastern walls of Casemate 18, which is east of Casemate 19 (Fig. 4), but no termites were found in them. Across the Plaza from the Casemate 19 were several rooms (or casemates) with dirt-filled roofs that formed the northern outer walls of the 5th level of the El Morro fortification. The dirt-filled roofs provided protection against shell bombardments from enemy ships approaching from the Atlantic Ocean (Fig. 6). On top of the dirt-filled roof were several pieces of wood with apparent termite damage. Old termite damage and foraging tubes were also found on the door and window frames of the casemates beneath the dirt-filled roofs.

2.2. Monitoring termite activity

Three methods were used to detect and quantify termite activity at the San Juan National Historic Site, including underground monitoring stations, aboveground monitoring stations, and an acoustic emission detector readings. When possible, a mark-



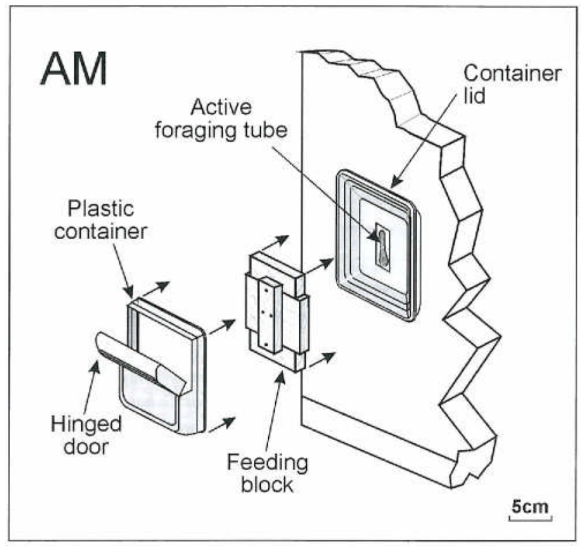


Figure 7: Underground monitoring stations (UM) were placed in soil, while aboveground monitoring stations (AM) were placed over active foraging tubes of termites to measure their activity.

recapture procedure was done to delineate the foraging range of a colony.

2.2.1. Underground monitoring stations (UM) and mark-recapture

To locate termite activity in soil, wooden (*Picea* sp.) stakes (2 by 3 by 30 cm) were driven into the courtyard grounds of the living quarters, in the lawn outside the south walls of San Cristóbal (Fig. 2), and in the dirt-filled roofs at the north end of the Plaza of El Morro (Fig. 4). When termites were found in survey stakes, we installed underground monitoring stations (plastic collars 17 cm in diameter and 15 cm in height) containing preweighed feeding blocks (six spruce boards [7 by 13 by 2 cm] nailed together)

(Fig. 7A) [8]. After the establishment of >2 active stations, worker termites collected from a station with high activity (>1,000 termites) were fed filter paper disks (Whatman No. 1, 5.5 cm) stained with 0.05% (wt/wt) Nile Blue A [9] for 3 days before being released back into the same station. In areas suspected of having multiple colonies, Neutral Red (0.05% wt/wt) was used for marking. One month after the release, stations nearby were examined for the presence of marked termites. The foraging range of a colony, defined as the area encompassed by interconnected stations, was determined by the presence of marked termites. Feeding blocks in the monitoring stations were collected every 1 or 2 months to measure the wood consumption rate of termites (gram of wood consumed per station per day), which represented the foraging activity of the colony.

2.2.2. Aboveground monitoring stations (AM)

Because soil was not always accessible in many sites, aboveground monitoring stations similar to those described by Su et al. [10] were used to measure the termite activity in some sites (Fig. 7B). The station was composed of a plastic box (12 by 15.5 by 4.5 cm) containing a pre-weighed wooden block (*Picea* sp., 2 pieces [each 9 by 3 by 2 cm and 8 by 5 by 2 cm] nailed together with a wooden handle [8.5 by 3 by 2 cm]) and was attached directly over foraging tubes so that termites could access the wooden block through a precut hole on the plastic container. A thermal insulation layer made of closed-cell polyethylene foam (21.5 by 25 by 0.3 cm) was attached over the station using Velcro tape for easy detachment. Aboveground monitoring stations were used in places with live foraging tubes, including the living quarters and the utility room in San Cristóbal, and Casemate 19 in El Morro.

2.2.3. Acoustic emission detector

An acoustic emission detector similar to that described by Scheffrahn et al. [11] was used to monitor termite activity in wooden shelves of the utility room of Plaza de Armas of San Cristóbal, and in wooden frames of the cistern entrance in Casemate 19 in El Morro. The detector unit consisted of a main processor compartment (10 by 19 by 3 cm) connected by coaxial cables to two resonant acoustic emission sensors with integral amplifiers. The detector recorded sound waves of ultrasonic frequency (>20 kHz) that were generated when wooden fibers were broken by termite mandibles. Using the detector, termite-feeding episodes were recorded along longitudinally oriented wood grain up to 80 cm [11].

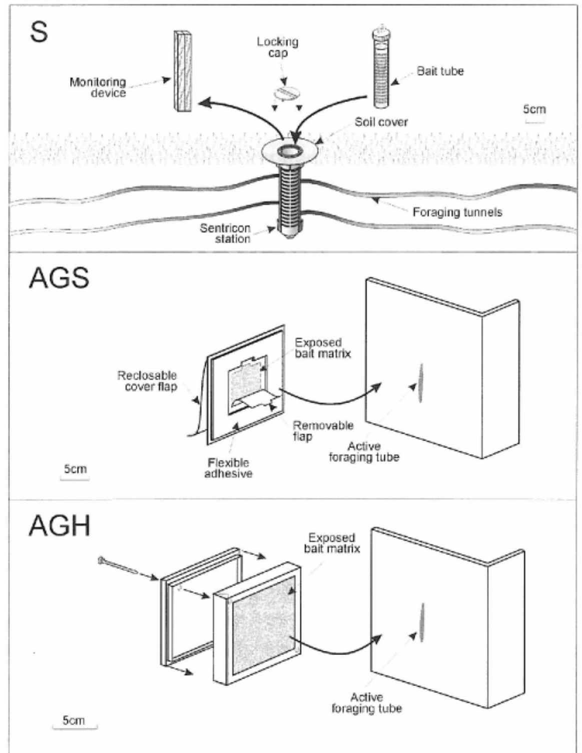


Figure 8: Baits containing 0.5% hexaflumuron were applied using in-ground Sentricon® stations (S), soft-style aboveground bait stations (AGS), or hard-style aboveground bait stations (AGH).

2.3. Applications of baits containing hexaflumuron

Three types of bait stations were used to deliver hexaflumuron baits to populations of subterranean termites; in-ground Sentricon® stations (S), soft-style aboveground bait stations (AGS), and hard-style aboveground bait stations (AGH).

2.3.1. In-ground Sentricon® station (S)

The Sentricon® station was composed of a plastic tube (4 cm inner diameter by 24 cm long) with rectangular holes on the tube surface to provide termite entry from soil (Fig. 8, S). The station was inserted into a pre-drilled hole in soil with the soil cover (15-cm diameter) extending on the surface. A monitoring device (two pieces of 1.4 by 2.8 by 21-cm wooden slats) was placed in the station and was inspected monthly or bi-monthly to examine termite activity. When termites were found in the station, the monitoring device was replaced by a bait tube (Recruit® II) containing 20-g of 0.5 % hexaflumuron bait. Bait tubes that were substantially consumed (>50% by visual estimate) by termites were replaced with new tubes.

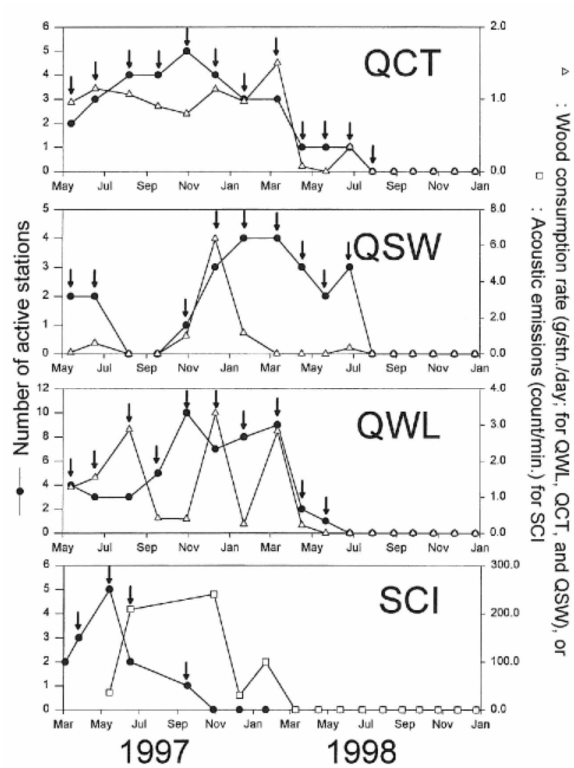


Figure 9: Termite activities, expressed by the number of both monitoring and baiting stations with live termites (black circles), wood consumption rates (open triangles), and acoustic emission counts (open squares) for three colonies of Heterotermes sp. (QSW, QCT, and QWL) in the living quarters, and one colony of C. havilandi (SCI) in an utility room of the Plaza de Armas of San Cristóbal. Arrows depict applications of baits containing 0.5% hexaflumuron.

2.3.2. Soft-style aboveground bait station (AGS)

The AGS consisted of a flexible plastic pouch (15 by 15 by 0.5 cm) containing 15 g of 0.5% hexaflumuron bait. On one side of the station was reclosable cover flap and on the other side was a removable flap (7 by 7 cm) surrounded by a 3.5-cm wide collar of flexible adhesive (Fig. 8, AGS). The bait matrix was first moistened with 30 - 40 cc water before the removable flap was pulled to expose the bait matrix and attached over the active infestation using the flexible adhesive so that it was accessible to foraging termites. The station was inspected monthly or bi-monthly. When bait was substantially consumed, the reclosable outer cover flap was removed, and another soft station was stacked over the old station so that additional bait was available to termites. AGSs were used to intercept the foraging tubes of *Heterotermes* sp. on the walls of the living quarters in San Cristóbal, and those of *C. havilandi* on the walls and floors of Casemate 19 in El Morro.

2.3.3. Hard-style aboveground bait station (AGH)

The AGH consisted of a plastic box (10 by 10 by 4 cm) containing 25 g of 0.5% hexaflumuron bait. The front side of the box was protected by a removable cover, and the other side was laid open to expose the bait matrix (Fig. 8, AGH). After moistening the exposed bait matrix with 30 - 40 cc water, the bait box was attached over an active infestation using hot glue so that the exposed bait was accessible to foraging termites. AGHs were placed on the infested shelves of the utility room of Plaza of San Cristóbal, and on the floors of Casemate 19 in El Morro to intercept live foraging tubes. The station was inspected monthly or bi-monthly by removing the front cover. When needed, another bait box was stacked over the old station so that additional bait was available to termites.

All bait stations were removed at the conclusion of bait application when termite activity ceased. The partially consumed baits were cleaned of soil debris, dried at 60 °C for 48 hr and cooled in a desiccator before re-weighing to determine bait consumption by termites.

3. Results and Discussion

3.1. Living Quarters, San Cristóbal

Termites did not enter any of the aboveground monitoring stations placed over the foraging tubes of the *Heterotermes* sp. on the walls of the living quarters, and the acoustic emission device did not detect feeding activity in the wooden members of these rooms. A stake survey detected soil activity of *Heterotermes* sp. in the courtyard, and subsequent mark-recapture using Nile Blue A and Neutral Red revealed the presence of 2 colonies, one near the center of the courtyard (QCT), and the other near the wall on the west side of the courtyard (QSW) (Fig. 2). Wooden stakes placed in the lawn between the living quarter and the fortress south walls also detected activity of *Heterotermes* sp., and the mark-recapture study using Nile Blue A indicated a colony (QWL) with a foraging distance of ≈20 m (Fig. 2). Despite being near the activity of *C. havilandi* in the fortress (SCI), stakes that had been placed in the lawn near the south walls did not detect any termite activity.

By May 1997, the monitoring device in an in-ground Sentricon® station was infested with termites from colony QCT and was replaced with a bait tube. More stations were attacked by QCT and additional baits were added during the following months, but termite activity remained the same (wood consumption rate: ≈1 - 1.5 g wood per station per day) throughout 1997 and the spring of 1998 (Fig. 9).

Table 1

Summary of bait application to control populations of *C. havilandi* (C) and *Heterotermes* sp. (H) at the San Cristóbal (QCT, QSW, QWL, and SCI) and El Morro (MORO1, MORO2, MORO3), San Juan National Historic Site

Colony	Sp.	Bait type [a]	No. of bait tube used	No. of AG station used	Bait matrix consumed (g)	AI consumed (mg)	Months baited
QCT	H	S	11	-	9.6	48.0	15
QSW	H	AGS, S	7	3	68.0	340.0	14
QWL	H	S	21	-	136.0	680.0	13
SCI	C	AGH	-	7	54.5	272.5	4
MORO1	C	AGS, AGH	-	7	20.0	100.0	8
MORO2	C	S	2	-	0	0	2
MORO3	H	S	26	-	299.0	1495.0	15

[a] S: in-ground Sentricon® station; AGS: soft-style aboveground bait station; AGH: hard-style aboveground bait station

In April 1998, 11 months after baiting was initiated, termite activity declined drastically, and only a small number of termites were found in one monitoring station. Baits were left in some Sentricon® stations May - July 1998, but no further feeding was recorded. During the 15-month baiting period, colony QCT consumed 9.6 g bait matrix from 11 Recruit® II, totaling 48 mg of hexaflumuron uptake by this colony (Table 1). Since July 1998, no termites have been found in any of the stations for colony QCT.

Following the consumption of a small amount of bait from one AGS between May and July 1997, activity of colony QSW ceased in August but reappeared in November (Fig. 9). Between November and December 1997, a strong recurrence of termite activity was recorded from the underground monitoring station (≈6 g wood per station per day) for colony QSW, and more baits were applied through both in-ground Sentricon® stations and soft-style aboveground bait stations (AGS). In January 1998, termite activity in the underground monitoring station declined sharply, but termites continued to feed on hexaflumuron baits through July 1998 (Fig. 9). By August 1998, termite activity ceased in all stations. We concluded that after consuming 68 g baits (340 mg hexaflumuron) from 7 AGS and 3 Sentricon® stations in 14 months, colony QSW was eliminated (Table 1).

Of the 8 Sentricon® stations placed in the lawn near the fortress walls, 3 were infested by colony QWL in May 1997, and Recruit® II were applied in these stations. More Sentricon® stations were placed near infested stations, and additional baits were added, but termites remained active in both underground monitoring stations and Sentricon® stations through March 1998. In April 1998 activity declined suddenly, and no termite or termite activity has been recorded since July 1998. We believe that colony QWL was eliminated after consuming 136 g bait matrix from 21 bait tubes during the 13-month baiting period.

3.2. Utility room of the Plaza, San Cristóbal

During the initial inspection on January 1997, acoustic emission (AE) counts taken from 11 spots on the shelves of the utility room facing the main plaza ranged between 6 - 255 counts per minute, indicating up to 255 feeding incidents per minute occurred in some portion of the shelves. Two aboveground monitoring stations (Fig. 3, AM) containing untreated wooden blocks were installed over foraging tubes, and were immediately infested by this *C. havilandi* colony (SCI) by March 1997 (Fig. 9). Two hard-style aboveground bait stations (AGH) that were placed over the foraging tubes in March were also extensively fed upon by colony SCI, and by May additional AGHs were stacked upon the infested stations (Fig. 2, AGH). Termite activity in AMs and AGHs began to decline May - November 1997, but AE counts remained high during this period (Fig. 9). Slight feeding on hexaflumuron baits continued in July and August, during which *C. havilandi* found in bait stations exhibited apparent symptoms of hexaflumuron effects such as marbled coloration on the worker's abdomen. By November 1997, no termite activity was recorded from any of the stations, and the AE counts also declined and reached zero in March 1998. The monthly follow-up inspection thus far revealed no termite activity for SCI. It took 4-month of baiting, during which 54.5 g bait was consumed from 7 AGHs, to eliminate this *C. havilandi* colony.

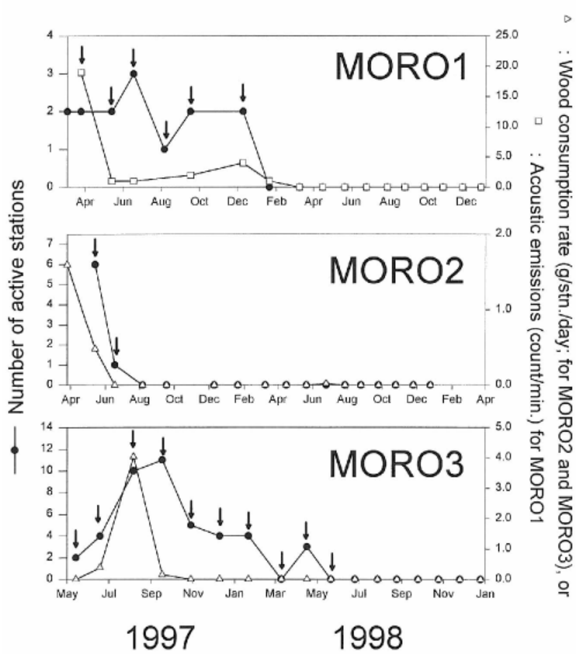


Figure 10: Termite activities, expressed by the number of both monitoring and baiting stations with live termites (black circles), wood consumption rates (open triangles), and acoustic emission counts (open squares) for two populations of C. havilandi (MORO1 and MORO2) and one population of Heterotermes sp. (MORO3) surrounding the Plaza de Armas of El Morro. Arrows depict applications of baits containing 0.5% hexaflumuron.

3.3. El Morro

Feeding activity of *C. havilandi* in the wooden frames of the cistern entrance in Casemate 19 was evident based on acoustic emissions of up to 22 counts per minute recorded in January 1997. Two aboveground monitoring stations (AM) that were installed over the foraging tubes on the walls were immediately infested with *C. havilandi*, and the mark-recapture procedure confirmed all termites in Casemate 19 belong to the same colony, MORO1. Wooden stakes placed in soil on the roof across the Plaza from Casemate 19 were also infested with *C. havilandi*, but marked termites released in Casemate 19 were not recaptured in any of the underground monitoring stations on the roof. The *C. havilandi* population on the dirt-filled roof across the Plaza from Casemate 19 was referred to as colony MORO2 (Fig. 4).

Following the bait application using both soft- and hard-style aboveground bait stations (AGS and AGH) in Casemate 19 in April 1997, the acoustic emission count declined in May, but termite feeding in AGS and AGH continued through January 1998 (Fig. 10). By February 1998, no termites were found in any of the bait stations and the acoustic emission counts in the wooden frames of the cistern entrance dropped to zero in May. During the 8-month baiting, MORO1 consumed 20 g bait from 7 aboveground bait stations.

Two underground monitoring stations placed in the dirt-filled roof were heavily damaged by MORO2 by April 1997 (wood consumption rate: 6 g per station per day), and baits were placed in 4 infested Sentricon® stations in May (Fig. 4), but feeding in these stations was so minimal that bait consumption could not be properly measured (Fig. 10). Despite the lack of bait consumption, *C. havilandi* activity in the underground monitoring stations declined to zero in June with only a small number of termites found in one Sentricon® station. Since August 1997, no termites have been detected from the area previously occupied by MORO2. Because activity of MORO2 vanished without consuming a noticeable amount of bait applied in the Sentricon® stations, we suspect that MORO2 may be part of MORO1 that consumed baits from 7 aboveground bait stations. The mark-recapture procedure did not connect MORO1 with MORO2, but there was a likelihood of linkage between these two populations at the cistern beneath the plaza due to their water requirement.

The stake survey conducted in the spring of 1997 also yielded a *Heterotermes* sp. population (MORO3) on the dirt-filled roof west of MORO2 (Fig. 4). Termites of MORO3 did not enter the underground monitoring station in May 1997, but they infested 2 Sentricon® stations (Fig. 10). Feeding on baits in the Sentricon® stations was intense and more stations were added to MORO3 during the following months. Despite the extensive bait consumption, activity of MORO3 increased from June – August (wood consumption rate: 4 g wood per station per day) in the monitoring station, and by October 1997 this *Heterotermes* colony was feeding on the hexaflumuron baits from 10 Sentricon® stations. Gradually, the activity declined and by November 1997 no termite was found in the monitoring station even though termites were still in the bait stations (Fig. 10). Feeding of baits in Sentricon® stations remained until March 1998. During our monthly visit in April 1998, a small number of *Heterotermes* sp. were found in 2 Sentricon® stations, but all termites exhibited marbled coloration, which is the secondary symptom of hexaflumuron effects. Since May 1998, no termite has been found from MORO3. We believe MORO3 was probably eliminated after consuming 299 g bait (1.495 g hexaflumuron) from 26 bait tubes during the 15-month period (Table 1).

4. Conclusion

It took substantially longer to eliminate colonies of the *Heterotermes* sp. (13 - 15 months) than *C. havilandi* (2 - 8 months) at the San Juan Historic Site. Similar results were recorded when hexaflumuron baits were used to eliminate *C. havilandi* colonies in Little Cayman (3 - 5 months) [12], and in South Florida (5 months) [13]. In another project using hexaflumuron baits to control populations of *Heterotermes* sp. in Fort Christiansvaern,

Christianstead National Historic Site, U.S. Virgin Islands, it took 4 - 31 months to reach a complete control (N.-Y. Su, unpublished data). *Coptotermes* spp., especially those in the tropics, appeared to respond faster to hexaflumuron than termite species in temperate regions. For example, colonies of the subterranean termite, *C. curvignathus* Holmgren, were eliminated 25 – 44 days after baiting with hexaflumuron in Malaysia [14]. We speculated that the difference may be due to the constant activity of these tropical species in association with the high year-round temperature in these regions [13], but this does not explain why it took longer to control *Heterotermes* sp. in the tropical West Indies. It could be that *Heterotermes* sp. colonies are small and rather fragmented, and the prolonged baiting period is the results of baiting multiple independent colonies.

Baits containing hexaflumuron were used to control subterranean termite populations in several historic sites [4], [5], [6], and the results have been successful. Since October 1997 when *R. flavipes* populations were eliminated by hexaflumuron baits from the Statute of Liberty National Monument, the site has been monitored quarterly, and thus far no termite activity has been detected on Liberty Island. San Juan Historic Site, however, is much larger than any of the historic sites where we have conducted control projects, and unlike the Statute of Liberty National Monument, it is in the tropics that is heavily populated with termites. All of the detected populations of *C. havilandi* and *Heterotermes* sp. were eliminated from the San Juan Historic Site. However, due to the size of this site, there are probably many more termite populations. As evidenced by the old foraging tubes on the walls of underground tunnels in San Cristóbal (Fig. 1), *Heterotermes* sp. is endemic to the island, and probably has been present at the site since the first fortress structure was erected. Our suspicion of more undetected termite populations was confirmed in July 1999 when we made an unscheduled site visit and found new and live foraging tubes of *C. havilandi* on the wooden frames of the cistern entrance in Casemate 19 of El Morro. Because it is nearly impossible to detect all termite populations in a large property such as the San Juan Historic Site, a routine monitoring program conducted by Park Service personnel is the key for early detection so that baits can be applied to eliminate the detectable populations before severe and irreversible damage occurs to this historic site.

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