Protecting Historic Properties from Subterranean Termites:

a Case Study With Fort Christiansvaern, Christiansted National Historic Site, United States Virgin Islands

A look at the economic impact of termite pests and its association with the values of structures they damage; also the insecticides and management technology used to control termite populations.

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Of the 50 termite species found in the United States, less than seven species are considered serious pests, but their economic importance is significant (Su and Scheffrahn 1990). Based on the insecticide sales figures and the expense ratio of pesticide cost to the control cost, the total amount spent by the consumers for subterranean termite control in the United States (excluding repair costs) was estimated at $2.2 billion annually in 1999 (Su 2002). The economic impact of termite pests is closely associated with the values of structures they damage. In the United States and Japan, for example, the presence of a single destructive species such as the Formosan subterranean termite, *Coptotermes formosanus* Shiraki, can sustain a multimillion-dollar termite control industry because the control cost easily surpasses the value of a house and damage potential by termites.

Historic structures are particularly vulnerable to subterranean termite damage given the traditional use of wood as a building material. Financial costs alone, however, do not account for losses caused by termites when they damage historic properties. Termite damage to historic buildings is irreversible and can diminish the historic significance of the structure through the loss of original materials.

Subterranean Termite Control

For the past half century, subterranean termite control has relied heavily on the use of organic insecticides to provide a barrier to exclude soil-borne termites from a structure. Typically, large volumes of liquid insecticide are applied to the soil beneath and surrounding an infested building. Creating an uninterrupted barrier of treated soil beneath a structure is extremely difficult, and gaps in the barrier invariably allow termite access. Conventional soil treatments may require drilling the foundation floor before liquid insecticides are injected into the subfoundation soil, an unacceptable practice for many historical buildings.

As an alternative to insecticide barriers, baiting technologies have been tested since the 1960s to control populations of subterranean termites (Esenther and Gray 1968). Effects of baiting on colony populations in most of the earlier field trial studies, however, were not adequately assessed because of the hidden foraging galleries of these species (Beard 1974; Esenther and Beal 1974, 1978; Ostaff and Gray 1975). One breakthrough for field evaluation of population management techniques against subterranean termites was reached by Lai (1977) who used a dye marker to identify colony affiliation of termites found in monitoring stations developed by Tamashiro et al. (1973). During field trials with fungal pathogens, Lai (1977) observed the disappearance of termites only from the fungi-release station but not from the nearby stations. By releasing termites marked with Sudan Red 7B, he confirmed the interconnection of several stations and revealed the repellency of fungal control

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agents by showing that termites avoided the fungi-treated stations (Lai et al. 1983).

Following Lai's lead, field evaluations with slow-acting baits adopted dye markers to define foraging ranges of subterranean termite colonies before bait applications (Su 1994; Su et al. 1991, 1995a). In early 1990s, Su (1994) confirmed the elimination of field colonies of subterranean termites by applications of baits containing the insect growth regulator, hexaflumuron. Thus far, 33 studies have documented elimination of at least 152 of 159 (96%) baited colonies or populations including 13 species of subterranean termites in 14 states of the United States, and in Australia, Japan, France, the United Kingdom, Italy, Cayman Islands, and Malaysia (Su 2003). Most of these field studies applied baits in interconnected stations (as confirmed by the presence of marked termites) and measured the effects in untreated stations, as originally described by Lai (1977). Results of these field studies formed the basis to support the efficacy claims of hexaflumuron baits, commercially known as the Sentricon Termite Colony Elimination System (Dow AgroSciences, Indianapolis).

Monitoring–Baiting Procedure and Historic Sites

The Sentricon system uses a cyclical process of monitoring and baiting for termite activity. Initially, stations containing monitoring devices are installed in the soil surrounding a structure. When termite activity is discovered in a station, the monitoring device is replaced with bait containing hexaflumuron. The hexaflumuron is distributed throughout the colony by foraging termites that feed on the baits. Control takes several months to achieve, but the end result is complete elimination. Once the colony is eliminated, monitoring continues to detect new subterranean colony incursion. Because hexaflumuron-containing baits are not used until termites are found, ≈1 g of hexaflumuron is sufficient to eliminate a colony of subterranean termite (Su 1994)—a drastic reduction of pesticide use compared with conventional soil insecticide barrier techniques for subterranean termite control.

The safety and nondisruptive features of the monitoring–baiting procedure have attracted a great deal of attention from property managers of environmentally and culturally sensitive historic sites. Under the support of the National Center for Preservation Technologies and Training (NCPTT) of the National Park Service, hexaflumuron baits have been used to control subterranean termite infestations in such historic sites as the Statue of Liberty National Monument (Su et al. 1998), the historic Cabildo Complex of French Quarter, New Orleans (Su et al. 2000), San Juan National Historic Site (Su et al. 2002), Cane River Creole National Historical Park, and New Orleans Jazz National Historical Park (Freytag et al. 2000). These trials are a joint effort by NCPTT, University of Florida, New Orleans Mosquito and Termite Control Board, and Dow AgroSciences to advance our knowledge of subterranean termite control in historic structures. In this article, we highlight a project to manage the populations of subterranean termites (*Heterotermes* sp.) in Fort Christiansvaern, Christiansted National Historic Site, St. Croix, U.S.Virgin Islands.

St. Croix, Christiansted, and Fort Christiansvaern

After being possessed by a succession of European powers including Spain, England, Holland, France, and the Knights of Malta between 1493 and the late 1600s, St. Croix was purchased by Denmark from France in 1733 (Lewisohn 1964). Officials and colonists came ashore at the site of a former village on the north-central coast called "Bassin" (the harbor). The Danes found a square-sided earthwork fortification, probably dating from the 1670s, which they rearmed and occupied. It became the cornerstone of the new town, Christiansted, named in honor of King Christian VI of Denmark and Norway. When this primitive structure was severely damaged by the storm surge from a 1738 hurricane, the Danish government

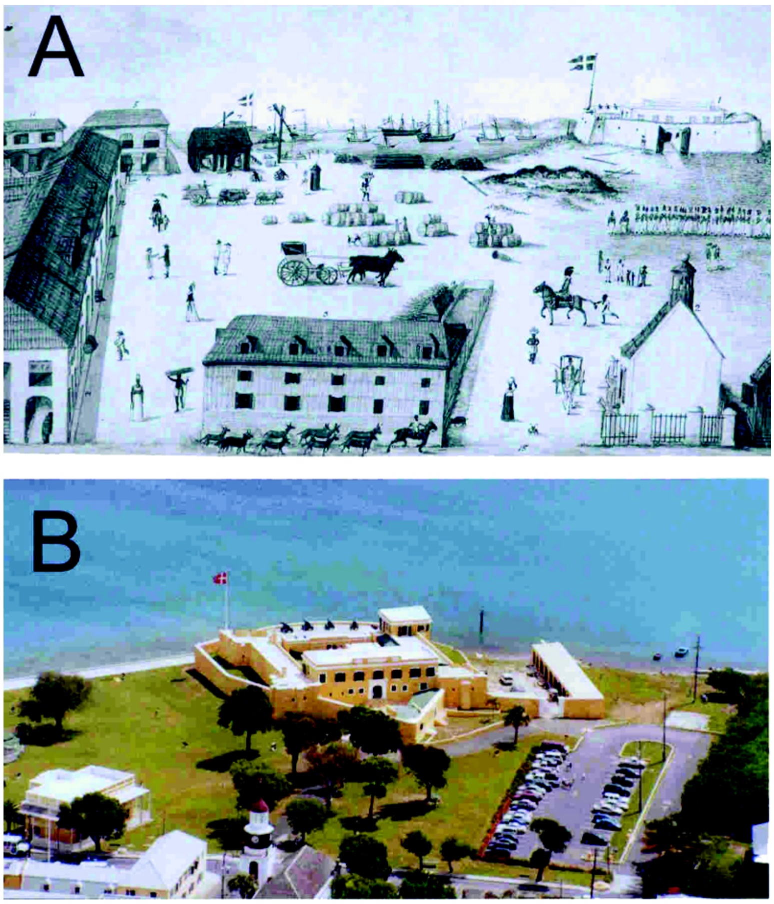

Fig. 1. 1815 watercolor entitled "The Wharf of St. Croix," with Fort Christiansvaern on the upper right corner (A), and an aerial view of the present day Fort Christiansvaern (B). The Steeple Building (A, lower right) and part of a town house (A, lower middle) are recognized landmarks of present-day downtown Christiansted (B). Courtesy of Rigsarkivet, Copenhagen by way of Christiansted National Historic Site, National Park Service, U.S. Department of Interior.

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replaced it with a masonry fort of standard European design on the same site (Fig. 1). Construction of the new fort spanned 1738–1749. Principally built of yellow Flensborg brick (Greene and Cissel 1988), the fort is a typical example of 17–18th century Danish military architecture. The fort was named Christiansvaern ("Christian's Defense").

Fort Christiansvaern was intended to serve a dual military role: to protect commercial shipping in the harbor from attack by pirates or privateers and to quarter troops as a deterrent to slave insurrections (Greene and Cissel 1988). The fort served other functions, notably that of jail for the town and the plantations within its jurisdiction. It was in Fort Christiansvaern that one Rachel Faucett Lawien was incarcerated for several months in 1749 for having abandoned her Danish husband. She later bore two sons out of wedlock to a struggling Scottish merchant on her home island of Nevis. The younger of the two boys was Alexander Hamilton, who lived in Christiansted between the ages of 9 and 17 before being sent to British North America to continue his education and a destiny with greatness.

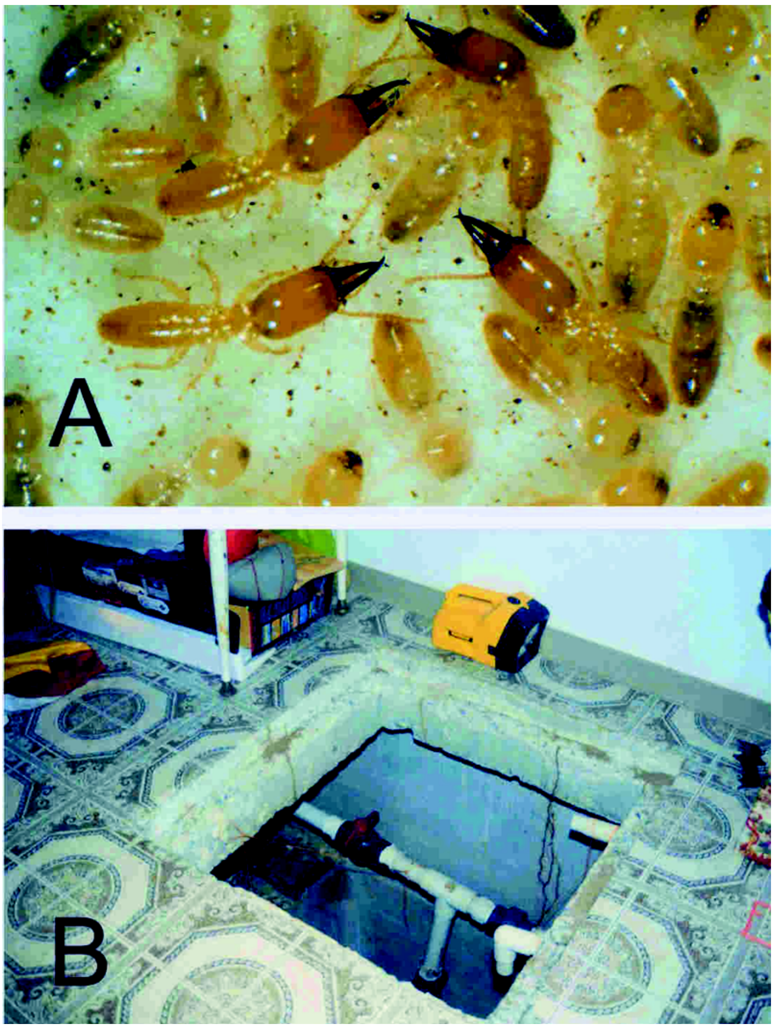

Fig. 2. *Heterotermes* sp. is the most economically important subterranean termite species on St. Croix (A). Their foraging tubes are often found extending into cisterns that provide drinking water for many households on the island (B).

Termites of St. Croix

A recent termite survey in St. Croix revealed 11 species from nine genera. Nine species are endemic to the West Indies (R.H.S., unpublished data). Of these, three drywood species: *Cryptotermes brevis* (Walker), *Cr. havilandi* (Sjöstedt), and *Incisitermes incisus* (Silverstri); the subterranean species, *Heterotermes* sp.; and two arboreal species: *Nasutitermes acajutlae* (Holmgren) and *N. costalis* (Holmgren), are considered serious pests to structures on the island.

The literature reports that two endemic species of *Heterotermes*, *H. convexinotatus* Snyder, and *H. tenuis* (Hagen), are present throughout the West Indies. Thus far, they are morphologically indistinguishable (Scheffrahn et al. 1994), and we refer to them as the *Heterotermes* sp. in this article (Fig. 2A). The thin (≈1–2 mm wide) foraging tubes of *Heterotermes* sp. are relatively nonbranching and are often found reaching down into cisterns that provide drinking water for households on the island (Fig. 2B).

Foraging tubes of *Nasutitermes* spp. are wider (≈5–10 mm) and are found on tree trunks throughout the islands. These species construct arboreal nests on trees, but they can enter structures from soil. They often enter structures of less traffic, such as abandoned houses, storage rooms, or vacation homes that are unoccupied most of the time.

Termite Infestations in Fort Christiansvaern

Being in the tropics with an abundance of termite species, it is likely that Fort Christiansvaern was subjected to termite infestation soon after it was erected in 1749. With the exception of hurricanes, the Danish colonial records seldom specified the cause for the periodic replacement of woodwork, particularly window- and doorframes, shutters, and doors. Fungal decay and subterranean and drywood termites are probable sources of damage. Only one passing reference has been found to termites in a survey of 18th century and early 19th century publications about St. Croix (W. F. Cissel, St. Croix National Park Group historian, personal communication). The Moravian Church historian C. G. A. Oldendorp (1777), who lived on St. Croix from 1767 to1769, attested that "the Kackerlacke [cockroach] and the wood lice [the West Indian colloquialism for termite], along with some varieties of ants, cause the greatest damage."

The Danish planter R. Haagensen (1754), describing conditions on St. Croix ca. 1754, noted "the construction of the fort…has been laid out in such a way that there is always a good supply of water. Under the walls of the fort there are two good freshwater springs which provide some 300 *toender* [an archaic Scandinavian system of liquid measure] of water; this water is consumed in part by the garrison and the others living there and in part by residents of the town, where there is a lack of water." Although this aquifer has long since ceased to be productive, primarily because of drier climate patterns, it may have contributed to the persistent termite infestations in Fort

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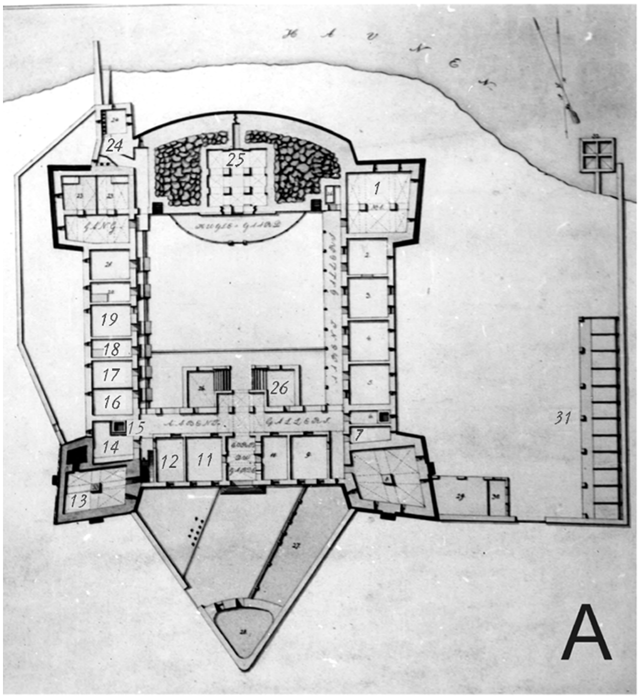

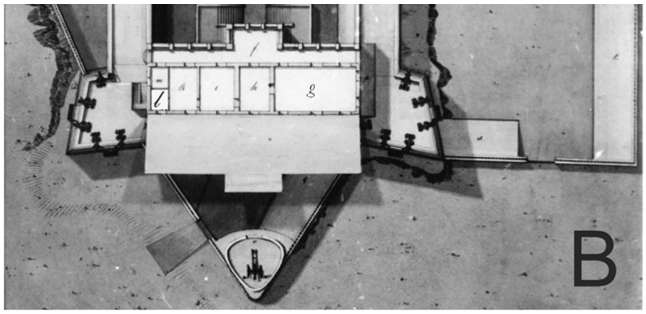

Fig. 3. Floor plan for Fort Christiansvaern dated 1836. First floor (A): 1, Arsenal; 7, passage to stable yard; 11, Guard Room; 12, second Commandant's Servant Room; 13, Soldier's Barracks; 14, Officer's Kitchen; 15, western Cistern Hatch; 16, Commandant's Servant Room; 17, Barracks for 4 Men; 18, Non-commissioned Officer's Cell; 19: Officer's Cell; 2, Officer's Latrine; 25, Gunpowder Magazine; 26, Detention Cell; 31, Stables. Second Floor (B): *g*: Reception Hall, *l*: Closet. For labeling purposes, the original letter and numerical designations for rooms mentioned in this article were digitally enhanced and enlarged. Names describing the historic use of each room are capitalized.

Christiansvaern so familiar to the National Park Service (W. F. Cissel, personal communication).

During a refurnishing project in the early 1990s, foraging tubes of *Heterotermes* sp. and damaged wood were found by park personnel in several rooms of the fort (Fig. 3) including the Arsenal (1) beneath the northeast bastion, the Dungeon beneath the Soldier's Barracks in the southwest bastion (13), Officer's Kitchen (14) above the cistern, the western Cistern Hatch (15), Commandant's Servant Room (16), 4-Men Barracks (17), Non-commissioned Officer's Cell (18), Gunpowder Magazine (25) beneath the Water Battery, and a Detention Cell (26) beneath the stairway facing the courtyard (Hillis 1991).

Our site inspection in the spring of 1994 did not uncover termite activity in the Dungeon and the Kitchen room, but live foraging tubes were found on the rafters of the 4-Men Barracks and the Non-commissioned Officer's Cell (3A-17 and 18), and on the masonry walls and floors of the Gunpowder Magazine and Arsenal (3A-25 and 1). Characteristic to *Heterotermes* sp., the thin and nonbranching tubes often suspended from the wooden rafters on the ceiling (Fig. 4A). Although the walls of the Gunpowder Magazine and Arsenal floors are made of bricks, termites appeared to tunnel through the mortar joints and the rubble fill between them (Fig. 4B). New foraging tubes were also found on the ceilings of the Guard Room (3A-11), the Closet (3B-*l*), and the Reception Hall (3B-*g*) on the second floor Commandant's Quarters above the Guard Room; the door frame leading into the Dungeon below a narrow passageway between the Officer's Kitchen (3A-14) and a second Commandant's Servant Room (3A-12); and the rafters of the passageway to the stable yard (3A-7). Numerous foraging tubes also were found on the walls and rafters of the Stable building east of the fort (3A-31).

Monitoring Termite Activities

We used aboveground monitoring stations (AGM) similar to those described by Su et al. (1996) to measure the termite activity at some sites (Fig.

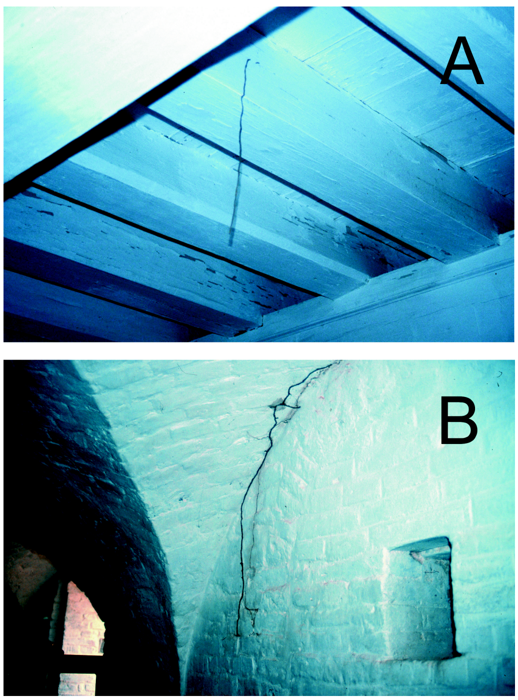

Fig. 4. Characteristic to *Heterotermes* sp., the thin and nonbranching foraging tubes often hang freely from the wooden beams on the ceiling (A). Although the walls and some floors of the fort are made of brick, termites appeared to tunnel through the mortar joints (B).

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5A). The stations were designed to be as unobtrusive as possible, blending in with the historic color schemes. Each station was composed of a plastic box (12 × 15.5 × 4.5 cm) containing a wooden block (*Picea* sp., two pieces [each 9 × 3 × 2 cm and 8 × 5 × 2 cm] nailed together with a wooden handle [8.5 × 3 × 2 cm]); the box 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 × 25 × 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 or with termite feeding activity as detected by the acoustic emission detector (Scheffrahn et al. 1993).

In addition to monitoring within-structure activity of *Heterotermes* sp., we used wooden (*Picea* sp.) stakes (2 × 3 × 30 cm), driven into the soil at an interval of ≈5 m near the foundation walls of the fort to monitor in-ground activity. Infested stakes were replaced with underground monitoring stations (plastic collars, 17 cm diam and 15 cm high) containing feeding blocks (six spruce boards [7 × 13 × 2 cm] nailed together) as described by Su and Scheffrahn (1986) (Fig. 5B).

Bait Applications

Three kinds of bait stations were used to deliver cellulose-based baits containing 0.5% hexaflumuron to *Heterotermes* sp. populations, soft-style aboveground bait stations (AGS), hard-style aboveground bait stations (AGH), and in-ground Sentricon stations.

The AGS consisted of a flexible plastic pouch (15 × 15 × 0.5 cm) containing hexaflumuron bait (Su et al. 1998). On one side of the station was a reclosable cover flap, and on the other side was a removable flap (7 × 7 cm) surrounded by a 3.5-cm wide collar of flexible adhesive (Fig. 5A, C). The bait matrix was moistened with water before the removable flap was pulled up to expose the bait matrix, and the station was attached over the active infestation using the flexible adhesive so that it was accessible to foraging termites. The station was inspected monthly or bimonthly. 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.

The AGH consisted of a plastic box (10 × 10 × 4 cm) containing hexaflumuron bait (Su et al. 1998). 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. 5D). After moistening the exposed bait matrix with 30–40 ml water, the bait box was attached over an active infestation using hot glue so that the exposed bait was accessible to foraging termites but sealed off from moisture loss and air movement. The station was inspected monthly or bimonthly by removing the front cover. When needed, another bait box was stacked over the old station so that additional bait was available to termites. The bait matrix was

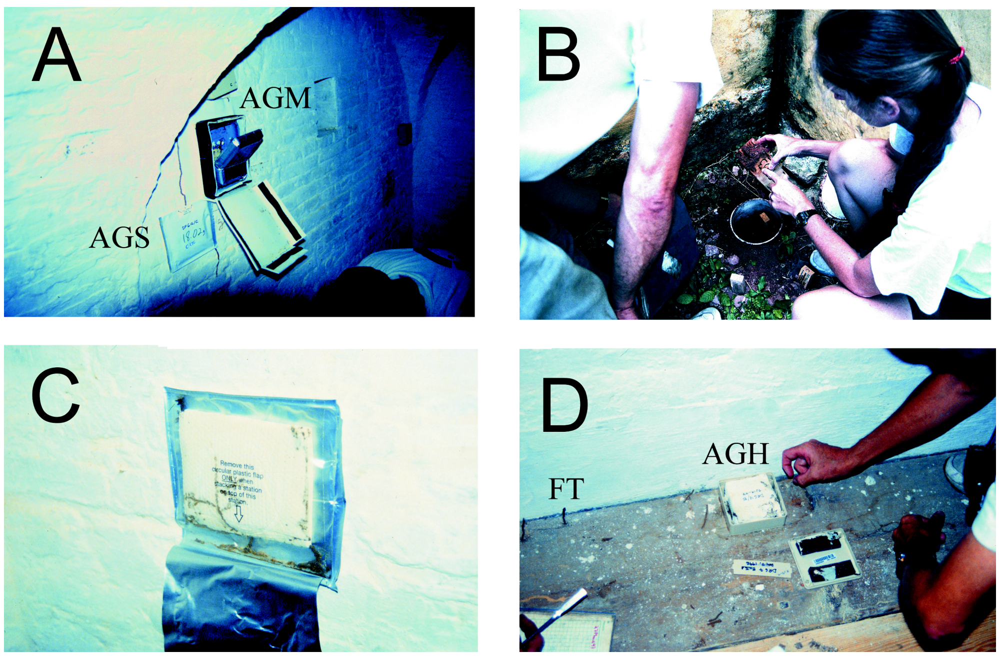

Fig. 5. Aboveground monitoring stations (AGM) composed of a plastic box containing a wooden block were attached directly over foraging tubes to monitor within-structure activity of *Heterotermes* sp. (A); underground monitoring stations were placed in soil surrounding the exterior walls of the fort to monitor in-ground activity (B). The soft-style aboveground bait station (AGS) consisted of a flexible plastic pouch containing hexaflumuron bait and was attached over the active infestation (A) so that termites readily entered the AGS to consume bait (C). The hard-style aboveground hard station (AGH) consisted of a plastic box containing hexaflumuron bait and was attached over an active foraging tube (FT) using hot glue so that the exposed bait was accessible to termites (D).

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moistened as needed. AGHs were used on flat surfaces.

Subterranean baiting consisted of commercial Sentricon stations. The Sentricon station was composed of a plastic tube (4 cm i.d. × 24 cm long) with rectangular holes on the tube surface to allow termite entry from soil (Su et al. 1995b). The station was inserted into a predrilled hole in soil with the soil cover (15-cm diam) extending on the surface. A monitoring device (two pieces of 1.4 × 2.8 × 21-cm wooden slats) was placed in the station and was inspected monthly or bimonthly to examine termite activity. When termites were found in the station, the monitoring device was replaced by a bait tube (Recruit II, Dow AgroSciences) containing 20 g of hexaflumuron bait. Bait tubes that were substantially consumed (>50% by visual estimate) by termites were replaced with new tubes.

At the conclusion of bait application when termite activity had ceased for at least two consecutive monitoring periods (Anonymous 1999), all bait stations (aboveground and in-ground baits) were removed. The partially consumed baits were cleaned of soil debris, dried at 60 °C for 48 hr, and cooled in a desiccator before reweighing to determine bait consumption by termites. A baiting period was defined as the time (months) during which termite activity was observed in the presence of baits.

Quantifying Termite Activity

In previous studies involving *Co. formosanus* or *Reticulitermes* spp., feeding blocks were collected monthly or bimonthly from monitoring stations for measuring wood consumption rates to represent termite activity (Su et al. 1991, Su 1994). At Fort Christiansvaern, however, frequent replacement of feeding blocks in the stations deterred *Heterotermes* sp. from returning. Moreover, feeding by *Heterotermes* sp. was not as extensive as *Co. formosanus* or *Reticulitermes* spp., so feeding blocks were often left in the stations for several months before they were substantially consumed and needed to be replaced. Because wood consumption rates were not measured regularly, we used the number of stations (monitoring stations and bait stations) with termite activity instead of the wood consumption to represent *Heterotermes* sp. activity in the fort. The presence of termites, new signs of feedings, foraging tubes in the stations, and newly infested wooden stakes were considered "active." Active foraging tubes on the walls of floors were also recorded and removed during each visit (Fig. 4A, B). Rebuilt foraging tubes appearing in subsequent visits were recorded as the "active loci." The total number of active loci, including the number of active stations, stakes, and active or new foraging tubes was used to represent the overall termite activity.

Results and Discussion

Between 1996 and 1998, we identified several clusters of termite activity throughout the fort and the stable on the east (Fig. 6). In previous field evaluation studies with baits, subterranean termite colonies were characterized by using the mark–recapture procedure to identify the interconnections between stations (Su 2003). Because our objective was to control the *Heterotermes* sp. populations rather than to evaluate bait efficacy, we did not identify the number of colonies or station interconnections at each activity cluster of the fort. Instead, the activity clusters were grouped into nine zones on the basis of their immediate proximity (Fig. 6). The criteria used here were similar to those used for other projects to control termite populations in historic sites where the mark–recapture procedure was impractical or logistically impossible (Su 2003). In control projects with historic sites, the overall termite activity was used to measure the outcome of bait applications (Su et al. 1998, Su and Hsu 2003).

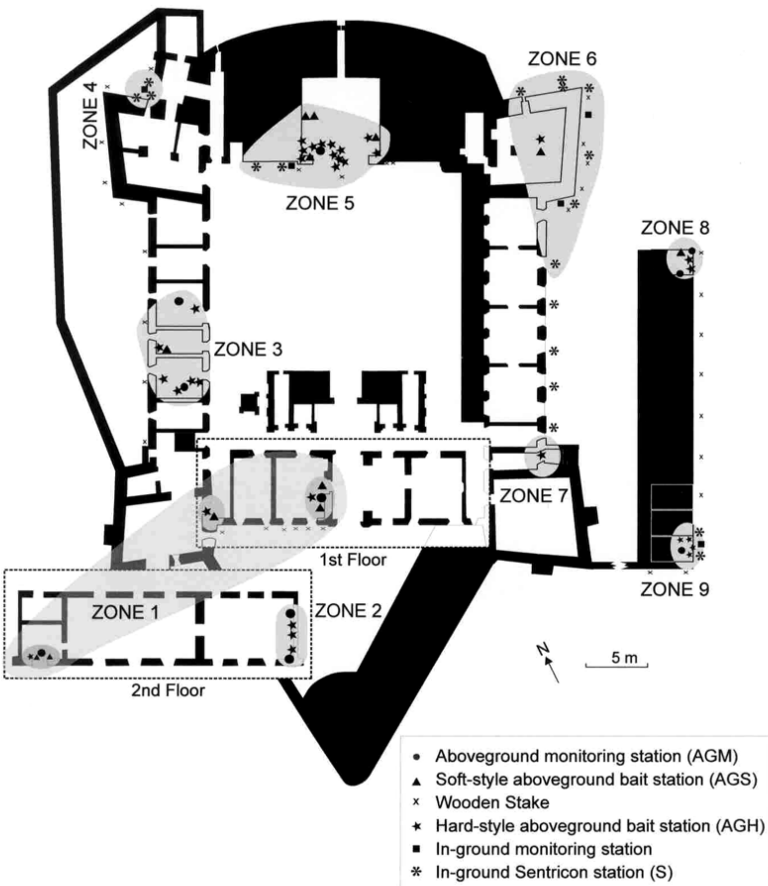

Fig. 6. *Heterotermes* sp. activities in Fort Christiansvaern were grouped into 9 zones (shaded area) on the basis of their close proximity.

Zone 1. This zone included three clusters of *Heterotermes* sp. activity located near the southwestern portion of the fort, including wooden beams on the ceiling of the Guard Room (Fig. 3A-11), the door frame leading into the Dungeon (Fig. 3A-13), and the Closet on the second floor (Fig. 3B-*l*), which is above the Dungeon door (Fig. 6). Five active loci (four AGMs and one active foraging tube) were recorded in August 1996 (Fig. 7). By October, seven active loci were identified, and four aboveground bait stations (two each of AGS and AGB) were placed on the foraging tubes with

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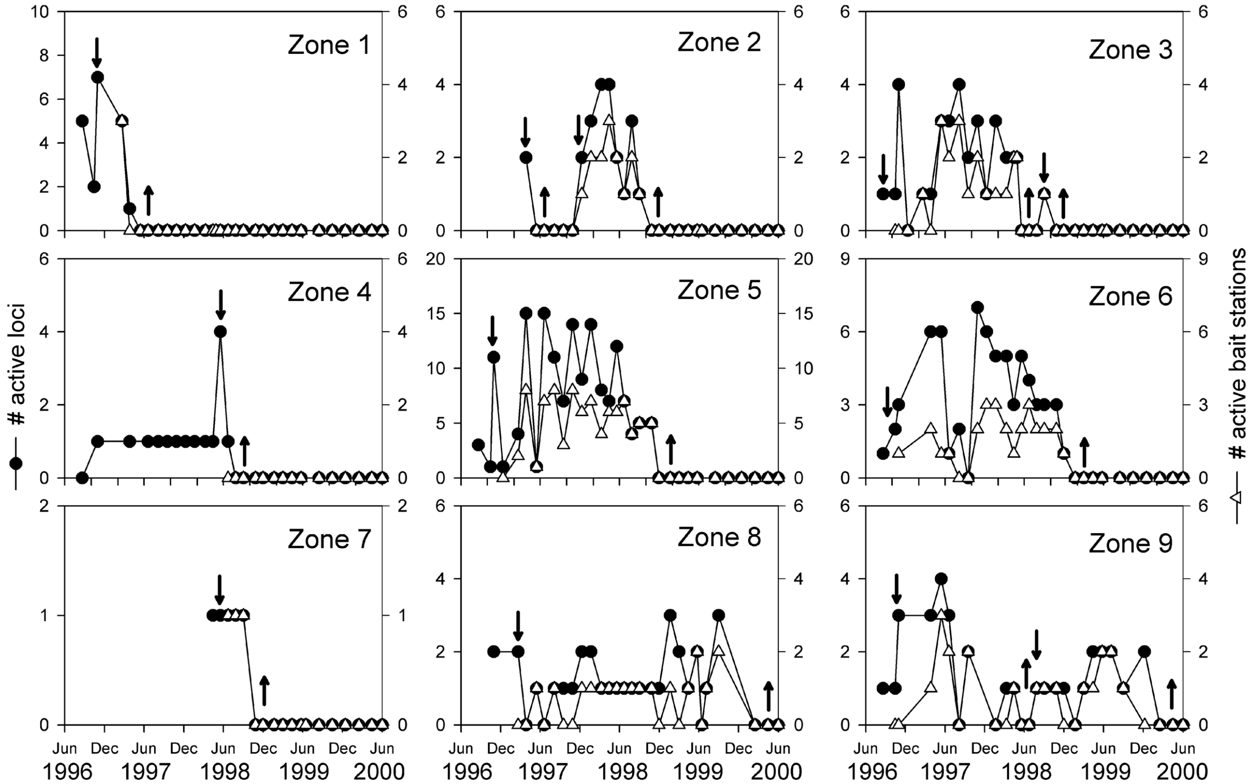

Fig. 7. Termite activities, expressed by number of active loci (circles) including the number of active stations, wooden stakes and newly formed foraging tubes, and the number of bait stations with live termites (open triangles) for 9 zones of *Heterotermes* sp. populations in Fort Christiansvaern, Christiansted National Historic Site. Down-arrows, the beginning of bait application; up-arrows, the removal of baits after the cessations of termite activity for at least two consecutive monitoring periods.

live termites. In December, bait consumption was noted in some bait stations, and one AGH and three AGS were added to this zone. In March 1997, only one AGM contained a small number of termites. Since May 1997, no termite activity has been found in this zone. During the 7-mo baiting between October 1996 and May 1997, termites consumed 105 mg hexaflumuron from 21 g of bait (Table 1).

Zone 2. In the spring of 1997, live foraging tubes were noted on the wooden beams on the ceiling of the eastern end of the Reception Hall (Fig. 3A-*g* and Fig. 6), and three AGHs were installed in March 1997. After slight bait consumption, termite activity ceased in May 1997, but baits were left in place. The cessation of *Heterotermes* sp. activity lasted 7 mo until December 1997 when termites were again found in one AGM and one AGH (Figs. 6 and 7). More AGHs were added in the spring and summer of 1998, during which time termites consumed most of the 19.3-g baits applied to this zone (Table 1). Termite activity declined in June, rebounded in the following month, and declined again. Since October 1998, no termite activity has been found in Zone 2. Seven AGHs were used during the 13-mo baiting period (March–May 1997 and December 1997–October 1998) (Table 1).

Zone 3. The characteristic hanging tubes of *Heterotermes* sp. (Fig. 4A) were found on the structural beams of the ceilings of the 4-Men Barracks (Fig. 3A-17) and Non-commissioned Officer's Cell (Fig. 3A-18), and foraging tubes were found on the walls of the Officer's Cell (Fig. 3A-19). Two AGMs and one AGH were installed in August 1996, but no substantial bait consumption was recorded until May 1997 (Fig. 6). Termite activity increased between May 1997 and March 1998, during which time additional bait stations (AGS and AGH) were placed on the walls and ceiling beams of Zone 3 (Fig. 7). After termites fed on baits from these stations for 10 mo, their activity

Table 1. Hexaflumuron bait applications for *Heterotermes* sp. populations at Fort Christiansvaern, St. Croix, U.S. Virgin Islands

Zone	Bait type[a]	No. bait tubes	No. aboveground stations	Bait consumed, g	Hexaflumuron consumed, mg	Months baited
1	AG	—	8	21.0	105.0	7
2	AG	—	7	19.3	96.5	13
3	AG	—	10	69.5	347.5	22
4	S	1	—	—	—	—
5	AG, S	1	32	325.0	1,625.0	25
6	AG, S	7	8	102.5	512.5	27
7	AG	—	1	27.0	135.0	4
8	AG	—	6	63.3	316.5	36
9	AG	—	8	68.8	344.0	39

[a]AG: aboveground stations including soft-style (AGS) and hard-style stations (AGH), S: in-ground Sentricon stations

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Fig. 8. Altar table of a historic church in northern Italy that had been severely damaged by termites. The church was treated with liquid insecticides for years, but the infestation continued.

Wooden stakes placed outside the Arsenal detected termites in soil on the north (facing the harbor) and east walls of the fort and were replaced with Sentricon stations.

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ceased in May 1998. Activity rebounded in September, but since October 1998, no termite has been found in this zone, which was once a chronic area of termite infestation. During a 22-mo baiting period (August 1996–May 1998 and September–October 1998), termites consumed 69.5 g of bait from 10 aboveground stations.

Zone 4. The stake survey uncovered *Heterotermes* sp. activity in soil west of the Officer's Latrine (Fig. 3A-24), and a small number of termites continued to feed in one in-ground monitoring station placed in October 1996 (Figs. 6 and 7). In May 1998, three wooden stakes were infested by *Heterotermes* sp. and were replaced with Sentricon stations. One bait tube (Recruit II) was placed in the station, but bait consumption was too marginal to measure (Table 1). Despite the lack of bait consumption, no termite activity has been found in the stations or any nearby wooden stakes since July 1998. Because of their proximity, termites found in Zone 4 could be part of the *Heterotermes* sp. populations in Zone 5, which consumed substantial amounts of baits.

Zone 5. Termite activity in the Gunpowder Magazine (Fig. 3A-25) had been the most extensive in the fort. Despite repeated control efforts of drilling and injecting liquid insecticide into foraging galleries between 1991 and 1995, new foraging tubes continued to appear on the walls and floors (Fig. 5A and D). Monitoring began in August 1996, and by October, a total of 11 active loci (new foraging tubes and active stations) were recorded, 8 of which received aboveground bait stations (Figs. 6 and 7). By March 1997, 15 active loci were recorded, and termites consumed baits from eight aboveground bait stations (AGSs and AGHs) (Fig. 7). There was a steep drop in termite activity in May 1997, when termites were found only in one AGH. Termite activity rebounded in the summer of 1997, during which time three wooden stakes near the Gunpowder Magazine entrance were infested by *Heterotermes* sp. and were replaced by one in-ground monitoring station and two Sentricon stations (Fig. 6). A cyclical activity pattern was recorded from June 1997 to May 1998, during which time, termites were found in 7–15 loci and consumed baits from three to eight bait stations (Fig. 7). Activity declined in June 1998, and by September–October, termites were found only in five aboveground bait stations. Since November 1998, no termites have been found in Zone 5. After consuming 325 g bait (≈1,625 mg hexaflumuron) from 32 aboveground bait stations and one Recruit II in 25 months (October 1996–November 1998), termite activity was eliminated from the Gunpowder Magazine room (Table 1).

Fig. 9. Many historic structures such as the Statue of Liberty National Monument are located next to harbors, and injecting a large quantity of liquid insecticide in soil may contaminate marine habitats.

In some cultures, admitting the presence of termite damage is considered an embarrassment, and it is not unusual to encounter "denials" of existing problems from property managers at historic monuments.

Zone 6. As in the Gunpowder Magazine, the Arsenal (Fig. 3A-1) also harbored persistent termite activity, and previous liquid insecticide application did not appear to stop termite activity in this room (Fig. 6). Wooden stakes placed outside the Arsenal detected termites in soil on the north (facing the harbor) and east walls of the fort and were replaced with Sentricon stations. One bait tube was placed in a Sentricon station in October 1996, and bait consumption was recorded in the following months. In the spring and summer of 1997, more baits were consumed from Sentricon stations and two aboveground bait stations placed over live foraging tubes on the Arsenal floor; in September 1997, no sign of termites or termite activity was found in the Arsenal or outside soil (Fig. 7). This cessation of termite activity, however, was only temporary, and in the following months, termite activities were recorded from seven loci including two bait stations. Termites were found inside and outside the Arsenal throughout 1998 and continued to consume baits from the aboveground bait stations and in-ground Sentricon stations. Activity slowly declined toward the end of the 1998, and since January 1999, no termites have been found in Zone 6. During the 27-mo baiting period (October 1996–January 1999), termites consumed 102.5 g of bait from seven bait tubes (Recruit II) and eight aboveground bait stations (Table 1).

Zone 7. Only a single active locus was found on the ceiling of the passage to the stable yard (Fig. 3A-7 and Fig. 6). One AGS was placed over an active foraging tube on June 1998, and 27 g of bait was consumed from this station between June and October (Table 1). After the 4-mo baiting (June – October 1998), termite activity was eliminated from Zone 7; and since October 1998, no sign of termites has been found (Fig. 7).

Zone 8. Active foraging tubes were found on the wooden ceiling and masonry walls of the northernmost room of the stables in October 1996 (Fig. 6). Two AGHs were installed on February 1997, but bait feeding was sporadic in one AGH throughout 1997 (Fig. 7). Wooden stakes placed outside of the room did not detect termites. More aboveground bait stations were added to Zone 8 in 1998 (Fig. 6), but bait feeding was recorded only from the same AGH (Fig. 7). In 1999, with the discovery of new foraging tubes, more aboveground bait stations were added, and after several months of sporadic bait consumption, termite activity ceased in June 1999. Termite activity rebounded in July–August with additional bait consumption through the end of 1999; since February 2000, no termite activity has been seen in this room. It took 36 mo of baiting (February 1997–February 2000) to eliminate termite activity from Zone 8, during which termites consumed only 63.3 g of bait (Table 1).

Zone 9. As in Zone 8, active foraging tubes were found on the wooden rafters and masonry walls of the southernmost room of the stables (Fig. 6). One AGM placed over the active foraging tube in August 1996 harbored termite activity, and four AGHs were placed in October, but bait consumption was not recorded until March 1997 (Fig. 7). Termite activity intensified in the spring and summer of 1997, but after consuming baits in May and June, termite activity declined to zero in August. The cessation of termite activity, however, was short-lived. Between September 1997 and February 2000, three additional episodes of total cessation followed by activity rebounds were recorded, including January 1998, May–June 1998, and January 1999 (Fig. 7). Wooden stakes in soil outside the generator room detected termite activity and were replaced with one in-ground monitoring station and two Sentricon stations, but termites did not appear in these stations. During the 39-mo baiting period (October 1996–May 1998 and June 1998–February 2000), bait consumption was sporadic and was recorded from only two AGHs. After consuming 68.8 g bait, termites were eliminated from Zone 9, and since February 2000, no termites have been found.

Akin to our previous experiences with *Heterotermes* sp., it took much longer for hexaflumuron baits to eliminate activity of *Heterotermes* sp. than other subterranean termite species such as *Co. formosanus* or *Reticulitermes flavipes* (Kollar) (Su et al. 2001). In another project to control termite populations in San Cristóbal and El Morro of San Juan National Historic Site in Puerto Rico, for example, 13–15 mo were required to eliminate *Heterotermes* sp. colonies, whereas 2–8 mo were needed to control *Co. havilandi* (Holmgren) (Su et al. 2002). Foraging ranges of *Heterotermes* sp. colonies tend to be smaller (≈ 5 m) than *Co. formosanus* (≈100 m) or *R. flavipes* (≈50 m) colonies, and several colonies may coexist in one site (Su et al. 2001, 2002). This may explain the repeating cessation–rebound cycles during the baiting in some zones in Fort Christiansvaern. A zone may have contained multiple colonies, and each cessation may represent the elimination of one colony only to be followed by a reinvasion by another nearby colony of *Heterotermes* sp. Similar cyclical activity patterns also were recorded when baiting *Heterotermes* sp. in Puerto Rico (Su et al. 2002).

By the spring of 2000, we concluded that all *Heterotermes* sp. populations infesting the fort had been eliminated by bait applications between 1996 and 1999. Because the site is located in the subtropics with abundance of termite species, however, we suspected that new termite populations would eventually reinfest the fort structures, and we asked the park personnel to remain alert for any sign of new termite activity. As of February 2003, there had been no sign of termite activity in the fort.

Protecting Historic Structures from Subterranean Termites

In all historic sites where we have been consulted for termite problems, infestations had been on-going for several years, even decades; and in some cases, the invaluable historical fabric of the structures had sustained serious termite damage.

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Fig. 10. A Jushoku (resident monk) of a Buddhist temple, Cho-ho Ji, points out stain marking on a 500-yr-old gate post caused by insecticide spraying to control *Co. formosanus*.

Often the site managers misidentified the problem or used improper control measures to remedy termite infestations, only to witness continuing damage to the cultural properties under their supervision (Fig. 8). In some cultures, admitting the presence of termite damage is considered an embarrassment, and it is not unusual to encounter "denials" of existing problems from property managers at historic monuments. There is a need to provide educational materials or workshops to those in charge of historic properties so that termite infestations can be accurately identified, their damaging potential properly understood, and adequate control measures taken.

Despite recent developments in baiting technologies, injecting or spraying of liquid insecticide remains the control choice at many sites in the world. Historic structures often are located in environmentally sensitive areas, and the use of soil insecticides may have to be avoided. The Statue of Liberty National Monument, San Juan National Historic Site, and Fort Christiansvaern are located next to harbors, and injecting a large quantity of liquid insecticide in soil may contaminate marine habitats (Fig. 9). With traditional control of subterranean termites, it is necessary to drill building foundations for sub-slab injection of soil insecticide, but such a practice can cause irreversible damage to the structures. Insecticide spraying alone may also cause damage to historic relics. In Cho-ho Ji, a 500-yr-old Buddhist temple in Wakayama, Japan, for example, wooden gates were irreversibly stained by the liquid insecticides used to control *Co. formosanus* infestation (Fig. 10). Many historic

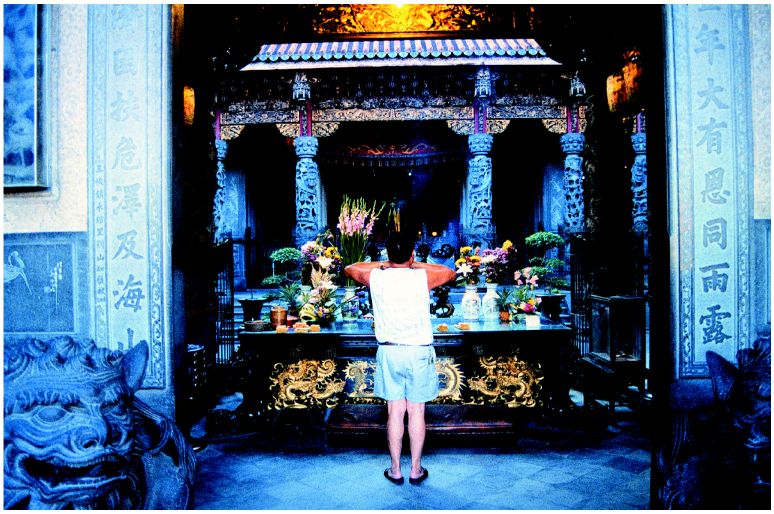

Fig. 11. Many historic monuments, such as this old temple in Taiwan, function as a place for daily prayers and offerings by the locals. Termite control treatment should not interrupt such activities.

structures also serve as public meeting places. Old temples in Taiwan, for example, function as sites for daily prayers and offerings by the locals, and termite control treatments should not interrupt such activities (Fig. 11).

Baiting technologies such as the Sentricon system described in this study and others (Su et al. 1998, 2000, 2002; Freytag et al. 2000; Su and Hsu 2003) are nonintrusive and noninterruptive and may provide important tools for managing subterranean termite infestations in historic sites. Baits, however, may not be effective against other termite species such as *Nasutitermes* spp. or drywood termites. For such species, heat or fumigation with inert gases, or localized treatment with liquid insecticides may have to be used.

One seeming disadvantage of using termite baits to protect historic properties is the lengthy time (months–years) required to eliminate termite populations from a site, during which additional damage may occur. However, because termite infestations at many historic sites have been on-going for decades, and in the case of Fort Christiansvaern,

Fig. 12. In the Statue of Liberty National Monument, in-ground Sentricon stations were installed in soil outside the monument walls for a continuing monitoring and early detection of new termite infestations.

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centuries, damage potential during the baiting period is probably smaller than damage that has already occurred. Although the conventional use of insecticide spraying or injection may provide a faster result by killing a small portion of termites at the point of treatments, it only drives termites from one section to other sections of the property without affecting the overall population. The time required by a baiting program could be well justified by the long-term protection provided by eliminating the structure-infesting populations of subterranean termites. Alternatively, the development of a new technology, baiting or otherwise, that can eliminate termite populations in historic sites more quickly is needed.

Once the structure-infesting populations of subterranean termites are eliminated, it is essential to implement an on-going monitoring program for early detection of new termite populations. At the Statue of Liberty National Monument, for example, in-ground Sentricon stations were installed in soil outside the monument walls (Fig. 12). In addition to the routine inspection by park personnel, the stations have been inspected quarterly since 1997 after the elimination of *R. flavipes* in the monument (Su et al. 1998), and thus far no termites have been detected. Because early detection is a key to minimizing termite damage to historic properties, it is important that a monitoring program remain in place to detect any sign of new termite infestations.

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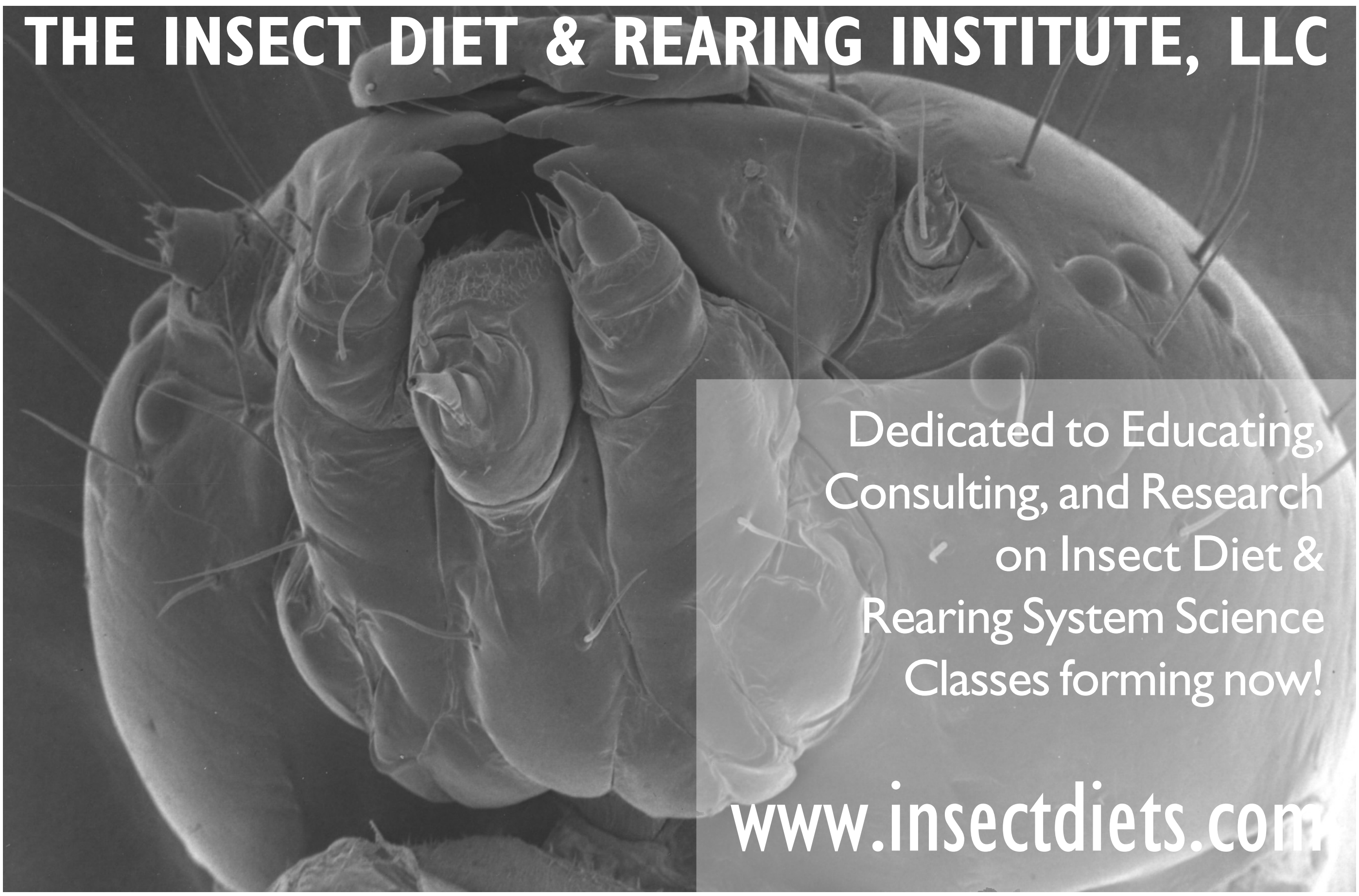

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