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Areawide Field Study on Effect of Three Chitin Synthesis Inhibitor Baits on Populations of *Coptotermes formosanus* and *Reticulitermes flavipes* (Isoptera: Rhinotermitidae)

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ABSTRACT Periodic sampling of 43 independent monitors, initially active with Formosan subterranean termite, *Coptotermes formosanus* Shiraki, or the eastern subterranean termite, *Reticulitermes flavipes* (Kollar) (Isoptera: Rhinotermitidae), was conducted to evaluate the effects of cellulose baits containing one of three chitin synthesis inhibitors (CSIs)—diflubenzuron, hexaflumuron, or chlorfluazuron—on termite populations. Diflubenzuron at 0.1% active ingredient (AI, wt:wt) had no noticeable effect on termite populations. Chlorfluazuron (0.25% [AI]) significantly reduced termite populations in ≈3 yr. Chlorfluazuron used after >2-yr diflubenzuron treatment significantly reduced termite populations within months. This suggests diflubenzuron exposure increased the termite's sensitivity to chlorfluazuron accelerating population collapse. Hexaflumuron (0.5% [AI]) also reduced termite populations in ≈2 yr. The process of removing most detectable termite populations from the ≈160,000-m^2 campus of the Southern Regional Research Center, New Orleans, LA, with CSIs baits required ≈3 yr. Adjustments in the specific bait formulations and application procedures might reduce time to suppression. Establishment of new independent termite populations provides a mechanism to minimize the effects of baits. Remedial control measures around and under structures should be considered when implementing an area wide management strategy.

KEY WORDS Formosan termite, eastern subterranean termite, diflubenzuron, chlorfluazuron, hexaflumuron

Total economic loss due to termites in the United States was estimated at US$11 billion/yr (Su 2002). The Formosan subterranean termite, *Coptotermes formosanus* Shiraki, is native to Asia (Bouillon 1970) but has been introduced into the southern United States where it has become a devastating pest (Su and Tamashiro 1987). In addition to structural infestations, *C. formosanus* infestations of living trees are common in the New Orleans, LA, area (Osbrink et al. 1999, Osbrink and Lax 2003). The eastern subterranean termite, *Reticulitermes flavipes* (Kollar), is the most widely distributed and economically significant termite species in the continental United States (Potter 1997). Control of termites is important to prevent the destruction of materials where it is undesirable.

Implementation of an areawide termite control strategy has merit if it reduces termite pressure in areas where structure and tree damage is undesirable (Su 2002, Lax and Osbrink 2003, Su and Lees 2009, Guillot et al. 2010). Areawide termite management is different from individually protecting a structure or tree as the objective is to also reduce termite populations in areas removed from structures with the objective to suppress reinvasion. Thus, if termite populations are suppressed around and in a structure, there may be less chance of attack over time than would occur with a barrier treatment (Su and Lees 2009). Bait treatments with chitin synthesis inhibitors (CSIs) have suppressed termite populations in areas adjacent to the treatments (Su and Lees 2009). Such baits, when effective, would suppress or eliminate colonies one by one and have an advantage over liquid soil treatments by reducing the amount of toxicant placed in the environment (Su and Lees 2009). Three commercial CSIs are hexaflumuron, diflubenzuron, and chlorfluazuron. Characteristics of CSIs that create a desirable model for termite baits are their slow acting (few weeks), nonrepellent, and dose-independent mode of intoxication (Su 2003). A suitable dose of CSI primarily causes termite mortality when the termite molts, independently of the amount consumed by the termite. This slow intoxication allows the active ingredient to become distributed through much of a termite population and prevents some types of bait avoidance because bait consumption is not associated with intoxication (Su and Lees 2009). Understanding the efficacy and dynamics of control measures is crit-

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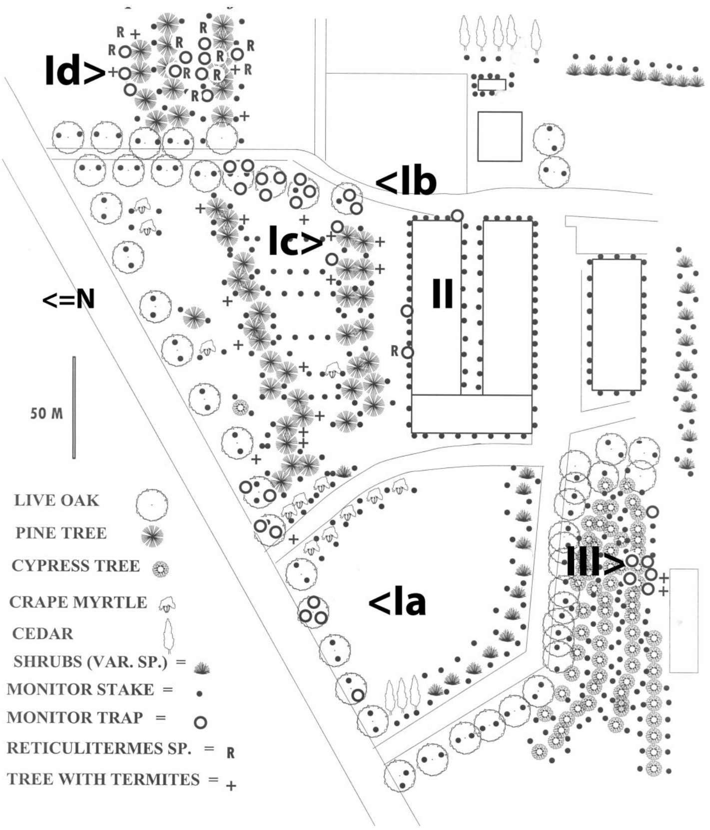

Fig. 1. Map of SRRC, New Orleans, indicating locations of termite monitors (open circles). Area I baited with diflubenzuron followed by chlorfluazuron in oak (Ia and Ib) and pine tree (Ic and Id) stands, area II baited hexaflumuron at building perimeter, and area III baited with chlorfluazuron in cypress stand. R indicates *R. flavipes*, otherwise *C. formosanus*. + indicates tree known to be infested with termites.

ical so they can be successfully integrated into an effective pest management strategy. The central objective of this research was to determine efficacy of three different CSIs in a cellulose matrix for an area-wide approach to suppress termite populations in New Orleans. To meet this objective, we conducted studies to monitor *C. formosanus* and *R. flavipes* colonies throughout a CSI treatment program through direct termite counts and acoustical emission detection. These studies provide evidence that area wide termite management through CSI baiting can be achieved.

Materials and Methods

Independent Monitors. In 1998, the ≈160,000-m^2 campus of the Southern Regional Research Center (SRRC), located at the northeastern corner of City Park, New Orleans, was surveyed for subterranean termites with placement of pine stakes (2 by 4 by 20 cm). City Park proper ≈1,600 m south of the SRRC was surveyed in a similar manner and used as untreated controls. At the SRRC, this resulted in the establishment of 43 independent termite monitor traps (MTs) (Su and Scheffrahn 1986) active with *C. formosanus* (32) or *R. flavipes* (11) located at a distance of 1–3 m around the perimeters of 17 trees and a building (Fig. 1). In untreated City Park proper the survey resulted in 28 and three MTs active with *C. formosanus* and *R. flavipes*, respectively. Termites were identified in accordance with Scheffrahn and Su (1994).

Toxic Bait. In September 1999, a contractor installed 114 Sentricon monitors every ≈5.5 m around the perimeter of a building (Fig. 1, area II) that, upon becoming infested with termites, were supplied with Recruit II that contained 0.5% hexaflumuron in cellulose. On 15 November 1999, four aboveground baits (0.5% hexaflumuron) were installed within the building in areas with active termite infestations. On 6 November 1999, Agricultural Research Service researchers installed 230 slotted plastic in-ground monitors ([IGMs], 10 cm in diameter by 20 cm in depth) in areas I (a–d) and III (Fig. 1). IGMs were used to deliver diflubenzuron or chlorfluazuron as follows. IGMs were placed every ≈7.3 m along transects tangent to termite infested MT. A MT was always <3 m from at least one IGM. IGMs (10 cm in diameter by 20 cm in depth) possessed six columns of 15 horizontal slots (5 by 300 mm). Inside the IGM slotted side walls were fitted wooden slats that left a vacant middle cavity in the monitor. After becoming infested with termites, 150 g of moist 0.1% diflubenzuron or 0.25% chlorfluazuron cellulose powder in wax paper bait bags were added to the IGM's vacant cavity with minimal disruption of wooden slats.

Termites were collected from MTs approximately monthly (less in winter), and the number of workers collected from each MT was estimated by weight (Osbrink et al. 2008). Mean number of workers per area per year (from July 1998 to September 2005) was calculated by dividing number of workers collected by number of monitors per area and analyzed using Kruskal–Wallis one-way analysis of variance on ranks (Systat Software 2008).

Acoustical Emission Detector (AED). An AED-2000 acoustical emissions detector (Acoustical Emissions Consulting, Inc., Fair Oaks, CA) was used to quantify termite activity within four southern live oak, *Quercus virginiana* P. Mill. (Fagaceae), trees (area Ib) and one loblolly pine, *Pinus taeda* L. (Pinaceae), tree (area Id), all of were adjacent to MTs. An untreated live oak tree in Brechtel Park, New Orleans, was used to verify proper functioning of the AED and to document termite activity in an untreated tree. Wave guides in the form of lag bolts (150 by 9 mm) were screwed into predrilled pilot holes in the trunk of test trees 20 cm from the ground facing northeast, south, and west. A fifth bolt was inserted into the east side of the trunk at a height of 122 cm from the ground. Acoustical emissions were detected with a sensor (model SP-1L probe with model DMH-30 high force magnetic accessory attachment, Acoustic Emission Consulting, Inc.). AED counts were captured in the mornings of June and November 2002 and January, April, and November 2003 with a laptop personal computer using software (Acoustical Emissions Consulting, Inc.) to convert termite sounds to counts per second in an Excel (Microsoft, Redmond, WA) spread sheet. Acoustical output for each attachment was captured for 60 s. Ten consecutive count values (10 s) were used to represent termite activity associated with each unique attachment. All five bolts per tree were evaluated with the greatest acoustical activity chosen to represent an individual tree at each time. Acoustical data were analyzed using Kruskal–Wallis one way analysis of variance on ranks (Systat 2008).

Alate Trapping. *C. formosanus* alates were trapped annually from 1999 to 2005 by using a universal blacklight trap with 12-Watt U-shaped black Light tube (BioQuip Products, Inc. Rancho Dominguez, CA). The light trap was located on the north wall of the SRRC Greenhouse, area III. The light trap was checked every morning during April, May, and June, representing the swarming season for *C. formosanus* in New Orleans. *R. flavipes* fly during the day and were not found in the light trap.

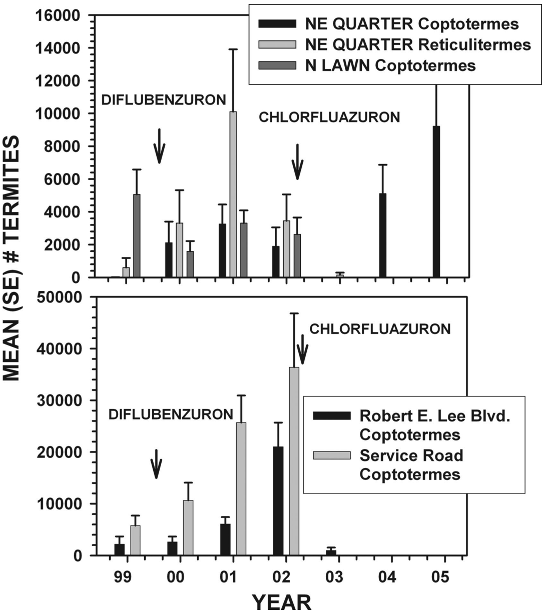

Fig. 2. Mean number of termites captured before and after treatment with diflubenzuron and chlorfluazuron (arrows).

Results

Diflubenzuron. Diflubenzuron (0.1%) did not have any observable effect on populations of either *C. formosanus* or *R. flavipes* in areas Ia, Ib, Ic, and Id (Fig. 2; Tables 1 and 2). MTs at the base of oak trees along Robert E. Lee Blvd. and the Service Rd., areas Ia and Ib, were occupied by *C. formosanus.* MTs in areas Ic (*C. formosanus*) and Id were located at the bases of pine trees with seven of 10 MTs in area Id occupied by *R. flavipes.* After ≈3 yr, diflubenzuron as delivered in this study, demonstrated no discernible effect on populations of either termite species in areas Ia (Robert E. Lee Blvd.), Ib (Service Rd.), Ic (North Lawn), and Id (North East Quarter), the CSI was switched to chlorfluazuron (0.25%) in the fall of 2002 (Fig. 2).

Chlorfluazuron. In areas Ia (Robert E. Lee Blvd.), Ib (Service Road), Ic (North Lawn), and Id (North East Quarter), diflubenzuron baits were switched to chlorfluazuron (0.25%) in fall 2002 (Fig. 2). After the switch, all detectable termites were eliminated before summer 2003. Some reinvasion of *C. formosanus* has been observed beginning 2004 in area Id (Fig. 2; Tables 1 and 2). A highly significant reduction of acoustical counts occurred during the same time span (2002 versus 2003), indicating reduced termite activity, further validating the suppression of populations adjacent to the treatments (Table 3). Termites in the control oak remained active throughout 2003 (Table 3).

The Formosan termites reoccupying MTs in area Id (North East Quarter) were from a large mature colony as indicated by the substantial numbers trapped (Su and Tamashiro 1987) and large worker size (3.7 ± 0.1 mg [mean ± SE]) (Grace et al. 1995).

When chlorfluazuron at 0.25% was applied in area III (SRRC greenhouse), which had not been previously treated with toxic baits, it caused the *C. formosanus* population to experience a highly significant

Table 1. Number of termite workers (mean ± SE) trapped in areas treated with diflubenzuron then chlorfluazuron

Yr	Diflubenzuron (1999–2002)/chlorfluazuron (2002–2005)				
	Coptotermes				*Reticulitermes*
	Ia	Ib	Ic.	Id	Id
No. monitors	8	11	2	3	7
1999	2,150 ± 1,521.5	5,759 ± 1,939.0	5,057.6 ± 1,519.5	8.3 ± 8.3	596.7 ± 588.0
2000	2,600.0 ± 1,053.7	1,0654.2 ± 3,411.58	1,586.4 ± 630.7	2,114.2 ± 1,288.5	3,309.2 ± 2,009.9
2001	6,079.3 ± 1,341.0	2,5684.9 ± 5,242.33	3,303.3 ± 782.1	3,249.0 ± 1,195.4	10,105.8 ± 3,802.1
2002	2,1003.8 ± 4,671.1	3,6384.5 ± 1,0404.3	2,621.3 ± 1033.4	1,889.8 ± 1,162.6	3,452.4 ± 1,607.4
2003	5,52.9 ± 356.9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.00	83.7 ± 82.1
2004	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.00	5,106.0 ± 1,761.4	0.0 ± 0.0
2005	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	9,213.2 ± 2866.2	0.0 ± 0.0
	$H = 42.6$ df = 6 $P < 0.001$	$H = 44.1$ df = 6 $P < 0.001$	$H = 31.4$ df = 6 $P < 0.001$	$H = 31.4$ df = 6 $P < 0.001$	$H = 23.4$ df = 6 $P < 0.001$

Kruskal–Wallis one way analysis of variance on ranks.

collapse to undetectable population levels after ≈3 yr (Fig. 3; Tables 4 and 5). Area III MTs were located in a stand of bald cypress, *Taxodium distichum* (L.) Richard 1810, just north of the SRRC greenhouse. During 2002, collected *C. formosanus* in area III and *R. flavipes* in area Id where chlorfluazuron baits were applied began to possess a subcuticular accumulation of chalky white deposits (Fig. 4). Also, collected *C. formosanus* worker size demonstrated a highly significant increase from 3.8 ± 0.1–5.1 ± 0.2 mg ([mean ± SE]; $t = 5.2$, df = 6, $P = 0.002$), attributed to increased mortality of smaller, earlier instars caused by greater frequency of molting when compared with later, larger instars (King and Spink 1974). No termites could be detected in area III since 2003.

Hexaflumuron. Only one and two MTs in area II (building) were occupied with R. *flavipes* and *C. formosanus*, respectively, with relatively low number of workers collected coinciding with the beginning of treatments with hexaflumuron. The mean numbers of *C. formosanus* workers were <500 per collection and <4,000 for an entire year (Fig. 3; Tables 4 and 5). Of 114 Sentricon monitors placed around the 527-m perimeter, 11 (9.7%) and three (2.6%) Sentricon monitors were occupied by *C. formosanus* and *R. flavipes*, respectively, by May 2000. Four aboveground station were also installed inside the building directly where termites were observed. Using Sentricon there were more monitors visited by termites than the pine stake and MTs placed in the same areas, with 11 Sentricon monitors occupied by *C. formosanus* by spring 2000 compared with two MTs. After ≈3 yr of baiting, no signs of *C formosanus* activity occurred in MTs by spring 2003 (Fig. 3; Tables 4 and 5). One MT in area II (hexaflumuron) was occupied by *R. flavipes*, with >46,000 workers trapped (mean, >5,700) in 2001 (Fig. 3; Tables 4 and 5). *R. flavipes* disappeared from the MT in 2002 after ≈2 yr of baiting in which three Sentricon stations were occupied with *R. flavipes.*

Controls. The untreated area in City Park produced substantial collections of *C. formosanus* and *R. flavipes* during 2004 and 2005 (Fig. 5; Table 4) in contrast to almost no detectable termites recovered from the treated areas of the SRRC.

Alate Trapping. Although substantial variation occurs in alate capture from year to year, *C. formosanus* alates were abundant in the years after the collapse of the termite population in area III (Fig. 6).

Discussion

Diflubenzuron. Little published data are available on field studies by using diflubenzuron. Green et al. (2008), using 0.25% diflubenzuron, observed an initial reduction in *R. flavipes* populations that rebounded in the second and third years of the study. Green et al. (2008) also reported that other areas of significant termite activity seemed to show no response to the diflubenzuron and concluded that such bait would not be adequate to suppress or eliminate the colony or colonies of termites present. Green et al. (2008) conclude that 0.25% diflubenzuron is too low a concen-

Table 2. Total number of termite workers trapped in areas baited with diflubenzuron then chlorfluazuron

Yr	Diflubenzuron (1999–2002)/chlorfluazuron (2002–2005)				
	Coptotermes			*Reticulitermes*	
	Ia	Ib	Ic.	Id	Id
No monitors	8	11	2	3	7
1999	19,355	51,832	45,518	75	53,370
2000	26,000	106,542	15,864	21,142	33,092
2001	48,634	205,479	26,426	25,992	80,846
2002	168,030	291,076	20,970	15,118	27,619
2003	3,870	0	0	0	586
2004	0	0	0	25,530	0
2005	0	0	0	82,919	0

Table 3. Number of AED acoustical counts (mean ± SE) detected in trees treated with diflubenzuron then chlorfluazuron

Date	Untreated *Coptotermes* Brechtel Park	Diflubenzuron/chlorfluazuron				
		Coptotermes area Ib Service Rd.				*Reticulitermes* area Id North East Quarter
	Oak	Oak 1	Oak 2	Oak 3	Oak 4	Pine
June 2002	N.D.[a]	16.9 ± 2.4	5.5 ± 1.2	1.6 ± 1.0	136.6 ± 15.9	N.D.
Nov. 2002	9.0 ± 1.6	222.6 ± 33.3	653.3 ± 415.9	276.0 ± 9.1	14.8 ± 8.4	17.1 ± 6.3020
Jan. 2003	1.5 ± 0.5	13.3 ± 8.6	28.6 ± 16.4	5.9 ± 4.4	0.0 ± 00	145.1 ± 55.9
April 2003	22.2 ± 3.7	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 00	0.0 ± 0.0	0.0 ± 0.0
Nov. 2003	6.1 ± 1.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	$H = 24.6$	$H = 32.4$	$H = 24.5$	$H = 28.9$	$H = 37.6$	$H = 20.1$
	df = 3	df = 4	df = 4	df = 4	df = 4	df = 3
	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$

Kruskal–Wallis one way analysis of variance on ranks.

[a] N.D., no data.

tration to suppress colonies of *R. flavipes,* and this concentration was more than double the 0.1% concentration in the current study, with performance consistent with these studies findings. As diflubenzuron concentrations increase, feeding deterrence must be considered, because Su and Scheffrahn (1993) reported diflubenzuron deterred feeding in *C. formosanus* laboratory studies at concentration as low as 2 ppm, with highest recorded mortality at 50%, concluding it is not effective in a bait against this species (Su 2003), consistent with the results of this current study. More recently, Su and Lees (2009) concluded from laboratory studies that diflubenzuron could be efficacious against *R. flavipes* only over a narrow range of concentration (7.8–31.3 ppm). Such a narrow range of activity lacks the robustness of a preferred termite treatment. Concerns about a toxicant with a narrow range of activity is that the total amount of bait ingested by termites cannot be manipulated (Su and Lees 2009), making optimization difficult under varying conditions. Rojas et al. (2008) report similar lack of activity of diflubenzuron against subterranean termites in Mississippi after several years.

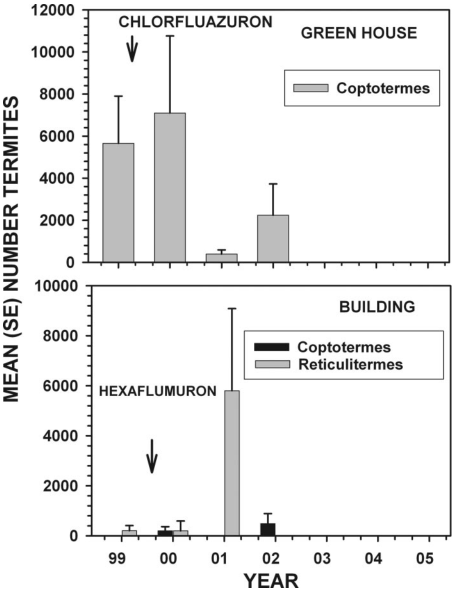

Fig. 3. Mean number of termites captured before and after treatment with chlorfluazuron alone or hexaflumuron (arrows).

Chlorfluazuron. The AED provide an effective tool for validation of reduced termite activity in trees; however, environmental noises such as leaf blowers, lawn mowers, traffic, and wind >16 km/h interfere with termite detection causing delay or termination of monitoring session at the cost of time.

C. formosanus populations seemed to be primarily centered in trees (Ehrhorn 1934. Osbrink et al. 1999, Osbrink and Lax 2002b). Hill (1942) wrote that all large *Coptotermes frenchi* Hill colonies are centered inside living trees and that colony developments in alternate locations do not achieve the size or the longevity of tree-centered colonies. Although *C. formosanus* has flexible nesting habits, available hardwood trees may be their definitive host. It provides ideal harborage and mechanical protection with the nest located in the self created lumen of a tree. Small incipient *C. formosanus* colonies are highly susceptible to desiccations (unpublished data). The tree trunk acts as a water-sink, providing moisture that a young incipient colony needs to prevent desiccation allowing the colony to become large enough to forage for water (Cornelius and Osbrink 2010). Living tree heartwood possesses high moisture content of 50–75% (Fromm et al. 2001). Buildings, sidewalks, streets, and other large moisture barriers also act as a water sink, delaying desiccation, but to a lesser extent as they possess no mechanisms of water transport as does a root system, maintaining moisture during drought. Tree nesting also allows *C. formosanus* to survive flooding (Cornelius et al. 2007, Osbrink et al. 2008). *C. formosanus* fungal-static nest also protects the tree lumen from destructive rot in a relationship, which seems mutualistic (Osbrink et al. 1999, Osbrink and Lax 2003, Apolinario and Martius 2004, Jayasimha and Henderson 2007, Chouvenc et al. 2009). Termites also aerate, reduce compactness, and add nutrients to soil to the benefit of the tree (Janzen 1976, Apolinario and Marius 2004). Termite biological nitrogen fixation in

Table 4. Number of termite workers (mean ± SE) trapped in areas with hexaflumuron, chlorfluazuron, or untreated control

Yr	*Coptotermes*			*Reticulitermes*	
	Hexaflumuron II	Chlorfluazuron III	City Park Untreated	Hexaflumuron II	City Park Untreated
No. monitors	2	6	28	1	3
1999	0.0 ± 0.00	5,655.3 ± 2,244.4	N.D.	206.3 ± 206.3	N.D.
2000	198.3 ± 169.8	7,096.2 ± 3,664.5	N.D.	754.1 ± 393.6	N.D.
2001	0.0 ± 0.00	393.3 ± 199.7	2,630.8 ± 463.1	5,799.9 ± 3,283.7	1,338.6 ± 667.6
2002	486.1 ± 405.0	2,237.8 ± 1,490.5	2,845.3 ± 274.7	0.0 ± 0.00	1,910.4 ± 641.9
2003	0.0 ± 0.00	0.0 ± 0.00	1,215.6 ± 136.6	0.0 ± 0.00	39.8 ± 39.8
2004	0.0 ± 0.00	0.0 ± 0.00	3,534.0 ± 250.6	0.0 ± 0.00	2,661.8 ± 665.3
2005	0.0 ± 0.00	0.0 ± 0.00	6,922.8 ± 614.1	0.0 ± 0.00	8,975.8 ± 1,695.6
	$H = 9.8$	$H = 29.0$	$H = 69.3$	$H = 16.8$	$H = 37.4$
	df = 6	df = 6	df = 4	df = 6	df = 4
	$P = 0.132$	$P < 0.001$	$P < 0.001$	$P = 0.010$	$P < 0.001$

Kruskal-Wallis one way analysis of variance on ranks.

[a] N.D., no data.

this relationship is analogous to rhizobium–legume symbiosis reducing atmospheric nitrogen (N_2) making it available as a plant nutrient (Burris 1988, Ohkuma et al. 1999). Occupied trees generally seem healthy and lose little strength when a hollowed trunk has <80% of its structure removed (Mattheck and Breloer 1994). Because of the affinity of the Formosan termite for living trees, they cannot be ignored in areawide population suppression efforts as they may be a primary source of termites (Osbrink et al. 1999, Osbrink and Lax 2002a, Osbrink and Lax 2003).

Chlorfluazuron applications after diflubenzuron baiting intoxicated the termite populations rapidly (3 mo) compared with area III (greenhouse) in which chlorfluazuron alone took ≈3 yr to eliminate all detectable termites (Fig. 3; Tables 4 and 5). The data suggest that the diflubenzuron exposure increased the termite's sensitivity to chlorfluazuron accelerating population collapse. Chlorfluazuron has been used with success in Australia and South-East Asia (Peters and Broadbent 2005). Aluko and Husseneder (2007) reported termite populations remained active when baited with chlorfluazuron over 2 yr at the Supreme Court Building in New Orleans. Peters and Fitzgerald (2003) reported 0.25% chlorfluazuron eliminating colonies of the mound building *Coptotermes acinaciformis* (Froggatt) in <4 mo by using pine studs to help channel termites to the bait, although there was one colony apparently unaffected by chlorfluazuron. Osbrink et al. (2001) and Osbrink and Lax (2002a) have demonstrated in laboratory studies that different colonies of *C. formosanus* can respond differently to insecticides, which could explain inconsistent results in some instances. Peters and Broadbent (2005) eliminated various species of termites with 0.1% chlorfluazuron bait in Thailand and Philippines within 4 mo. Sukartana et al. (2009) baited *Coptotermes curvignathus* Holmgren with 0.1% chlorfluazuron and eliminate colonies within 2 mo by using aboveground stations but had minimal termite visitation to in-ground stations. Green et al. (2008) had some initial success in field tests with 0.25% diflubenzuron termite bait against *R. flavipes* in the northern U.S. climate of central Wisconsin, but baits experienced reduced effectiveness in the 2 subsequent years of their study.

Table 5. Total number of termite workers trapped in areas with hexaflumuron or chlorfluazuron

Yr	*Coptotermes*		*Reticulitermes*
	Hexaflumuron II	Chlorfluazuron III	Hexaflumuron II
No. monitors	2	6	1
1999	0	50,898	1,857
2000	1,983	70,962	7,541
2001	0	3,146	46,399
2002	3,889	17,902	0
2003	0	0	0
2004	0	0	0
2005	0	0	0

Hexaflumuron. Low collection numbers may indicate that these MTs were visited by small populations, populations on the extreme edge of their foraging range, or being outcompeted with a preferred food source (e.g., alternate wood sources including Sentricon monitors). An alternate explanation as suggested for *C. frenchi* is that *C. formosanus* do not develop huge populations when not centered in a tree (Hill 1942).

Numerous publications document hexaflumuron's efficacy against *C. formosanus* and *R. flavipes* (Su 2003). Most studies indicate rapid (months) population suppression or colony elimination with this CSI as reviewed by Su (2003) and Su and Scheffrahn (1998). Su (2003) summarized hexaflumuron performance as 98.5% successful colony elimination from 13691 sites, with 199 sites experiencing control problems. However, Glenn and Gold (2002) baited *C. formosanus* with hexaflumuron for 2 yr in Beaumont, TX, and found termites remained active in or around two of five structures. Glenn and Gold (2002) consider monthly monitoring of bait stations inadequate against the aggressive Formosan termite who will abandon a bait station when empty, which may explain the ≈3 yr required for *C. formosanus* control in this study that used a monthly station maintenance schedule. Using hexaflumuron, Su et al. (2004) continued to detect *C. formosanus* populations for ≈2 yr after initiating an areawide community test. Messenger et al. (2005) used hexaflumuron to eliminate Formosan termite col-

Fig. 4. *C. formosanus* worker with subcuticular white aggregate associated with chlorfluazuron intoxication. (Online figure in color.)

onies in Armstrong Park, New Orleans, in 3 mo but observed reinvasion almost immediately. Guillot et al. (2010) reported hexaflumuron treated areas in the French Quarter, LA, had 3–4% of independent monitors remained active for ≈5 yr possibly due to difficulty in bait placement in areas of common wall construction and ultimately changed active ingredients to noviflumuron. Potter et al. (2001) baited 22 *R. flavipes*-infested houses with hexaflumuron and report two of these houses with termites after 24 mo because the bait was never taken. Vargo (2003) continued to have monitor visitation after 2 yr in four of nine hexaflumuron treated apartments in which new *R. flavipes* colonies would appear. Thus, colonies can be eliminated rapidly in areawide management, but termite populations may remain as they may not come into contact with treatments.

Alate Trapping. This small contribution of the adjacent in ground termite population to the alate capture is consistent with the findings of Simms and Husseneder (2009) and Messenger and Mullins (2005) and indicates that Formosan termite alates are capable flyers that can reinfest locations which have been subjected to area wide termite control strategies.

The pretreatment climax population structure apparently consisted of a few large colonies dominating resources. Suppression of the large colonies makes available resources in their lost home range. The population structure of reinvading secondary succession termites will be composed of many newer colonies expanding over time (years) until they compete for resources or merge into supercolonies. Agonistic interactions between neighboring colonies have been much studied and are little understood. Concurrently, neighboring mature colonies expand their home ranges to compete for the same resources.

Detection of slow growing newly established incipient colonies is difficult, with 4-yr-old laboratory colonies possessing only 100,000 termites (Su and Tamashiro 1987). It would be difficult for new colonies to become established in areas already occupied with preexisting mature colonies because the latter will stop incipient colony formation (unpublished data). Colony elimination thus promotes the establishment of new colonies in the same areas and the expansion of surviving colonies (Husseneder et al. 2007). Annual reinvasion of suppressed areas with alates establishing new colonies eventually will lead to a resurgence of termite pressure. The resulting new populations will be independent of one another, different from the larger suppressed populations, potentially altering the performance of continuing

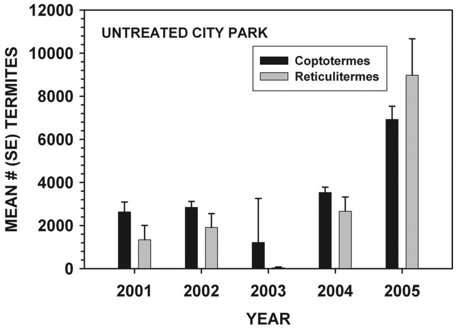

Fig. 5. Mean number of termites captured in untreated control are of City Park, New Orleans.

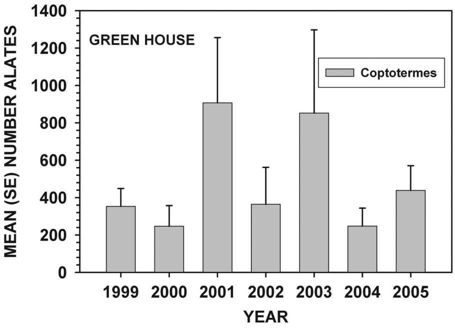

Fig. 6. Mean number of *C. formosanus* alates captured in chlorfluazuron treated cypress stand north of greenhouse, area III.

bait treatments (Husseneder et al. 2007). Such a dynamic may promote the establishment of many separate populations, similar to disturbed landscapes studied by Aluko and Husseneder (2007), possibly reducing the impact of baits over time. Termite baits will be more effective against a few larger mature populations compared with numerous independent populations. Thus, large numbers of independent termite populations established upon reinvasion provide a mechanism of demographic resistance to lessen the effects of baits on overall termite populations possibly responsible for control plateaus reported in other areawide control studies (Guillot et al. 2010). Similarities may exist in the proliferation of polygyne over mongyne red imported fire ants, *Solenopsis invicta* Buren, accompanying area wide baiting with hydramethylnon (Glancy et al. 1987). Larger numbers of reproductives in a given area may improve survivability of social insects under baiting pressure by increasing the chances that some reproductives will escape treatment and reproduce.

In conclusion, after ≈3 yr of areawide treatment, there were almost no detectable termites except for 108,449 *C. formosanus* and 586 *R. flavipes* in area Id (North East Quarter, Table 2). Starting in 2006, additional *C. formosanus* reinvasion has begun (unpublished). Overall area wide termite suppression was achieved after a 3-yr process. Modification of the specific bait formulations and application procedures may reduce time to suppression. The reinvasion and establishment of new independent termite populations provides a mechanism over time to decrease the structure protecting effectiveness of baits. Thus, continuous reevaluation of changing circumstance becomes critical for implementation of the best control strategies, including tree evaluations, to protect structures from reinvading colonies. Remedial control around and under structures should be considered in an area wide termite management strategy.

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References Cited

Aluko, G., and C. Husseneder. 2007. Colony dynamics of the Formosan subterranean termite in a frequently disturbed urban landscape. J. Econ. Entomol. 100: 1037–1046.

Apolinario, F., and C. Martius. 2004. Ecological role of termites (Insecta, Isoptera) in tree trunks in central Amazonian rain forest. For. Ecol. Manag. 194: 23–28.

Bouillon, A. 1970. Termites of the Ethiopian region, pp. 153–280. *In* K. Krishna and F. M. Weesner (eds.), Biology of termites, vol. 2. Academic, New York.

Burris, R. H. 1988. Biological nitrogen fixation: a scientific perspective. Plant Soil 108: 7–14.

Chouvenc, T., N.-Y. Su, and A. Robert. 2009. Inhibition of *Metarhizium anisopliae* in the alimentary tract of the eastern subterranean termite *Reticulitermes flavipes.* J. Invertebr. Pathol. 101: 130–136.

Cornelius, M. L., L. M. Duplessis, and W. L A. Osbrink. 2007. The impact of Hurricane Katrina on the distribution of subterranean termite colonies (Isoptera: Rhinotermitidae) in City Park, New Orleans, Louisiana. Sociobiology 50: 1–25.

Cornelius, M. L., and W.L.A. Osbrink. 2010. Effect of soil type and moisture availability on the foraging behavior of the Formosan Subterranean termite (Isoptera: Rhinotermitidae). J. Econ. Entomol. 103: 799–807.

Ehrhorn, E. M. 1934. The termites of Hawaii, their economic significance and control, and the distribution of termites by commerce, pp. 293–305. *In* C. A. Kofoid (ed.), Termites and termite control. University of California Press, Berkeley, CA.

Fromm, J., I. Sautter, D. Matthies, J. Kremer, P. Schumacher, and C. Ganter. 2001. Xylem water content and wood density in spruce and oak trees detected by high-resolution computed tomography. Plant Physiol. 127: 416–425.

Glancy, B., J. Nickerson, D. Wojcik, J. Trager, W. Banks, and C. Adams. 1987. The increasing incidence of the poygynous form of the red imported fire ant, *Solenopsis invicta* (Hymenoptera: Formicidae), in Florida. Fla. Entomol. 70: 400–402.

Glenn, G. J., and R. E. Gold. 2002. Evaluation of commercial termite baiting systems for pest management of the Formosan subterranean termite (Isoptera: Rhinotermitidae), pp. 325–334. *In* S. Jones, J. Zhai, and W. Robinson W (eds.), Proceedings, 4th International Conference on Urban Pests, 7–10 July 2002, Charleston, SC. Pocahontas Press, Inc., Blacksburg, VA.

Grace, J. K., R. T. Yamamoto, and M. Tamashiro. 1995. relationship of individual worker mass and population decline in a Formosan subterranean termite colony (Isoptera: Rhinotermitidae). Environ. Entomol. 24: 1258–1262.

Green III, F., R. Arango, and G. Esenther. 2008. Community-wide suppression of *R. flavipes* from Endeavor, Wisconsin—search for the holy grail, pp. 1–10. *In* The International Research Group on Wood Protection, IRG/WP 08-10674. IRG Secretariat Stockholm, Sweden.

Guillot, F., D. Ring, D. Lax, A. Morgan, K. Brown, C. Riegel, and D. Boykin. 2010. Are-wide management of the Formosan subterranean termite, Coptotermes formosanus Shiraki (Isoptera: Rhinotermitidae), in the new Orleans French Quarter. Sociobiology 55: 311–338.

Hill, G. 1942. *Coptotermes frenchi* Hill, pp. 149–152. *In* G. Hill, Termites (Isoptera) from the Australian Region. Commonwealth of Australia Council for Scientific and Industrial Research. H. E. Daw, Government Printer, Melbourne, Australia.

Husseneder, C., D. Simms, and C. Riegel. 2007. Evaluation of treatment success and patterns of reinfestation of the Formosan subterranean termite (Isoptera: Rhinotermitidae). J. Econ. Entomol. 100: 1370–1380.

Janzen, D. H. 1976. Why tropical trees have rotten cores. Biotropica 8: 110.

Jayasimha, P., and G. Henderson. 2007. Suppression of growth of a brown rot fungus, *Gloeophyllum trabeum,* by Formosan subterranean termites (Isoptera: Rhinotermitidae) Ann. Entomol. Soc. Am. 100: 506–511.

King, E., and W. Spink. 1974. Laboratory studies on the biology of the Formosan subterranean termite with primary emphasis on young colony development. Ann. Entomol. Soc. Am. 67: 953–958.

Lax, A. R., and W.L.A. Osbrink. 2003. United States Department of Agriculture–Agriculture Research Service research on targeted management of the Formosan subterranean termite *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae). Pest Manag. Sci. 59: 788–800.

Mattheck, C., and H. Breloer. 1994. The body language of trees, a handbook for failure analysis. HMSO Publications Center, London, United Kingdom.

Messenger, M., and A. Mullins. 2005. New flight distance recorded for *Coptotermes formosanus* (Isoptera: Rhinotermitidae). Fla. Entomol. 88: 99–100.

Messenger, M. T., N.-Y. Su, C. Husseneder, and J. K. Grace. 2005. Elimination and reinvasion studies with *Coptotermes formosanus* (Isoptera: Rhinotermitidae) in Louisiana. J. Econ. Entomol. 98: 916–929.

Ohkuma, M., S. Noda, and T. Kudo. 1999. Phylogenetic diversity of nitrogen fixation genes in the symbiotic microbial community in the gut of diverse termites. Appl. Environ. Microbiol. 65: 4926–4934.

Osbrink, W.L.A., and A. R. Lax. 2002a. Effect of tolerance to insecticides on substrate penetration by Formosan subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol. 95: 989–1000.

Osbrink, W.L.A., and A. R. Lax. 2002b. Termite (Isoptera) gallery characterization in living trees using digital resistograph technology, pp. 251–257. *In* W. C. Jones, J. Zhai, and W. H. Robinson (eds.), Proceedings, 4th International Conference on Urban Pests, 7–10 July 2002, Charleston, SC. Pocahontas Press, Inc. Blacksburg, VA.

Osbrink, W.L.A., and A. R. Lax. 2003. Effect of imidacloprid tree treatments on the occurrence of Formosan subterranean termites, Coptotermes formosanus Shiraki (Isoptera: Rhinotermitidae). J. Econ. Entomol. 96: 117–125.

Osbrink, W.L.A., W. D. Woodson, and A. R. Lax. 1999. Population of Formosan subterranean termite, *Coptotermes formosanus* (Isoptera: Rhinotermitidae), established in living urban trees in New Orleans, Louisiana, U.S.A., pp. 341–345. *In* W. H. Robinson, F. Rettich, and G. W. Rambo (eds.), Proceedings, 3rd International Conference on Urban Pests, 19–22 July 1999, Prague, Czech Republic. Graficke zavody Hronov, Prague, Czech Republic.

Osbrink, W.L.A., A. R. Lax, and R. J. Brenner. 2001. Insecticide susceptibility in *Coptotermes formosanus* and *Reticulitermes virginicus* (Isoptera: Rhinotermitidae). J. Econ. Entomol. 94: 1217–1228.

Osbrink, W.L.A., M. L. Cornelius, and R. Lax. 2008. Effects of flooding on field populations of Formosan subterranean termites (Isoptera: Rhinotermitidae) in New Orleans, Louisiana. J. Econ. Entomol. 101: 1367–1372.

Peters, B., and C. Fitzgerald. 2003. Field evaluation of the bait toxicant chlorfluazuron in eliminating *Coptotermes acinaciformis* (Froggatt) (Isoptera: Rhinotermitidae). J. Econ. Entomol. 96: 1828–1831.

Peters, B., and S. Broadbent. 2005. Evaluating a termite interception and baiting system in Australia, Thailand and the Philippines, pp. 229–232. *In* Chow-Yang Lee and William H. Robinson (eds.), Proceedings, 5th International Conference on Urban Pests, 10–13 July 2005, Suntec, Singapore. Perniagaan Ph'ng P&Y Design Network, Malaysia.

Potter, M. 1997. Termites,, pp. 232–333. *In* S. A. Hedges and D. Moreland (eds.), Mallis handbook of pest control, 8th ed. Mallis Handbook and Technical Training Company, Cleveland, OH.

Potter, M., E. Eliason, K. Davis, and R. Bessin. 2001. Managing subterranean termites (Isoptera: Rhinotermitidae) in the Midwest with a hexaflumuron bait and placement considerations around structures. Sociobiology 38: 565–584.

Rojas, M., J. Morales-Ramos, M. Lockwood, L. Etheridge, J. Carroll, C. Coker, and P. Knight. 2008. Area-wide management of subterranean termites in south Mississippi using baits. USDA–ARS Tech. Bull. 1917.

Scheffrahn, R. H., and N.-Y. Su. 1994. Keys to soldiers and winged adult termites (Isoptera) of Florida. Fla. Entomol. 77: 460–474.

Simms, D., and C. Husseneder. 2009. Assigning individual alates of the Formosan subterranean termite (Isoptera: Rhinotermitidae) to their colonies of origin within the context of an area-wide management program. Sociobiology 53: 631–650.

Su, N.-Y. 2002. Novel technologies for subterranean termite control. Sociobiology 40: 95–101.

Su, N.-Y. 2003. Baits as a tool for population control of the Formosan subterranean termite. Sociobiology 41: 177–192.

Su, N.-Y., and M. Lees. 2009. Biological activities of a bait toxicant for population management of subterranean termites, pp. 87–96. *In* C. J. Peterson and D. M. Stout II (eds.), Pesticides in household, structural and residential pest management. Am. Chem. Soc. Symp. Ser. 1015. American Chemical Society, Washington, DC.

Su, N.-Y., and M. Tamashiro. 1987. An overview of the Formosan subterranean termite (Isoptera: Rhinotermitidae) in the world, pp. 3–15. *In* M. Tamashiro and N.-Y. Su (eds.), biology and control of the Formosan subterranean termite. Hawaii Institute of Tropical Agriculture and Human Resources Research Extension Series 083, University of Hawaii and Manoa, Honolulu, HI.

Su, N.-Y., and R. Scheffrahn. 1986. A method to access, trap, and monitor field populations of the Formosan subterranean termite (Isoptera: Rhinotermitidae) in the urban environment. Sociobiology 12: 299–304.

Su, N.-Y., and R. H. Scheffrahn. 1993. Laboratory evaluation of two chitin synthesis inhibitors, hexaflumuron and diflubenzuron, as bait toxicants against Formosan and eastern subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol. 86: 1453–1457.

Su, N.-Y., and R. H. Scheffrahn. 1998. A review of subterranean termite control practices and prospects for integrated pest management programs. Integr. Pest Manag. Rev. 3: 1–13.

Su, N.-Y., and M. Tamashiro. 1987. An overview of the Formosan subterranean termite (Isoptera: Rhinotermitidae) in the world, pp. 3–15. *In* M. Tamashiro and N.-Y. Su (eds.), Biology and control of the Formosan subterranean termite. College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu, HI.

Su, N.-Y., P. Ban, and R. H. Scheffrahn. 2004. Use of a bait impact index to assess effects of bait application against populations of Formosan subterranean termite. J. Econ. Entomol. 97: 2029–2034.

Sukartana, P., G. Sumarni, and S. Broadbent. 2009. Evaluation of chlorfluazuron in controlling the subterranean termite *Coptotermes curvignathus* (Isoptera: Rhinotermitidae) in Indonesia. J. Trop. For. Sci. 21: 13–18.

Systat Software. 2008. SigmaPlot users guide: statistics, version 11. Systat Software, San Jose, CA.

Vargo, E. 2003. Genetic structure of *Reticulitermes flavipes* and *R. virginicus* (Isoptera: Rhinotermitidae) colonies in an urban habitat and tracking of colonies following treatment with hexaflumuron bait. Environ. Entomol. 32: 1271–1282.

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