Persistence and Efficacy of Termiticides Used in Preconstruction Treatments to Soil in Mississippi

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ABSTRACT Laboratory and field studies were conducted to determine the persistence and efficacy of termiticides used as preconstruction treatments against subterranean termites. Bifenthrin (0.067%), chlorpyrifos (0.75%), and imidacloprid (0.05%) ([AI]; wt:wt) were applied to soil beneath a monolithic concrete slab at their minimum labeled rates. Soil samples were taken from three depths (0–2.5, 2.6–7.6, and 7.7–15.2 cm) at six sampling times (0, 3, 6, 9, 12 and 48 mo) from sites in Harrison and Oktibbeha counties in Mississippi. Residue analyses were conducted on the 0–2.5- and 2.6–7.5-cm depths, and bioassays were conducted using all three depths. In field studies, significant termiticide degradation occurred between sampling times 0 and 48 mo for all termiticides. At all sampling times, the top 2.5 cm of soil contained more termiticide than the other depths. Time to 50% dissipation of termiticide in the 0–2.5-cm depth was 9, 6, and 2 mo for bifenthrin, chlorpyrifos, and imidacloprid, respectively. Termite mortalities in contact bioassays remained high for bifenthrin and chlorpyrifos throughout the 48-mo sampling period; however, mortality of termites exposed to imidacloprid-treated soil dropped after the initial sampling. Termites readily penetrated all termiticide-treated soil in bioassays of 52-mm soil cores at 48 mo. Percentage of mortality in these bioassays was 15, 43, and 13 for bifenthrin, chlorpyrifos, and imidacloprid respectively.

KEY WORDS termiticide, residue, toxicity

Preconstruction treatment of soil with termiticides is a common practice, especially in the southern United States. Whereas registered termiticides are expected to protect a home for 5 yr, the efficacy and longevity of termiticides vary with the chemical class of termiticide, type of soil, amount of annual rainfall, and to some extent the amount of termite pressure. Numerous studies have documented the efficacy of termiticides applied to soil as barriers to termite penetration (Jones 1990; Smith and Rust 1990, 1991, 1992; Su and Scheffrahn 1990; Grace 1991; Forschler 1994; Su et al. 1995; Gold et al. 1996). But only a few studies have compared the persistence and efficacy of termiticides in the field. Both Su et al. (1993) and Gold et al. (1996) showed diminishing effectiveness of termiticides over time.

Studies of termiticide degradation have been done by Racke et al. (1994) who conducted dissipation studies of chlorpyrifos in soil and foliar applications. Also, Baskaran et al. (1999) determined the degradation of bifenthrin, chlorpyrifos, and imidacloprid applied at termiticide rates to different soils in the laboratory.

At the time of initiation of this research in 1998, there were three classes of registered termiticides: organophosphates, pyrethroids, and chloronicotinyls. As might be expected, each class has different effects on termites. Organophosphates kill termites quickly after minimal penetration into treated soil (Su et al. 1982, Smith and Rust 1990). Pyrethroids are highly toxic to termites; however, termites rarely enter treated areas because pyrethroids are also highly repellent to termites (Su et al. 1993). Chloronicotinyls are the newest class of termiticides in this study. This class of termiticide is represented in this study by imidacloprid, which has been called a delayed action, nonrepellent chemical because of its slow toxicity and imperceptibility to termites at registered rates.

In this study, three termiticides, registered for pretreatment of soil, were evaluated for the amount of termiticide residue present in soil on the day of treatment and up to 4 yr posttreatment. Specifically, information pertaining to the depth of the termiticide barrier in the soil was sought. The efficacy of the termiticides in this study against termites also was evaluated over time in laboratory bioassays.

Materials and Methods

Site Description. The two sites used in this study were located on the John W. Starr Memorial Forest in Okitibbeha County, Mississippi, and the Harrison Experimental Forest in Harrison County, Mississippi, on

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the central Gulf Coast. Oktibbeha County generally has a warm, humid climate with average temperatures ranging from 7°C in January to 27°C in July. Average rainfall is ≈130 cm per year, and the soil type at the site is a Prentiss silt loam with an average pH of 5.17. The Prentiss series consists of 38% sand, 58% silt, and 4% clay.

Harrison County also has a warm, humid climate with temperatures ranging from 7°C in January to 35°C in July. The average rainfall is 170 cm per year, and the soil type is Rumford sandy loam with an average pH of 5.10. The Rumford series contains 70% sand, 25% silt, and 5% clay.

Monolithic Slab Study. In June 1998, square plots at both sites were cleared of debris on the soil surface and roots within the soil so that termiticide penetration into the soil would not be inhibited. A 61.0-cm square frame constructed of 2.5- by-2.5-cm pine strips was placed over the cleared area, and the area inside the wooden frame was treated with one of the following termiticide solutions at a volume of 4.07 liters/m^2: bifenthrin (Biflex TC, 0.067%, FMC Corp., Agricultural Products Group, Philadelphia, PA.), chlorpyrifos (Dursban TC, 0.75%, Dow Agrosciences, LLC, Indianapolis, IN), or imidacloprid (Premise FT, 0.05%, Bayer CropScience, Research Triangle Park, NC) ([AI]; wt:wt). A water only control treatment was placed in each group of plots. A 6-mm-thick polyethylene vapor barrier was placed over each treated area, and concrete was poured over the vapor barrier until it reached the top of the wooden frame. The next day, after the concrete had hardened, soil samples for the 0 time period were collected from beneath the slab by lifting the slab with a hoe and inserting a soil sampling probe. This procedure was replicated five times at both sites for each termiticide concentration and the control for a total of 20 plots per site.

Three soil cores were collected from each site from each of three depths (0–2.5, 2.6–7.6, and 7.7–15.2 cm) at 0-, 3-, 6-, and 12-mo intervals. The three soil cores from each depth were combined to form a composite soil sample representing each depth.

Residue Analysis. During the first 12 mo of the study, residue analyses were conducted at the Mississippi State Chemical Laboratory, Mississippi State University. Moisture content determinations were made for each sample by weighing 5.0-g aliquots, heating in a 105°C oven for 24 h, and then reweighing to determine weight loss. Samples for bifenthrin and chlorpyrifos analyses were extracted by a modification of EPA Method 3550. A 2.0-g sample was extracted with 10 ml of acetone by using a Heat Systems-Ultrasonics Models W-385 sonicator equipped with a micro-tip probe for 2 min on a 50% duty cycle with a 2-s cycle time delay. Samples were centrifuged 10 min at 1000 rpm, and the acetone was pipetted into a graduated concentrator tube. The extraction was repeated two additional times, and the extracts were combined. Volume adjustment was made to 20 ml followed by appropriate dilutions with hexane.

Imidacloprid samples (25.0 g) were weighed into 250-ml centrifuge bottles, and 50 ml of acetonitrile/water (80:20) was added. The samples were shaken on a wrist-action shaker for 15 min and then centrifuged at 1500 × g for 5 min. The extract was decanted into a graduated cylinder, and the extraction was repeated two more times. Extracts were combined and final volume was adjusted to 150 ml.

All samples were analyzed with five-point calibration curves (0.995 correlation or better) and midpoint verifications (10%). Samples for bifenthrin and chlorpyrifos were analyzed on a Varian 3600 gas chromatograph equipped with dual electron capture detectors and a Varian 8100 autosampler. The primary column was a J&W 30-m DB-5 megabore (0.53-mm i.d.) with 1.5-μm film thickness. The parameters of the residue analysis method were as follows: injection volume, 1 μl; carrier gas, hydrogen; make-up gas, nitrogen; injector temperature, 230°C; detector temperature, 300°C; and oven temperature program, 150°C for 5 min, 5°C/min ramp to 170°C, 10°C/min ramp to 220°C for 15 min. Retention times of chlorpyrifos and bifenthrin were 18.024 and 30.026 min, respectively.

Imidacloprid samples were analyzed using a Waters carbamate analysis system equipped with a model 712B WISP autosampler and Waters 484 UV detector. The parameters of the residue analysis method were as follows: column, Phenomenex Lichrosphere 5 RP-Select B (250 ×4.00 mm) and guard cartridge; mobile phase, acetonitrile/water (isocratic) (50:50) at 1.0 ml/min; wavelength, 270 nm; and injection volume, 50 μl. Retention time of imidacloprid was 3.48 min.

During residue analyses, moisture content was determined for each sample collected, and quality controls consisting of a blank soil sample, a spiked sample, and two duplicates for each termiticide were run for each sample period from each site. Percentage of recoveries of termiticides from soil by using extraction methods during the first year were chlorpyrifos, 95 ± 4.3, bifenthrin, 93 ± 3.9; and imidacloprid, 101 ± 1.3%.

At the 48-mo sampling, four 15.2-cm and three 10.0-cm-deep soil samples from each plot were collected in 2.5-cm-diameter butyrate (Tenite) sampling tubes by using a soil sampling probe. One of the 15.2-cm cores was used for residue analysis. The remaining three 15.2- and the 10.0-cm cores were used in contact and penetration bioassays, respectively. Samples collected at 48 mo were analyzed by the Wood Products Insect Research Unit, Starkville, MS. Extraction of residues was done using an accelerated solvent extractor, ASE-200 (Dionex, Sunnyvale, CA). The 15.2-cm tubes containing soil cores were cut into 0.2.5- and 2.6–7.5-cm sections by using a bandsaw. Soil from each layer was removed from tubes and mixed in a 100-ml beaker. Chem-Tube Hydromatrix (Varian, Palo Alto, CA) was mixed with the soil to bring the volume of soil and Hydromatrix to 40 ml. The contents of the beaker were then poured into a 33-ml extraction tube. Extraction was made with the ASE-200 by using a 70:30 mixture of acetone/acetonitrile at a total volume of 50 ml. Oven temperature and pressure were 100°C and 105.4 kg/cm^2 with a 5-min static time. Extraction volume was reduced to 10 ml under nitrogen by using a Rapid Vac (Labconco, Kansas City, MO). An Agilent 5990

gas chromatograph was used to analyze for bifenthrin and chlorpyrifos. Bifethrin residues were analyzed using an electron capture detector. The parameters of the bifenthrin analysis method were as follows: injection volume, 1 μl; carrier gas, helium; make-up gas, argon/methane; injector temperature, 250°C; detector temperature, 300°C; and oven program, 225°C initial temperature with a 30°C/min ramp to 280°C for 8 min. An Agilent 25-m Ultra-1 methyl silicone gum phase column (0.32-mm i.d.) with 0.52-μm film thickness was used. Retention time of bifenthrin was 6.906 min.

Chlorpyrifos residues were analyzed using a flame photometric detector. The parameters of the chlorpyrifos analysis method were as follows: injection volume, 1 μl; carrier gas, helium; injector temperature, 200°C; detector temperature, 250°C; and oven program, 125°C initial temperature with a 25°C/min ramp to 250°C for 2 min. An Agilent 25-m Ultra-1 methyl silicone gum phase column (0.32-mm i.d.) with 0.52-μm film thickness was used. Retention time of chlorpyrifos was 6.776 min.

Imidacloprid residues were analyzed using a Waters Alliance 2695 high-pressure liquid chromatograph equipped with a Waters 996 photodiode array detector. The parameters of the residue analysis method were as follows: column, Agilent Zorbax Elipse XDB-C18 column (4.6 by 150 mm); mobile phase, acetonitrile/water (gradient) (65:35) at 2.0 ml/min; wavelength, 254 nm; and injection volume, 10 μl. Retention time of imidacloprid was 3.547 min. Percentage of recoveries of termiticides from soil by using extraction methods at 48 mo were chlorpyrifos, 107 ± 1.8, bifenthrin, 100 ± 9.8; and imidacloprid, 51 ± 2.4%.

Contact Bioassay. Termites were collected from fallen logs on the Noxubee National Wildlife Refuge outside of Starkville and held in 37-liter galvanized cans in the laboratory. The bioassay unit was similar to the one described by Jones (1986). During the 0–12-mo sampling interval, contact toxicity of each termiticide was determined by confining 10 worker termites, *Reticulitermes flavipes* (Kollar), in a 2.5-cm-diameter petri dish that contained a thin layer of 1% agar in the bottom of the dish beneath the soil. Bioassays of bifenthrin and chlorpyrifos were terminated after 48 h. The bioassay of imidacloprid was terminated after 7 d. Two controls consisting of five 2.5-cm petri dishes were used in the bioassays, one control for comparison with bifenthrin and chlorpyrifos and one control for imidacloprid. The control and bioassay units for imidacloprid contained a pine block that was added to each petri dish as a food source because of the extended evaluation period. Any termites found on pine blocks during mortality readings were brushed from the block onto the treated soil by using a small paint brush. Bioassays for the termiticides were replicated five times at each sample period for each depth and site, for a total of 110 bioassay units per sample period.

Contact bioassays at the 48-mo sampling were the same as at the 0–12-mo sample times except that 10 workers from each of three *Reticulitermes* spp. colonies were used for each soil sample. Also, there was only one set of controls instead of one each for the bifenthrin–chlorpyrifos group and one for imidacloprid. These controls were inadvertently discarded after the 48-h mortality recordings instead of after the 7-d mortality recordings of imidacloprid.

Penetration Bioassay. At the 48-mo sample time, a penetration bioassay was conducted in addition to the contact bioassay. Bioassays were conducted with termites from three *Reticulitermes* spp. colonies that were collected from fallen pine logs separated from each other by at least 1,000 m in the Tombigbee National Forest near Ackerman, MS, and held at ambient temperature in 37-liter galvanized trash cans in the laboratory.

The bioassay method used was similar to that described by Su et al. (1993). In our bioassay, the 10.0 cm of soil in the sample tube was reduced to 5.2 cm by pushing out the bottom 4.8 cm of soil. The tube containing the 5.2 cm of soil was connected by a Tygon tubing collar to another tube containing 80 workers and one soldier. The 5.2-cm soil core was sandwiched between two 3.0-cm agar segments with a 0.5-cm layer of sand between the soil and the lower agar segment to prevent possible movement of termiticide from the soil to the agar. Wooden sticks of southern yellow pine, *Pinus taeda* L., and paper strips provided food and harborage for termites in both the tube containing termites and the tube with soil, so that termites had a source of food both above and below the treated soil. The bioassay was terminated after 7 d at which time mortality as well as distance tunneled through treated soil (penetration) was determined.

Data Analysis. Models of termiticide degradation (log residue = month) for each termiticide and soil depth were obtained using PROC REG of SAS (SAS Institute 2001). Half-lives of each termiticide at each soil depth were then calculated (assuming first order degradation kinetics) by dividing the natural log of 0.5 (0.69) by the estimated slope of the regression. The monolithic slab study was a split-plot study with site as whole plot and depth as subplot. Termite mortality was analyzed as repeated measures by using the mixed procedure (PROC MIXED) of SAS. Termite mortalities from each soil depth were analyzed separately. Mean separation was made using the PDIFF option.

Results and Discussion

There were no significant differences in termite mortality, penetration, and termiticide residue between sites. Therefore, all data were averaged over sites.

Residue. The termiticides used in this study decreased in concentration over time. Mean residues (±SEM) for each termiticide are shown in Table 1, and the degradation models and R^2 values are shown in Table 2. Bifenthrin, chlorpyrifos, and imidacloprid residues in the 0–2.5-cm depth had half-lives of 13.0, 8.2, and 4.9 mo, respectively.

Bifenthrin residue in the 0–2.5-cm depth at 6 mo was about one-half of the initial concentration on the

Table 1. Residues (ppm) of termiticides (mean ± SEM) in soil collected from two depth ranges

Mo posttreatment	Bifenthrin	Chlorpyrifos	Imidacloprid
0–2.5-cm depth			
0	51.4 ± 5.3	616.0 ± 29.2	60.4 ± 5.7
3	48.0 ± 7.0	353.0 ± 26.9	18.4 ± 2.9
6	29.4 ± 3.2	300.0 ± 42.9	15.7 ± 1.8
9	24.9 ± 2.6	230.0 ± 18.5	10.8 ± 1.6
12	25.0 ± 2.3	296.0 ± 42.4	9.8 ± 1.6
48	5.1 ± 1.3	11.9 ± 2.8	0.7 ± 0.4
2.6–7.6-cm depth			
0	0.9 ± 0.2	56.1 ± 9.1	2.8 ± 0.8
3	3.5 ± 1.1	41.0 ± 7.2	4.1 ± 1.3
6	1.8 ± 0.6	25.3 ± 10.1	2.5 ± 0.3
9	1.5 ± 0.3	22.2 ± 5.0	1.9 ± 0.2
12	0.8 ± 0.1	39.3 ± 5.9	1.7 ± 0.3
48	0.2 ± 0.1	2.3 ± 0.1	0.9 ± 0.8

day of treatment. The degradation model for bifenthrin applied at 0.067% was log residue = 3.79–0.053 (mo) (Table 2). Su et al. (1999a) applied bifenthrin at 0.031% to sand in Florida and obtained a degradation model of ln(ppm) = 1.66–0.1316 (mo) over 60 mo in samples at a 0–5-cm depth. The model by Su et al. (1999a) had a higher degradation rate, most likely because of a lower application rate. Gold et al. (1996) uniformly treated five different sieved soils in Texas with registered formulations of six different active ingredients by using a cement mixer. The mean concentration of bifenthrin in covered plots, averaged over all soils, at 48 mo was 2.4 ppm, which is slightly lower than the 5.1 ppm concentration in the 0–2.5-cm soil layer in our study.

Degradation of chlorpyrifos has been shown to be concentration dependent, i.e., lower application rates degrade faster (Cink and Coats 1993). Racke et al. (1994) in dissipation studies of chlorpyrifos under laboratory conditions obtained half-lives of 175, 214, 230, 335, and 1576 d in five soils from different U.S. states. The half-life of chlorpyrifos, 8.2 mo (249 d), found in our study was most similar to that of a sandy loam (76% sand, 15% silt, 9% clay, pH 5.7) from Hawaii in which chlorpyrifos had a half-life of 335 d in test of Racke et al. (1994). The degradation of chlorpyrifos would be expected to be faster in our field test compared with constant temperature and moisture in a laboratory.

Baskaran et al. (1999) determined half-lives of bifenthrin, chlorpyrifos, and imidacloprid in Australian soil in the laboratory under constant temperature (25°C) and moisture (60% maximum water holding capacity) to be 1332 d (43.8 mo), 462 d (15.2 mo), and 990 d (32.6 mo), respectively. Their estimates of half-lives for these termiticides were greater than those in our field study in Mississippi, which would be expected for soil in a controlled environment. Bayer Corporation (1997) reported a half-life of imidacloprid of 6–12 mo, which is somewhat longer than our value of 4.9 mo.

Table 2. Termiticide half-lives and regressions of residue on time

Termiticide	Depth (cm)	Half-life (mo)	Model	R^2
Bifenthrin	0–2.5	13.0	Log residue = 3.79–0.053 (mo)	0.75
	2.6–7.6	13.8	Log residue = 0.38–0.050 (mo)	0.35
Chlorpyrifos	0–2.5	8.2	Log residue = 6.27–0.084 (mo)	0.89
	2.6–7.6	9.2	Log residue = 3.71–0.075 (mo)	0.60
Imidacloprid	0–2.5	4.9	Log residue = 3.63–0.140 (mo)	0.72
	2.6–7.6	6.8	Log residue = 1.31–0.102 (mo)	0.55

Table 3. Results of analysis of variance of mortality in contact bioassays

Effect	Numerator df	Denominator df	*F* value	*P* value
Depth 0–2.5 cm				
Termiticide	4	5	160.08	<0.0001
Termiticide*mo	18	213	6.32	<0.0001
Depth 2.6–7.6 cm				
Termiticide	4	5	49.97	0.0002
Termiticide*mo	18	211	5.20	<0.0001
Depth 7.7–15.2 cm				
Termiticide	4	5	49.27	0.0002
Termiticide*mo	18	210	4.54	<0.0001

Contact Bioassay. Significant differences in termite mortality were found among termiticides at all soil depths (Table 3). Significant interactions between termiticide and month also were found for each soil depth (Table 3). Termite mortality generally remained high throughout the sampling times for all compounds except imidacloprid (Table 4). Mortalities during the 6-mo bioassay were unusually low for all treatments except the control. These low mortalities cannot be explained.

Mortalities ranged from 70 to 100% at the three depths at day 0 for all termiticides except imidacloprid at 7.7–15.2-cm depth. The high mortalities observed in contact bioassays of soil below 2.5 cm immediately after application suggest that these compounds were penetrating below 7.7 cm within 24 h of application (Table 4). Beal and Carter (1968) collected soil samples down to 9.5 cm 24 h after application with an emulsifiable concentrate formulation of dieldrin to sandy soil in Florida. They reported recovering 7.4% (106 ppm) of the total amount found in the soil profile at the 4.4–7.0-cm depth and 2.3% (32.6 ppm) at the 7.0–9.5-cm depth. Smith and Rust (1992), in a laboratory study of water-induced movement of termiticides down soil columns, observed lethal effects of chlorpyrifos, chlordane, and cypermethrin at soil depths of 30, 7, and 7 cm, respectively. In our test, residues of termiticides penetrating to the 2.6–7.6-cm depth 24 h after application ranged from 56.1 ppm for chlorpyrifos to 0.90 ppm for bifenthrin (Table 1).

The susceptibility of termites to pyrethroids and organophosphates has been demonstrated in contact bioassays by the USDA Forest Service, Starkville (unpublished data). In one such bioassay conducted 9.5 yr after soil had been treated with bifenthrin at 5.0 ppm, termites exhibited signs of sluggishness after 30-min

Table 4. Mortality (mean ± SEM) of termites after 48-h exposure to termiticide-treated soil from three depths in contact bioassays

Mo posttreatment	Bifenthrin	Chlorpyrifos	Imidacloprid[a]	48-h Control	7-d Control
			0–2.5-cm depth		
0	100 ± 0.0a	100 ± 0.0a	100 ± 0.0a	3 ± 1.5b	1 ± 1.0b
3	93 ± 2.6a	99 ± 1.0a	26 ± 14.1b	1 ± 1.0a	37 ± 14.5b
6	77 ± 5.6a	35 ± 4.8b	22 ± 13.1bc	2 ± 1.3d	8 ± 3.6c
9	93 ± 3.7a	95 ± 4.0a	40 ± 12.8b	10 ± 9.0c	6 ± 2.2c
12	89 ± 9.0a	85 ± 4.0a	34 ± 14.5b	6 ± 4.0c	15 ± 4.8bc
48	97 ± 3.3a	96 ± 2.7a	0 ± 0.0b	0 ± 0.0b	—[b]
			2.6–7.6-cm depth		
0	92 ± 2.5a	84 ± 4.5a	74 ± 17.8a	3 ± 1.5b	1 ± 1.0b
3	90 ± 4.2a	92 ± 3.4a	14 ± 9.9c	1 ± 1.0d	37 ± 14.5bc
6	22 ± 9.9a	29 ± 8.9a	21 ± 9.2a	2 ± 1.3b	8 ± 3.6b
9	72 ± 7.0a	72 ± 6.3a	61 ± 13.2a	10 ± 9.0b	6 ± 2.2b
12	56 ± 6.4a	67 ± 7.3a	38 ± 14.7a	6 ± 4.0b	15 ± 4.8b
48	16 ± 6.2a	18 ± 6.1a	1 ± 0.7b	0 ± 0.0b	—[b]
			7.7–15.2-cm depth		
0	89 ± 4.3a	70 ± 8.7a	22 ± 19.6b	3 ± 1.5c	1 ± 1.0c
3	90 ± 5.8a	98 ± 2.1a	32 ± 15.0b	1 ± 1.0c	37 ± 14.5b
6	30 ± 6.7a	15 ± 6.2a	13 ± 3.7ab	2 ± 1.3b	8 ± 3.6b
9	67 ± 8.7a	74 ± 6.7a	29 ± 10.7b	10 ± 9.0bc	6 ± 2.2c
12	55 ± 8.5ab	74 ± 6.5a	43 ± 15.6b	6 ± 4.0c	15 ± 4.8c
48	6 ± 4.0a	4 ± 1.6a	0 ± 0.0a	0 ± 0.0a	—[b]

In a row, percentages followed by the same letter are not significantly different ($P > 0.05$) as determined by PDIFF (SAS Institute 2001).
[a] Bioassays of imidacloprid were run for 7 d.
[b] Seven-day control mortality was not taken.

exposure, and 100% were moribund after 1 h and 45 min. Results of another bioassay showed that 100% of termites were moribund 24 h after exposure to soil treated with 50 ppm chlorpyrifos 5.5 yr before the bioassay. Smith and Rust (1990) showed that soil treated with bifenthrin at just 3 ppm killed 100% of termites placed on it within 3 h. The results of these previous studies indicate that the high mortalities observed in our test should be expected when termites are directly exposed to low concentrations of pyrethroids and organophosphates.

Penetration Bioassay. In tube bioassays of soil samples collected 48 mo after treatment, chlorpyrifos-treated soil had the highest toxicity ($F = 7.88, 3, 3; P > F = 0.0619$) (Table 5). Mortalities of termites on bifenthrin and imidacloprid treated soils were not different from that of the control. Termite penetration of soil treated with bifenthrin, chlorpyrifos, and imidacloprid was not significantly different from the control (Table 5).

Su et al. (1999a) determined field degradation rates of pyrethroids and organophosphates under miniature slabs. Termite mortality was 15.2% in penetration bioassays of soil cores from plots treated with bifenthrin (0.033%) 48 mo after application. Termites penetrated an average of 45 of 50 mm of treated soil. In our study, termite mortality (15%) and penetration (41 mm) in soil treated with bifenthrin at 0.067% was similar to that observed by Su et al. (1999a) in fill-sand treated with one-half the rate of bifenthrin. These results may be because of differences in bifenthrin's activity in the sandy loam of our tests compared with the sand used by Su et al. (1999a). Others have reported on the importance of soil type in efficacy tests. Harris (1972) in his review of insecticide efficacy in soil reported that insecticide activity varied greatly in relation to soil type and moisture. Insecticide efficacy varies inversely with clay content of soil. Forschler and Townsend (1996) found higher termiticidal activity in constant exposure bioassays in sand versus a sandy loam, a sandy clay loam, and a sandy clay soil. Smith and Rust (1993) showed that sand with high concentrations of clay (10–20%) binds chlorpyrifos, making it less apparent and less toxic to termites. Although, clay concentrations in the soils in Mississippi were only ≈5%, it could have been enough to reduce the bioavailability of bifenthrin residues.

Table 5. Average termite mortality and termite penetration (mean ± SEM) into 52-mm cores of termiticide-treated soil collected 48 mo after initial application

Treatment	AI (%)	7-d Mortality (%)	7-d Penetration (mm)
Bifenthrin	0.067	15 ± 3.3b	41 ± 3.4a
Chlorpyrifos	0.75	43 ± 7.0a	46 ± 2.7a
Imidacloprid	0.05	13 ± 2.0b	47 ± 2.9a
Control	0.0	12 ± 1.7b	43 ± 3.6a

In a column, means not followed by the same letter are significantly different ($P \leq 0.0619$) as determined by PDIFF (SAS Institute 2001).

As with bifenthrin, termite mortality (13%) and penetration (47 mm) of imidacloprid-treated soils was not significantly different from the control (Table 5). Gahlhoff and Koehler (2001) observed 20% mortality and complete penetration (50 mm) of sand treated with imidacloprid at 10 ppm, which is 10 times the level of imidacloprid (0.9 ppm) that was recovered from soil at 48 mo in our test.

Soil cores from plots treated with chlorpyrifos (1.0%) by Su et al. (1999a) had a mean termite mortality of 23.5% and a mean penetration of 50 of 50 mm,

48 mo after application. Su et al. (1999b), in concrete slab tests of chlorpyrifos degradation, treated 50- by 50-cm plots of fill-sand with a 1.0% solution of Dursban TC. In penetration tests of 5.0-cm sand cores at 48 mo, termite mortality and penetration were 15% and 49 mm, respectively. Termite mortality (43%) was higher at 48 mo after application with chlorpyrifos at 0.75% in our study, whereas penetration (46 mm) was similar to that of Su et al. (1999b) (Table 5). Differences in mortality could be because of differences in characteristics of soils used in the two studies.

Su et al. (1982) stated that diazinon, chlorpyrifos, chlordane, and carbaryl, which quickly kill termites upon entering a treated area, become repellent to termites when many dead and decaying individuals accumulate in a treated area. In our study, 43% of termites in tubes with chlorpyrifos-treated soil died, yet penetration was not reduced. However, the rate at which termites in this study died is not known nor is the location of death.

There were two types of bioassays conducted at 48 mo after application: contact and penetration bioassays. The disparity of results between the two bioassays (Tables 4 and 5) reflects inherent differences in test methods. In a contact bioassay, termites are placed directly on treated soil and are exposed to termiticide residues for the duration of the test (48 h). In a penetration bioassay, termites are not in direct contact with treated soil for the duration of the test. The low mortality and reduced repellency in the penetration bioassay suggests that termites tunneling into treated soil may be able to avoid contact with toxic concentrations of termiticide in the construction of their tunnels (Table 5). The amount of exposure of individual termites is unknown. Individual termites involved in tunnel construction may limit the amount of time spent exposed to toxic residues by sharing in the construction of tunnels, thus reducing uptake of the termiticide by individual termites (Jones 1990). Also, the top and bottom of the tube are open spaces free of treated soil where termites can avoid exposure. Tunnels were constructed mostly between the soil core and the interior wall of the tube in our study, thus minimizing the amount of contact termites had with treated soil.

The influence of soil type on termiticide performance has been discussed previously. The preparation of soil before termiticide treatment also could have effects on termiticide efficacy. Researchers have reported making application of bifenthrin to sieved soil (Smith and Rust 1990), fill-grade sand (Su and Scheffrahn 1990), and soil in a cement mixer (Gold et al. 1996). The overall results of these studies show no termite penetration into soil that contained 1.0–2.4 ppm bifenthrin. In our study, soil cores containing 5.1 ppm bifenthrin were penetrated by termites. Treatment of sieved soil, fill-grade sand, and soil in a cement mixer are vastly different than application to soil in a forest as was done in our study. It is possible that soil cores collected from our study sites in the forest contained roots and other organic matter as well as excavations created by other soil invertebrates that could provide passage ways for termites through treated soil. The relatively low concentration of bifenthrin in the soil at 48 mo and opportunities to avoid bifenthrin residues (i.e., tube walls, roots and organic matter, and excavations of other soil invertebrates) are possible reasons why termites were able to overcome the repellency and toxicity of bifenthrin in our penetration bioassay.

Results of this study provide evidence that most of the termiticide encountered by termites is within the top 2.5 cm of soil. Therefore, application of a thorough, continuous termiticide barrier to the soil beneath structures is essential for protection against termite infestation. Any disruption of this barrier by construction workers, pest control operators, or building inspectors after application and before construction of the building foundation will diminish the effectiveness of the barrier.

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