



RESEARCH ARTICLE - TERMITES

Field Distance Effects of Fipronil and Chlorfenapyr as Soil Termiticides Against the Desert Subterranean Termite, *Heterotermes aureus* (Blattodea: Rhinotermitidae)

PB BAKER, JG MIGUELENA

Department of Entomology, University of Arizona. Tucson, Arizona, USA

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Og DeSouza, UFV, Brazil

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Corresponding author

Paul B. Baker

Department of Entomology

University of Arizona

Baker & Associate LLC

24733 S. Stoney Lake Dr. Sun Lakes,
AZ 85248 - Tucson, Arizona, USA.

E-Mail: pbaker@ag.arizona.edu

Abstract

A desirable trait of termiticides is that they suppress termite activity at a distance from the site of application. Fipronil and chlorfenapyr are two non-repellent termiticides that display delayed toxicity and are therefore good candidates for yielding distance effects. We assessed their effects as soil-applied termiticides for the management of the desert subterranean termite, *Heterotermes aureus* (Snyder), under field conditions in southern Arizona. Our approach involved recording termite activity within field experimental grids consisting of termite-monitoring stations at selected distances from a termiticide application perimeter. Fipronil-treated plots experienced large and significant reductions in termite presence and abundance relative to controls in stations immediately adjacent to treated soil. However, there was no evidence of reductions in termite activity in stations further away from the soil treatment. In contrast, termite abundance and presence in stations decreased relatively to controls after chlorfenapyr application in whole experimental grids and in several grid sections spatially separated from treated soil. These reductions were especially evident in the five central stations surrounded by the treatment perimeter and in the furthest set of stations. The spatial pattern of changes in chlorfenapyr plots was consistent with termiticide transfer as a mechanism behind distance effects. The impact of fipronil and chlorfenapyr on termite populations in our study suggest that they can both be useful for the management of *H. aureus*, although each might be suited for different management goals. Our results also suggest that perimeter treatments alone are not sufficient to accomplish full control of large *H. aureus* infestations.

Introduction

The desert subterranean termite, *Heterotermes aureus* (Snyder), is the main termite of economic importance in the southwestern United States (Su & Scheffrahn, 1990) and the northwestern coast of Mexico (Canello & Myles, 2000). Desert subterranean termites are considered a structural pest due to their capacity to consume and damage wood and other cellulose-based products. With as many as 300,000 individuals per colony (Baker & Haverty, 2007), unchecked infestations can cause severe structural damage. Liquid insecticides applied to the soil are one of the main tools

employed for the management of this species since they can be used to increase termite mortality and create a protective barrier around structures (Rust & Su, 2012).

A desirable trait of termiticides is that they cause mortality or suppression of termite activity at a distance from the site of application. This reduces the effort and cost of managing infestations and allows for the prevention and reduction of termite damage, even in locations that are hard to reach. One way that these effects may occur is by the transfer of termiticides between nestmates. In termiticide transfer, termites exposed to an insecticide come in contact with unexposed termites and pass a dose of toxicant to them through



social interactions. These recipients may in turn transfer the insecticide to other termites in the colony, thus magnifying the potential for termite mortality. Termiticides capable of being transferred should be non-repellent in order to facilitate exposure by a large number of individuals. They should also display delayed toxicity; that is, mortality and impairment of termites should occur some time after exposure allowing for the possibility of movement and interactions with nestmates (Paul et al., 2018). Delayed toxicity is also important in preventing secondary repellency, which might arise from the accumulation of dead termites and their products near treated areas (Fei & Henderson, 2005; Su, 2005).

Fipronil and chlorfenapyr are two non-repellent insecticides that display delayed toxicity and are therefore good candidates for yielding distance effects when used to treat termite infestations. Fipronil is a broad-spectrum insecticide in the phenylpyrazole chemical family (Hainzl & Casida, 1996). It is widely used in a variety of formulations for the treatment of termite infestations. Formulations containing fipronil are sold under the trade names Termidor (BASF, Florham Park, NJ, USA), Ultrathor (Ensystem, Auburn, NSW, Australia), and Taurus (Control Solutions Inc., Pasadena, TX, USA). Laboratory research has shown that horizontal transfer of fipronil occurs in a variety of termite species (Saran & Rust, 2007; Spomer et al., 2008; Neoh et al., 2014). Furthermore, a few field studies have reported distance effects of fipronil soil application on termite presence near structures in the eastern subterranean termite, *Reticulitermes flavipes* (Kollar) (Potter & Hillery, 2002; Vargo & Parman, 2012).

Chlorfenapyr is an insecticide in the halogenated pyrroles chemical family (Treacy et al., 1994). It is sold under the trade name Phantom by BASF. Laboratory assays with chlorfenapyr have reported varying degrees of horizontal transfer among termites (e.g., Rust & Saran, 2006; Shelton et al., 2006; Misbah-Ul-Haq et al., 2016). Although the effectiveness of fipronil and chlorfenapyr in the management of *H. aureus* is well established (Shelton et al., 2014), no previous research has considered if either insecticide is capable of having distance effects on *H. aureus* activity when applied to soil. To our knowledge, United States Department of Agriculture (USDA) termiticide testing (Shelton et al., 2014) is the only source of information on the efficiency of chlorfenapyr under field conditions currently available in the published literature. In soil adsorption studies, both fipronil (Ying & Kookana, 2006) and chlorfenapyr (Al-Smadi et al., 2019) have been shown to have low potential for mobility and leaching, which suggests that any termite mortality at a distance would result from their interactions with termite behavior and colony structure instead of insecticide dispersal in the soil.

In this study, we assessed the effects of fipronil and chlorfenapyr as soil-applied termiticides for the management of *H. aureus* under field conditions. Considering their delayed toxicity, non-repellency and overall lethality to termites, we hypothesized that fipronil and chlorfenapyr would be capable of having effects on *H. aureus* populations at a distance from

the site of application. Our approach involved recording termite presence and abundance within field experimental grids consisting of termite-monitoring stations at several distances from an application perimeter. This allowed us to consider the capacity of the termiticides to reduce termite activity inside that perimeter and their effect at several distances (< 8 m) from the site of application.

Material and Methods

Study site

The study was conducted at the Santa Rita Experimental Range (SRER), approximately 40 km south of Tucson, AZ (N 31.88397; W 110.88375). The area is classified as a semi-desert grassland (Brown, 1994), which includes cacti, small shrubs, and trees scattered among grasses. Over 50 % of the yearly rainfall is concentrated in July and September, while precipitation is rare from April to June (English et al., 2005). As an area devoted to research for over a hundred years (Sayre, 2003), the SRER has been the site of foundational studies on the biology of desert subterranean termites, such as those by Haverty and Nutting (1975) and Jones (1990). Elevation at our study sites was approximately 984 m. Although we did not take into account precipitation explicitly in our analyses of termite activity, we considered rainfall data from the rain gauge station nearest to our study plots (SRER Station 164) to help make sense of seasonal fluctuations in termite activity.

Field Plot Design

We first surveyed the research area looking for sites heavily infested with *H. aureus*. Then, several transects consisting of 10 to 15 termite-collecting stations were placed within a 1.03 km² area during the spring of 2004. Each collection station consisted of three corrugated cardboard rolls (0.04 × 1.0 m strip of CR 30 × 250 B-flute SF cardboard, Tucson Container Corp, Tucson, AZ) wrapped around a piece of ash wood (*Fraxinus sp.*) (7.5 × 2.5 × 1.25 cm). Cardboard rolls were placed within a section of 0.15 m diameter × 0.15 m long PVC pipe and covered with a concrete brick (20.3 × 15.2 × 2.5 cm). Collection stations were visually inspected monthly for the presence of termites. Once a station was determined to contain several hundred termites, a circular feeding grid was constructed around it. Circular grids were designed to allow measuring the effects of termiticide application at several distances from treated soil. Each grid consisted of 50 collection stations surrounding the central station and placed equidistantly (≈ 3.13 m apart) along the circumference of five circles or rings with increasing radii of 1.5, 2.0, 4.0, 7.0 and 10.0 m. Each ring was designated A-E with the central station being designated by X (Fig 1). Cardboard rolls were labeled to link them to their corresponding monitoring station.

Our setup did not replicate the conditions typical of termite management situations, in which construction features and a combination of treatments (e.g., pre-construction treatments,

wall injections, wood treatments) affect the development of infestations, but it allowed us to assess the effect of soil termiticide perimeters separately from other strategies. Our experimental design also had the advantage of incorporating controls, which are often excluded from field studies in which valuable structures must be protected from damage (Forschler, 2011).

Three untreated control grids were established during the fall and winter of 2004 and were used to assess termite activity in the area for several related studies. Termites from those grids were also used in a mark-recapture study which determined that individuals from all stations within each

control grid belonged to the same colony (Baker et al., 2010).

Three grids designated for treatment with fipronil were established in early 2005 and three more for treatment with chlorfenapyr in the fall of the same year. Visual inspections and collection of termites from stations within grids were conducted monthly from their establishment to mid-2007. Termites present in each station were identified, and those outside cardboard rolls were counted in the field. Termite-infested cardboard rolls inside stations were replaced with new ones and were taken to our laboratory where the termites feeding on them were also counted. Collected termites were not returned to the field.

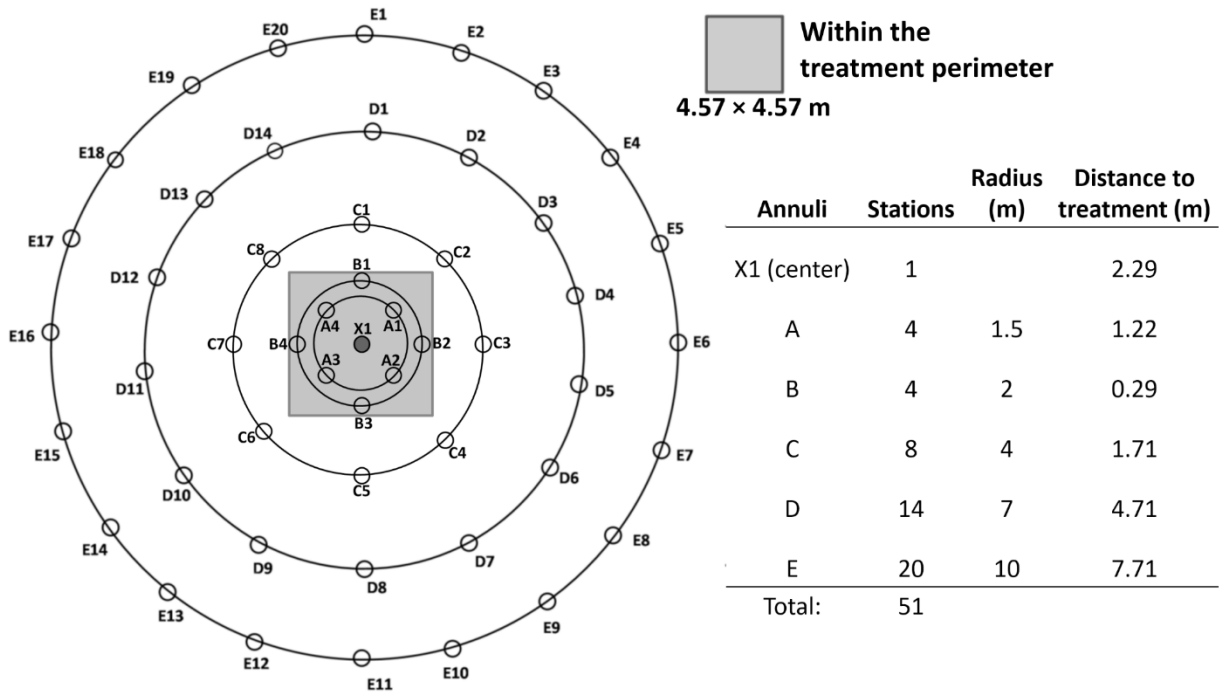


Fig 1. Diagram of experimental grids indicating the location of termite stations, grid sections, and the treatment perimeter. Distances to treatment are minimum horizontal or vertical distances to a side of the treatment perimeter. Exact distances to treated soil vary from station to station and may be smaller.

Termiticides

Fipronil (Termidor SC; 9.1% active ingredient; BASF Corporation, Florham Park, NJ, USA) was applied at a concentration of 0.06 % on November 14, 2005, to three designated plots. The control plots ($n = 3$) were treated with only water on the same day. Chlorfenapyr (Phantom SC; 21.45 % active ingredient; BASF Corporation, Florham Park, NJ, USA) was applied to another three plots at a concentration of 0.125 % on September 19, 2006. All applications were made by the standard procedure of rod and trench at a rate of 4.97 L per m of trench and a depth of 15.4 cm to approximately 18.3 m of soil between the B and C rings of the experimental grids (Fig 1). Applications were made in accordance with label instructions by Johnston's Pest Solutions, a local pest management company. Our final dataset consisted of nine months before and 20 months after application for fipronil, and 12 months before and after application for chlorfenapyr.

Statistical Analysis

We considered two variables to assess changes in termite activity after treatment application: the average counts of termites per station and the percentage of stations occupied by termites. Termite counts consisted of the sum of the termites found inside each station in the field and those inside infested cardboard rolls. Counts of individual termites reflect the intensity of foraging activity of *H. aureus* within the experimental grids and indicate the capacity of the termite population to cause damage to wood products. In contrast, the proportion of stations occupied by termites is an indication of the capacity of the termiticides to exclude termites from sections of the grid or to change termite distribution. Termites of species other than *H. aureus*, which appeared occasionally in stations, were not included in the analysis.

Our statistical analysis was based on mixed-effects regression models used to compare the variables mentioned above in control and treated plots before and after treatment.

Monthly values from each replicate grid were used as response variables. For models considering average termite counts, a cube root transformation was used to improve their normality and homogeneity of variance. Both the abundance and presence of *H. aureus* within stations varied greatly from month to month, so we treated the time of collection as a random effect, and used a restricted effects maximum likelihood approach (REML). A number identifying the plot from which termites were collected was also included as a random effect in order to take into account the particularities of each plot's location that might affect termite activity. Since collections for fipronil and chlorfenapyr grids were done at different times, their data were compared to different subsets of the monthly data from the controls. The models generated compared controls against treated plots and results obtained before or after application, as well as an interaction between those two parameters. The interaction term tested the hypothesis that the response variables from control and treatment plots significantly diverged from each other after application. Since termite activity is greatly influenced by weather and other local environmental factors, experimental plots in the same area resemble each other in the presence and abundance of foraging termites. If termiticides have an effect on termite activity, we would expect the activity levels in treated plots to deviate from those in control plots after application.

The same analyses were performed for whole grids, and subsets of them including the five central stations (the

central station and the A ring), and each of the rings beyond them (B, C, D, and E). The statistical software used for all analyses was JMP 13.1 (SAS Institute, 2016).

Results

A total of 691,572 desert subterranean termites were counted in the field and collected from experimental grids during this study.

Monthly termite activity levels were highly variable during the study period. In control grids, average monthly termite counts of all stations in a given plot ranged between 0.03 and 207.14. Similarly, the monthly percentage of stations occupied by termites ranged from 0 to 64.71 % in control grids. Nevertheless, these fluctuations showed a predictable pattern with activity peaks occurring in September and October and low activity levels taking place during the winter months. According to precipitation data from a nearby rain gauge, activity peaks occurred in months with moderate precipitation (~10 mm in average) that followed one or two months of relatively heavy rains (over 40 mm).

Fipronil

Overall, the pattern of fluctuations in termite counts was similar between control and fipronil plots (Fig 2). According to our mixed-effects model considering termite counts from control and fipronil-treated plots, monthly variations in termite

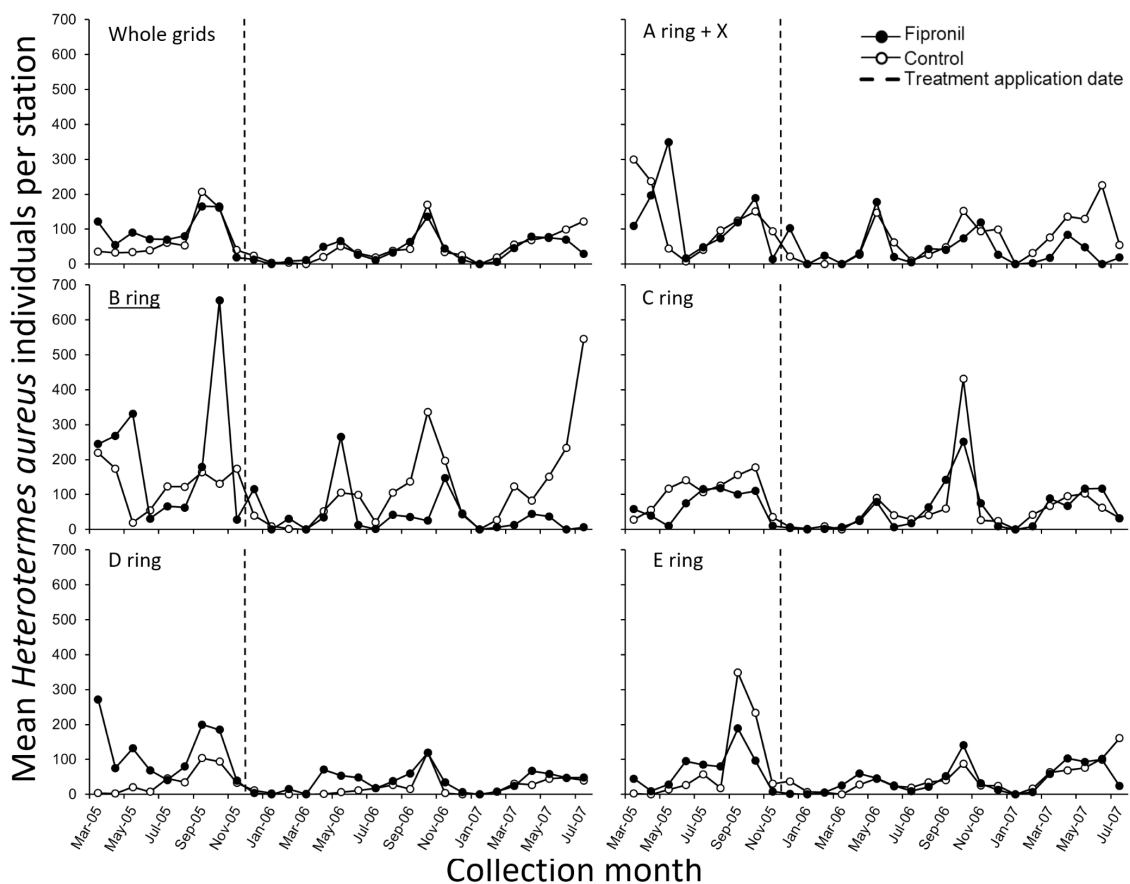


Fig 2. Average number of desert subterranean termites collected per station per month in whole control and fipronil experimental grids and each of their sections ($n = 3$ for each treatment). Labels for every other collection month are included in the horizontal axes. The names of grid sections for which analysis showed a significant change in termite counts with respect to controls after treatment application are shown underlined.

activity occurring simultaneously in all plots accounted for 51.67% of the total variance observed (Wald $p = 0.0011$). Variation due to the particular character of individual plots did not represent a significant proportion of the total variance (Wald $p = 0.24$). Our model also detected a significant decrease in *H. aureus* activity after fipronil application in whole plots (Table 1). However, the interaction term was not significant, indicating that the decrease happened similarly in both control and fipronil-treated plots (Table 1).

Our analyses of termite count from each section of the experimental grids revealed significant effects of the fipronil

treatment only for the stations closest to treated soil (B ring). There were no significant differences between the mean number of termites per station before or after application or between control and fipronil plots (Table 1). The interaction of these two factors was not significant for the five central stations (center station and A ring), or the C, D, and E rings. However, it was highly significant for the B ring (Table 1, Fig 2). In fact, for two of the fipronil replicate grids, the number of termites collected from the B ring became zero immediately after application and remained that way for the rest of the study period, except for one month when two individuals

Table 1. Results of mixed-effects multiple linear regression models for differences between control and fipronil-treated experimental grids based on the mean number of termites collected per station. Parameter estimates are displayed with their 95% confidence intervals. Parameter estimates and confidence intervals were back-transformed before including them in this table. For the interaction term, positive parameter estimates imply higher percentages of stations occupied by *H. aureus* relative to controls after treatment, while negative values imply a decrease. Only fixed effects are included.

Grid section	Intercept	Treatment (control vs fipronil ^a)	Time (before vs after ^a application)	Treatment × Time
Whole plots	37.69(21.17 – 61.13)	0(–0.06 – 0.2)	–0.11(–0.85 – 0)	0(–0.02 – 0)
$R^2 = 0.68$	$p < 0.0001^*$	$p = 0.6296$	$p = 0.0400^*$	$p = 0.2570$
A ring + X	5.58(0.35 – 23)	–0.01(–2.26 – 0.64)	–0.01(–0.25 – 0.01)	–0.01(–0.1 – 0)
$R^2 = 0.36$	$p = 0.0076^*$	$p = 0.6008$	$p = 0.3143$	$p = 0.2191$
B ring	9.9(2.25 – 26.6)	–0.07(–2 – 0.08)	–0.05(–0.44 – 0)	–0.69(–1.72 – (–0.19))
$R^2 = 0.40$	$p = 0.0010^*$	$p = 0.2511$	$p = 0.0760$	$p < 0.0001^*$
C ring	23.95(5.14 – 65.91)	0(–2.09 – 1.24)	–0.03(–0.56 – 0)	0.01(0 – 0.12)
$R^2 = 0.43$	$p = 0.0009^*$	$p = 0.8220$	$p = 0.1881$	$p = 0.1753$
D ring	15.67(5.34 – 34.54)	0.28(0 – 2.7)	–0.09(–0.75 – 0)	–0.01(–0.1 – 0)
$R^2 = 0.51$	$p < 0.0001^*$	$p = 0.0705$	$p = 0.0603$	$p = 0.0788$
E ring	21.58(8.64 – 43.45)	0(–0.1 – 0.53)	0(–0.2 – 0.15)	0(–0.05 – 0)
$R^2 = 0.59$	$p < 0.0001^*$	$p = 0.5111$	$p = 0.9098$	$p = 0.1615$

^a The levels of categorical variables used as a base for comparisons were “fipronil” for the treatment variable and “after” for the time with respect to application.

* Significant at $p < 0.05$.

were found within a single station. The B ring from the third replicate had varying degrees of termite activity after application, but the number of termites counted had also decreased to zero by the last three months of the study period.

Our regression models considering the proportion of stations occupied within experimental grids produced similar results to those based on termite counts. Monthly fluctuations affecting all grids accounted for 58.21 % of the variation in termite presence (Wald $p = 0.0007$). Control and fipronil plots mostly resembled each other in the amount of change in termite presence after application (Fig 3). We found no significant differences suggesting an effect of fipronil on the proportion of stations occupied in whole grids or grid sections, with the exception of the B ring (Table 2), which experienced a 79.68 % mean decrease in termite presence in stations after fipronil application (Fig 3).

Chlorfenapyr

Similarly to the results obtained from fipronil plots, our analysis of *H. aureus* counts from chlorfenapyr whole plots and

the controls for the corresponding period showed that a large and significant portion of the variation in termite activity among plots was the result of monthly fluctuations affecting all grids simultaneously (44.28 %, Wald $p = 0.0039$). Variation due to the particularities of individual plots explained a non-significant proportion of the observed variance (Wald $p = 0.1977$).

Our analysis of termite counts from whole chlorfenapyr and control plots showed a significant decrease with respect to controls after application. There were no significant differences in mean termite counts between chlorfenapyr and control plots or between counts before and after the treatment application date (Table 3). Nevertheless, the interaction between those two factors was highly significant, pointing to a decrease in termite counts specific to chlorfenapyr plots after application (Table 3). Examination of termite abundance trends after application shows that this difference was the result of termite counts in chlorfenapyr plots decreasing even as those from control plots increased (Fig 4).

Several grid sections also experienced significant decreases in termite counts relative to controls after

chlorfenapyr application. We detected no overall significant differences in termite counts between chlorfenapyr and control plots or before and after the treatment application date (Table 3).

However, the interaction of these two factors was significant for the five central stations (central station and A ring), and the D and E rings. The magnitude of the interaction parameter

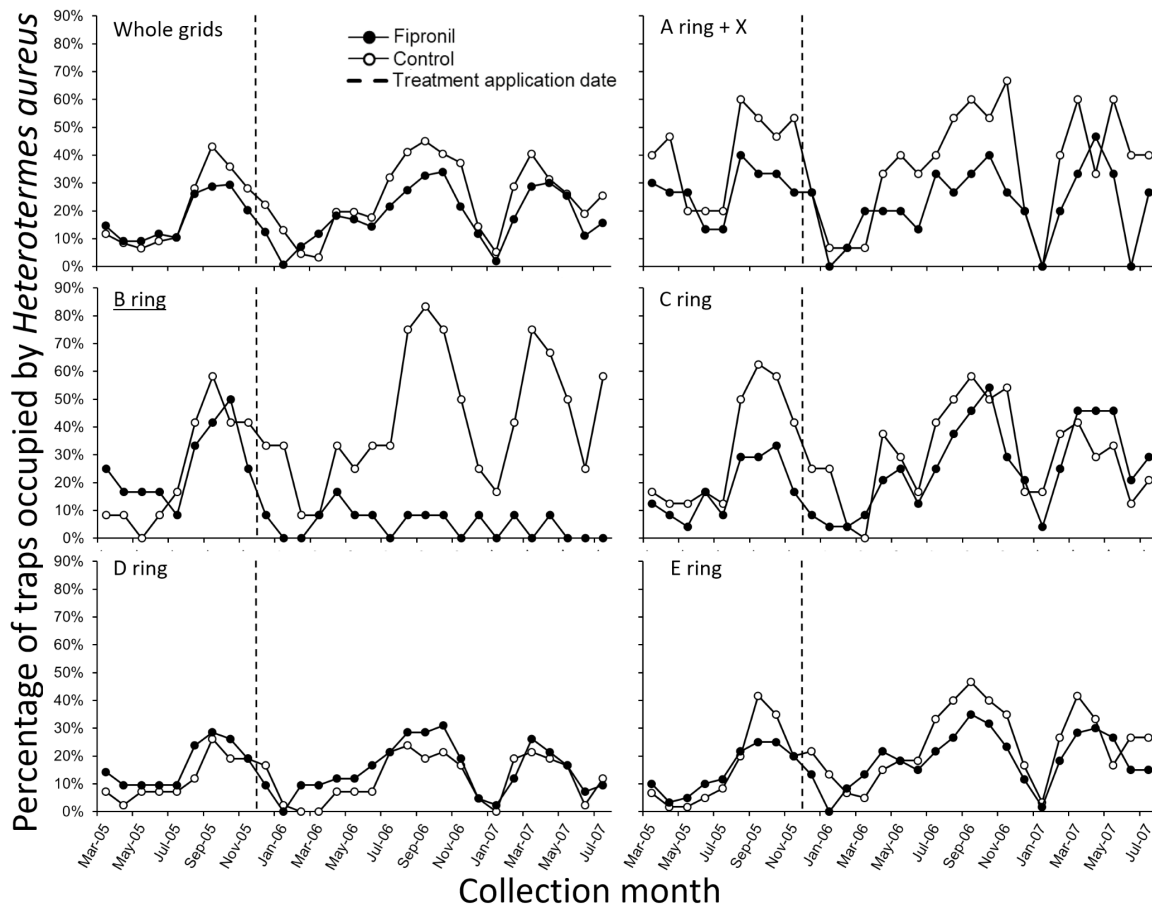


Fig 3. Average percentage of termite stations occupied by *H. aureus* per month in whole control and fipronil experimental grids and each of their sections (n = 3 for each treatment). Labels for every other collection month are included in the horizontal axes. The names of grid sections for which analysis showed a significant change in the percentage of stations occupied by *H. aureus* with respect to controls after treatment application are shown underlined.

Table 2. Results of mixed-effects multiple linear regression models for differences between control and fipronil-treated experimental grids based on the percentage of stations occupied by *H. aureus*. Parameter estimates are displayed with their 95% confidence intervals. For the interaction term, positive parameter estimates imply higher percentages of stations occupied by *H. aureus* relative to controls after treatment, while negative values imply a decrease. Only fixed effects are included.

Grid section	Intercept	Treatment (control vs fipronil ^a)	Time (before vs after ^a application)	Treatment × Time
Whole plots	19.68(14.16 – 25.21)	-2.21(-6.79 – 2.37)	1.6(-2.76 – 5.95)	-0.86(-2.16 – 0.43)
R ² = 0.72	p < 0.0001*	p = 0.2564	p = 0.4598	p = 0.1896
A ring + X	31.17(17.3 – 45.04)	-6.72(-20.85 – 7.41)	-2(-7.74 – 3.74)	-0.11(-3.05 – 2.83)
R ² = 0.55	p = 0.0015*	p = 0.2594	p = 0.4817	p = 0.9415
B ring	24.15(11.26 – 37.04)	-9.42(-22.52 – 3.67)	-0.44(-5.93 – 5.05)	-9.37(-12.84 – (-5.9))
R ² = 0.54	p = 0.0040*	p = 0.1177	p = 0.8697	p < 0.0001*
C ring	25.82(8.04 – 43.59)	-4.64(-22.79 – 13.5)	2.13(-3.98 – 8.24)	2.59(-0.2 – 5.38)
R ² = 0.6206	p = 0.0128*	p = 0.5183	p = 0.4820	p = 0.0688
D ring	13.41(7.46 – 19.35)	1.92(-3.96 – 7.81)	0.13(-3.21 – 3.47)	-0.29(-1.56 – 0.98)
R ² = 0.63	p = 0.0007*	p = 0.4188	p = 0.9362	p = 0.6512
E ring	18.11(11.2 – 25.02)	-1.58(-8.22 – 5.06)	3.47(-0.85 – 7.79)	-1.09(-2.54 – 0.36)
R ² = 0.69	p < 0.0001*	p = 0.5476	p = 0.1111	p = 0.1385

^a The levels of categorical variables used as a base for comparisons were “fipronil” for the treatment variable and “after” for the time with respect to application.
^{*} Significant at p < 0.05.

estimates suggested lower termite counts relative to controls within each of those grid sections after chlorfenapyr application (Table 3, Fig 4). The largest estimated effect was observed in

the E ring (Table 3), where a decrease in the termite counts in chlorfenapyr-treated plots after application occurred simultaneously to an increase in control plots (Fig 4).

Table 3. Results of mixed-effects multiple linear regression models for differences between control and chlorfenapyr-treated experimental grids based on the mean number of termites collected per station. Parameter estimates are displayed with their 95% confidence intervals. Parameter estimates and confidence intervals were back-transformed before including them in this table. For the interaction term, positive parameter estimates imply higher percentages of stations occupied by *H. aureus* relative to controls after treatment, while negative values imply a decrease. Only fixed effects are included.

Grid section	Intercept	Treatment (control vs chlorfenapyr ^a)	Time (before vs after ^a application)	Treatment × Time
Whole plots	26.53(10.28 – 54.45)	-0.01(-1.03 – 0.18)	0(-0.04 – 0.27)	-0.05(-0.16 – (-0.01))
R ² = 0.67	p < 0.0001*	p = 0.4814	p = 0.5162	p < 0.0001*
A ring + X	17.73(3.05 – 53.38)	-0.09(-4.26 – 0.4)	0.01(-0.03 – 0.43)	-0.1(-0.39 – (-0.01))
R ² = 0.54	p = 0.0014*	p = 0.3574	p = 0.3876	p = 0.0006*
B ring	12.47(2.25 – 36.83)	-0.76(-7.3 – 0)	0.02(-0.01 – 0.39)	-0.02(-0.22 – 0)
R ² = 0.44	p = 0.0016*	p = 0.0690	p = 0.2592	p = 0.0649
C ring	15.87(0.37 – 79.85)	-0.02(-9.21 – 3.75)	0.07(0 – 0.76)	0(-0.02 – 0.02)
R ² = 0.59	p = 0.0160*	p = 0.7007	p = 0.0995	p = 0.8897
D ring	8.89(3.77 – 17.3)	0(-0.04 – 0.08)	0(-0.05 – 0.2)	-0.01(-0.1 – 0)
R ² = 0.42	p < 0.0001*	p = 0.7769	p = 0.6355	p = 0.0473*
E ring	18.36(2.36 – 61.37)	-0.1(-5.9 – 0.65)	0(-0.12 – 0.14)	-0.15(-0.46 – (-0.03))
R ² = 0.61	p = 0.0029*	p = 0.3829	p = 0.9564	p < 0.0001*

^a The levels of categorical variables used as a base for comparisons were “chlorfenapyr” for the treatment variable and “after” for the time with respect to application. * Significant at p < 0.05.

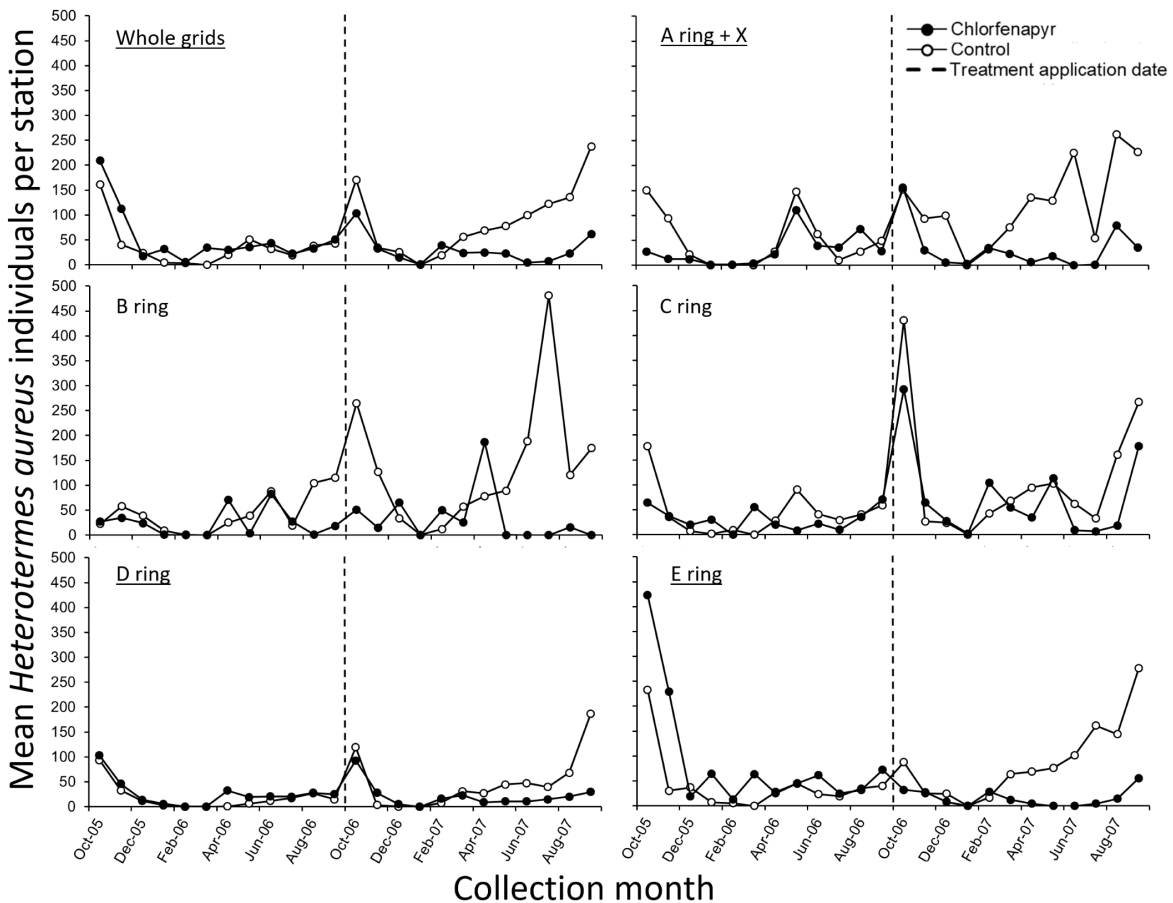


Fig 4. Average number of desert subterranean termites collected per station per month in whole control and chlorfenapyr experimental grids and each of their sections (n = 3 for each treatment). Labels for every other collection month are included in the horizontal axes. The names of grid sections for which analysis showed a significant change in termite counts with respect to controls after treatment application are shown underlined.

As with termite counts, month to month variations accounted for a large portion of the variance in station occupancy by termites (40.65 %, Wald $p = 0.0037$). For whole grids, the interaction between time with respect to application and treatment was significant, suggesting a decrease in the proportion of stations occupied by termites in chlorfenapyr grids (Table 4).

The analysis of termite presence in stations within each grid section revealed a pattern that was similar, although

not identical to that obtained from analyzing termite counts. The five central stations (A ring + X), and the B and E station rings had a significant interaction term between the time with respect to application and treatment (Table 4). The parameter estimates for those interaction terms suggested a lower percentage of stations occupied by termites relative to controls after treatment in each of those grid sections (Table 4, Fig 5).

Table 4. Results of mixed-effects multiple linear regression models for differences between control and chlorfenapyr-treated experimental grids based on the percentage of stations occupied by *H. aureus*. Parameter estimates are displayed with their 95% confidence intervals. For the interaction term, positive parameter estimates imply higher percentages of stations occupied by *H. aureus* relative to controls after treatment, while negative values imply a decrease. Only fixed effects are included.

Grid section	Intercept	Treatment (control vs chlorfenapyr ^a)	Time (before vs after ^a application)	Treatment × Time
Whole plots	21.66(13.28 – 30.05)	-5.46(-13.92 – 3)	1.18(-3.02 – 5.39)	-2.41(-3.83 – (-0.99))
R ² = 0.73	p = 0.0004*	p = 0.1475	p = 0.5653	p = 0.0010*
A ring + X	35.83(15.6 – 56.07)	-3.61(-24.29 – 17.07)	1.67(-5.49 – 8.83)	-3.89(-7.25 – (-0.53))
R ² = 0.59	p = 0.0056*	p = 0.6532	p = 0.6341	p = 0.0238*
B ring	27.95(13.09 – 42.81)	-16.49(-31.67 – (-1.32))	2.6(-3.09 – 8.3)	-4.34(-7.5 – (-1.19))
R ² = 0.64	p = 0.0043*	p = 0.0392*	p = 0.3535	p = 0.0074*
C ring	25(2.6 – 47.4)	-9.38(-32.13 – 13.38)	1.91(-3.62 – 7.44)	-0.17(-2.89 – 2.55)
R ² = 0.69	p = 0.0354*	p = 0.3165	p = 0.4811	p = 0.8996
D ring	13.94(9.11 – 18.77)	-0.45(-5.11 – 4.22)	1.74(-1.42 – 4.89)	-0.74(-2.13 – 0.65)
R ² = 0.52	P < 0.0001*	p = 0.8037	p = 0.2660	p = 0.2913
E ring	20.94(7.75 – 34.12)	-5.66(-19.12 – 7.8)	0.1(-3.92 – 4.12)	-3.72(-5.54 – (-1.89))
R ² = 0.68	p = 0.0095*	p = 0.3078	p = 0.9576	p < 0.0001*

^a The levels of categorical variables used as a base for comparisons were “chlorfenapyr” for the treatment variable and “after” for the time with respect to application.

* Significant at $p < 0.05$.

Discussion

Fluctuations in *H. aureus* abundance and presence in collection stations within our experimental grids had a large temporal component that was associated with local weather. Foraging activity by *H. aureus* was highest in the months following the monsoon rains and lowest in the winter months. Our results are in line with previously reported monthly fluctuations in foraging intensity by *H. aureus* (Jones et al., 1987). The relatively large magnitude of these seasonal variation illustrates the importance of control plots to provide a baseline that allows an accurate interpretation of the significance of changes in termite activity.

In fipronil designated plots, we observed a strong and significant reduction in termite presence and foraging activity in the stations immediately adjacent to the treatment perimeter. This result is consistent with abundant evidence of the efficacy of fipronil in reducing termite activity in a variety of termite species (Hu, 2005; Peterson, 2010), including *H. aureus* (Shelton et al., 2014). However, our analyses revealed no evidence of reductions in termite foraging activity in any stations spatially separated from the site of application, not even those that were surrounded by the treatment perimeter.

These results are in contrast with research by Potter and Hillery (2002) and Vargo and Parman (2012) which reported effective management of structure-infesting eastern subterranean termites (*R. flavipes*) based on perimeter treatments of fipronil. Both studies described reductions in termite activity at a few meters (< 5 m) from treated soil. Furthermore, the study by Vargo and Parman (2012) reported the apparent elimination of colonies exposed to treatment. However, our results are in agreement with other field research that has found much weaker distance effects of fipronil soil treatments on termite populations. Work by Ripa et al. (2007) considering the effect of fipronil soil treatments on *R. flavipes* found limited reductions on termite activity which occurred at short distances (< 2 m) from treated soil and were insufficient for termite management. A study by Shelton (2013) that recorded the effects of small fipronil sub-slab treatments on surrounding *R. flavipes* activity at distances of up to 1.8 m found reductions in wood consumption that decreased rapidly with distance from treated soil and no evidence of full feeding cessation or colony elimination.

Previous laboratory studies help illuminate the mechanisms that might make distance effects possible or prevent them from occurring. When distance effects are

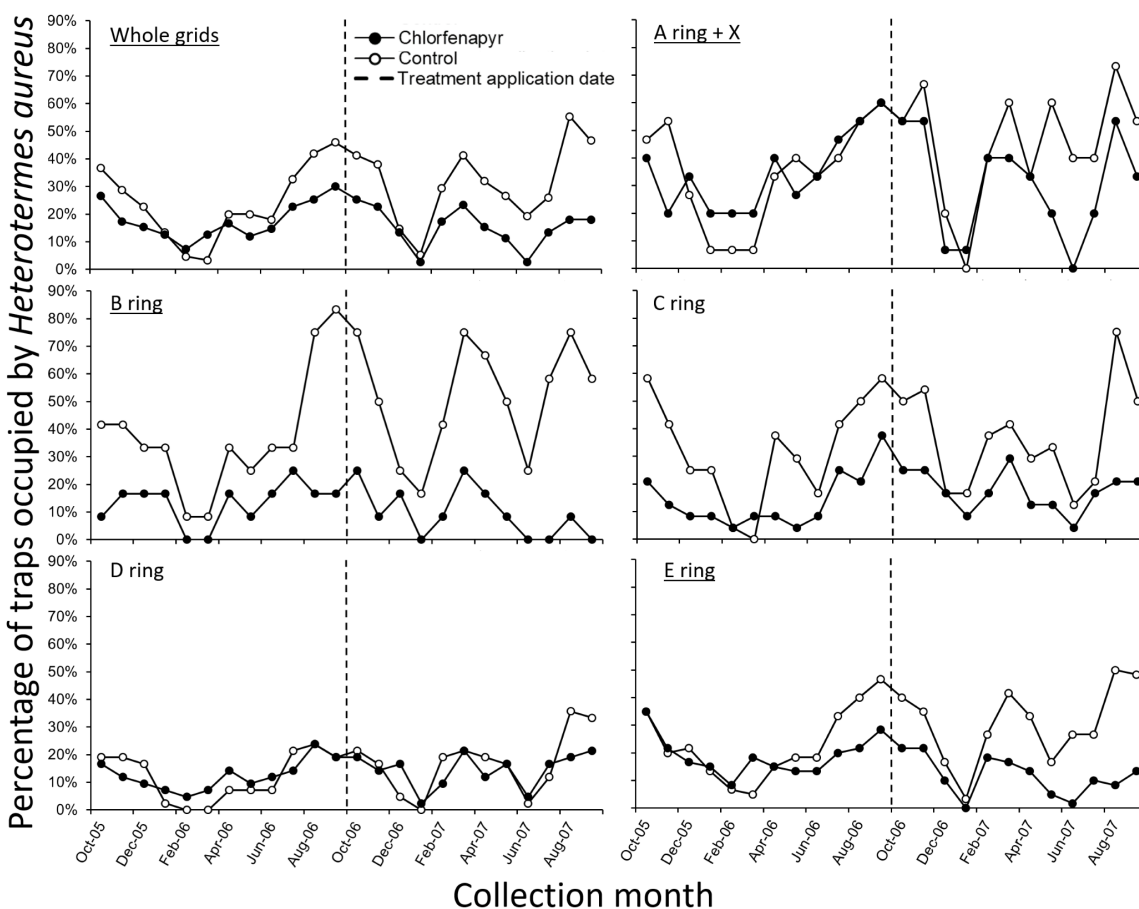


Fig 5. Average percentage of termite stations occupied by *H. aureus* per month in whole control and chlorfenapyr experimental grids and each of their sections ($n = 3$ for each treatment). Labels for every other collection month are included in the horizontal axes. The names of grid sections for which analysis showed a significant change in the percentage of stations occupied by *H. aureus* with respect to controls after treatment application are shown underlined.

observed, it is often assumed that they are at least in part the result of horizontal termiticide transfer. Horizontal transfer of fipronil has been observed under laboratory conditions in a variety of termite species (Su, 2005; Spomer et al., 2008; Bagnères et al., 2009; Chen et al., 2015). However, laboratory studies have also pointed out two aspects that might prevent effective transfer from occurring under field conditions. Firstly, even if termiticides do not kill termites instantly, intoxication might nevertheless result in impairment that prevents them from moving and interacting with nestmates, thus limiting the social interactions necessary for termiticide transfer. This kind of impairment after exposure to fipronil has been reported in *Reticulitermes hesperus* Banks (Saran & Rust, 2007) and *R. flavipes* (Forschler, 2009; Quarcoo et al., 2012).

Secondly, if the termiticide produces significant mortality near the site of application, this might generate an accumulation of dead bodies and their products, which results in termites avoiding that area in what has been called *secondary repellency*. This phenomenon has been observed in laboratory colonies of two termite species with large foraging territories: *Coptotermes formosanus* Shiraki (Su, 2005) and *Coptotermes geostroi* (Wasmann) (Chouvenc, 2018). In those studies, termite colonies avoided treated areas and either

became divided into two subcolonies (Su, 2005) or used alternative foraging tunnels (Chouvenc, 2018). Some of the results from our fipronil experimental grids are consistent with secondary repellency. Termites were excluded from stations adjacent to treated soil (B ring) in two of our grids, and their numbers were dramatically reduced in the other. Nevertheless, termite activity remained comparable to that in controls in all other grid sections. Even if horizontal transfer did not take place, such drastic reduction could reasonably be expected to be accompanied by some reduction in termite activity in nearby station rings as a result of attrition and disruption of foraging pathways. The lack of such reductions suggests that termite populations might have avoided greater mortality by preventing contact with treated soil through secondary repellency.

Overall, the variety of outcomes from field and laboratory studies dealing with fipronil transfer and distance effects illustrate the limitations of considering non-repellent insecticides as liquid termite baits. Both impairment and mortality produced by non-repellent insecticides depend on the dose of active ingredient that termites are exposed to. Therefore, in order for transfer to occur, soil concentrations of the toxicant must be high enough for recipients to acquire

a lethal dose but low enough for mortality and impairment of donors to be delayed (Su & Lees, 2009). Since reaching and maintaining the right soil termiticide concentration is not a central priority of current management practices, the right concentrations for transfer might only be achieved occasionally. Regardless, even in studies in which distance effects have been reported for fipronil, the maximum reach of such effects is significantly smaller than the reported foraging distances for *H. aureus*, which might exceed 60 m (Jones, 1990; Baker & Haverty, 2007).

In contrast, we observed reductions in termite activity that can be considered distance effects of chlorfenapyr. Termite counts and presence in stations decreased relative to controls after chlorfenapyr application in whole experimental grids and in several of the station rings making up those grids. These reductions were especially evident in the five central stations (A ring and X) and the outermost set of stations (E ring). The reduction in termite presence in the outermost ring of chlorfenapyr-treated stations with respect to controls suggests that the insecticide treatment temporarily reduced the foraging range of termite populations or at least prevented the expansion of their territory possible with the environmental conditions at the time.

Although we did not explicitly determine the mechanisms behind the distance effects of chlorfenapyr, the spatial pattern of changes we observed is consistent with horizontal transfer playing a significant role. The fact that termites were not eliminated from any of the grid sections suggests that mortality was probably not high enough to produce distance effects from attrition alone. Some of the more significant reductions in termite activity occurred at a considerable distance (~ 7 m) from treated soil, which could be explained by termites dispersing the termiticide within the colony through transfer. Since termite counts in stations directly adjacent to treated soil (B ring) remained similar to those from controls, it is apparent that a portion of the termite population continued to be exposed to the treatment, which would have allowed continuous intake of the toxicant by the colony.

Studies considering the transfer of chlorfenapyr under laboratory conditions have had mixed results with some evidence suggesting that transfer might be a significant source of mortality in the field. Transfer of chlorfenapyr between nestmate termites has been observed in several species (Rust & Saran, 2006; Shelton et al., 2006; Neoh et al., 2014). In *Heterotermes indicola* (Wasmann), a species in the same genus as *H. aureus*, chlorfenapyr transfer was only evident at very low concentration (Misbah-Ul-Haq et al., 2016). In their research with *R. hesperus*, Rust and Saran (2006) found that transfer of chlorfenapyr only occurred between donor termites and the recipients that came in contact with them but did not extend to secondary recipients. They also noted that donor termites showed significant impairment, which may prevent transfer. However, Forschler (2009) reported that *R. flavipes* showed no signs of impairment after being

exposed to chlorfenapyr. This was in contrast with other termiticides tested (fipronil, imidacloprid, and indoxacarb) which all produced significant impairment. Although these studies are useful in showing that chlorfenapyr transfer is possible under certain conditions, studies considering full laboratory colonies and further field research are necessary to understand the significance of that mechanism in producing termite mortality.

Although we are confident in our results, we do not consider that they are necessarily applicable to other termite species under different circumstances. The outcomes of termiticide treatments are dependent upon a variety of factors including termite species, soil characteristics, application technique, and termiticide concentration (Hu, 2011). The differences in susceptibility among termite species are illustrated by our previously reported analyses of the effects of chlorfenapyr and fipronil in the same experimental grids considered here on *Gnathamitermes perplexus* (Miguelena & Baker, 2012), a termite of no economic importance that competes with *H. aureus* (Jones & Trosset, 1991). While chlorfenapyr decreased overall *H. aureus* activity, *G. perplexus* activity increased significantly; probably aided by reduced competition from *H. aureus*. Conversely, although fipronil had only a localized effect on *H. aureus* activity, it produced a more widespread reduction in *G. perplexus* activity.

The effects of fipronil and chlorfenapyr on termite populations in this study suggest that they can both be useful for the management of *H. aureus* populations, although each might be suited for different sets of management goals. The apparent high toxicity of fipronil at short distances indicates that it can be used to produce high mortality and exclude termites in spots where they are known to be present. Besides the soil-applied formulation, there are currently several other products containing fipronil that can be used for that purpose. Conversely, chlorfenapyr might best be suited for situations in which it is desirable to suppress termite populations and reduce termite damage within an area with limited time and resources. If similar results to the ones we obtained can be replicated with other species, chlorfenapyr might be a valuable tool in efforts aimed at containing invasive termite species. It might also be particularly useful in circumstances where the physical configuration of structures prevents treatment application directly next to affected areas. However, since termite populations were not eliminated with either insecticide using them on their own to manage *H. aureus* infestations would not be an advisable strategy in circumstances in which any risk of damage must be avoided or when colony eliminations is a priority.

In conclusion, of the two insecticides tested only chlorfenapyr produced changes in *H. aureus* activity that can be considered distance effects. In contrast, fipronil had considerable effects only in stations adjacent to the soil treatment. Furthermore, our results suggest that perimeter treatments on their own are not sufficient to accomplish full

control of large, active *H. aureus* infestations. Instead, a combination of techniques and application locations (inside and outside structures) are more likely to be successful in such cases. It remains to be determined if under more typical construction circumstances that include pre-construction and wood treatments as well as structural features impeding free termite movement, the termiticides tested would have more drastic effects on *H. aureus* activity and colony survival.

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References

- Al-Smadi, B.M., Al Oran, E.H., & Abu Hajar, H.A. (2019). Adsorption-desorption of cypermethrin and chlorfenapyr on Jordanian soils. *Arabian Journal of Geosciences*, 12: 465. doi: 10.1007/s12517-019-4614-7
- Bagnères, A. G., Pichon, A., Hope, J., Davis, R. W., & Clément, J. L. (2009). Contact versus feeding intoxication by fipronil in *Reticulitermes* termites (Isoptera: Rhinotermitidae): laboratory evaluation of toxicity, uptake, clearance, and transfer among individuals. *Journal of Economic Entomology*, 102: 347-356. doi: 10.1603/029.102.0145
- Baker, P.B., Hagler, J.R., Marchosky, R., Machtley, S.A., Brown, J.M., Riehle, M.A., & Bellamy, D.E. (2010). Utilizing rabbit immunoglobulin G protein for mark-capture studies on the desert subterranean termite, *Heterotermes aureus* (Snyder). *Insectes Sociaux*, 57: 147-155. doi: 10.1007/s00040-009-0060-y
- Baker, P. B., & Haverty, M. I. (2007). Foraging populations and distances of the desert subterranean termite, *Heterotermes aureus* (Isoptera: Rhinotermitidae), associated with structures in southern Arizona. *Journal of Economic Entomology*, 100: 1381-1390. doi: 10.1093/jee/100.4.1381
- Brown, D.E. (1994). *Biotic Communities: Southwestern United States and Northwestern Mexico* (2nd ed.). Salt Lake City: University of Utah Press, 346 p.
- Canello, E. M., & Myles, T. G. (2000). Isoptera. In J.E. Llorente-Bousquets, E. González-Soriano & N. Papavero (Eds.), *Biodiversidad, Taxonomía y Biogeografía de artrópodos de México: hacia una síntesis de su conocimiento* (Vol. II, pp. 295-315). Mexico: UNAM.
- Chen, Z., Qu, Y., Xiao, D., Song, L., Zhang, S., Gao, X., Desneux, N., & Song, D. (2015). Lethal and social-mediated effects of ten insecticides on the subterranean termite *Reticulitermes speratus*. *Journal of Pest Science*, 88: 741-751. doi: 10.1007/s10340-015-0656-0
- Chouvenec, T. (2018). Comparative impact of chitin synthesis inhibitor baits and non-repellent liquid termiticides on subterranean termite colonies over foraging distances: colony elimination versus localized termite exclusion. *Journal of Economic Entomology*, 111: 2317-2328. doi: 10.1093/jee/toy210
- English, N., Weltzin, J., Fravolini, A., Thomas, L., & Williams, D. (2005). The influence of soil texture and vegetation on soil moisture under rainout shelters in a semi-desert grassland. *Journal of Arid Environments*, 63: 324-343. doi: 10.1016/j.jaridenv.2005.03.013
- Fei, H., & Henderson, G. (2005). Repellency of Formosan subterranean termites (Isoptera: Rhinotermitidae) to dead termites and attraction to 2-phenoxyethanol with and without nonrepellent insecticides. *Journal of Agricultural and Urban Entomology*, 22: 159-172.
- Forschler, B.T. (2009). Screening insecticides for use as soil termiticides requires a series of bioassays: lessons from trials using *Reticulitermes flavipes* (Isoptera: Rhinotermitidae). In C. J. Peterson & D. M. Stout (Eds.), *Pesticides in Household, Structural and Residential Pest Management* (pp. 53-74). Washington, DC: American Chemical Society.
- Forschler, B.T. (2011). Sustainable termite management using an integrated pest management approach. In P. Dhang (Ed.), *Urban Pest Management: An Environmental Perspective* (pp. 133-144). Wallingford, UK: CAB International.
- Hainzl, D., & Casida, J.E. (1996). Fipronil insecticide: novel photochemical desulfinylation with retention of neurotoxicity. *Proceedings of the National Academy of Sciences*, 93: 12764-12767.
- Haverty, M.I., & Nutting, W.L. (1975). Density, dispersion, and composition of desert termite foraging populations and their relationship to superficial dead wood. *Environmental Entomology*, 4: 480-486.
- Hu, X.P. (2005). Evaluation of efficacy and nonrepellency of indoxacarb and fipronil-treated soil at various concentrations and thicknesses against two subterranean termites (Isoptera: Rhinotermitidae). *Journal of Economic Entomology*, 98: 509-517. doi: 10.1093/jee/98.2.509
- Hu, X.P. (2011). Liquid termiticides: their role in subterranean termite management. In P. Dhang (Ed.), *Urban pest management: an environmental perspective* (pp. 114-132). Wallingford, UK: CAB International.
- Jones, S.C. (1990). Delineation of *Heterotermes aureus* (Isoptera: Rhinotermitidae) foraging territories in a Sonoran desert grassland. *Environmental Entomology*, 19: 1047-1054.
- Jones, S.C., & Trosset, M.W. (1991). Interference competition in desert subterranean termites. *Entomologia Experimentalis et Applicata*, 61: 83-90.

- Jones, S.C., Trosset, M.W., & Nutting, W.L. (1987). Biotic and abiotic influences on foraging of *Heterotermes aureus* (Snyder) (Isoptera: Rhinotermitidae). *Environmental Entomology*, 16: 791-795.
- Miguelena, J. G., & Baker, P. B. (2012). Foraging populations of tube building termites, *Gnathamitermes perplexus* (Banks), associated with termiticide experiments in southern Arizona (Isoptera: Termitidae). *Sociobiology*, 59: 641.
- Misbah-Ul-Haq, M., Khan, I. ., Farid, A., Ullah, M., Gouge, D.H., & Baker, P.B. (2016). Efficacy of indoxacarb and chlorfenapyr against Subterranean termite *Heterotermes indicola* (Wasmann) (Isoptera: Rhinotermitidae) in the laboratory. *Turkish Journal of Entomology*, 40. doi: 10.16970/ted.89871
- Neoh, K.B., Yeoh, B.H., & Lee, C.Y. (2014). Mortality patterns in *Coptotermes gestroi* (Blattodea: Rhinotermitidae) following horizontal transfer of nonrepellent and repellent insecticides: effects of donor: recipient ratio and exposure time. *Journal of Economic Entomology*, 107: 1563-1572. doi: 10.1603/EC14080
- Paul, B., Singh, S., Shankarganesh, K., & Khan, M. A. (2018). Synthetic Insecticides: The Backbone of Termite Management. In M. A. Khan & W. Ahmad (Eds.), *Termites and Sustainable Management* (pp. 233-260). Cham, Switzerland: Springer.
- Peterson, C.J. (2010). Effect of vegetation on the longevity, mobility and activity of fipronil applied at the termiticidal rate in laboratory soil columns. *Pest Management Science*, 66: 944-948. doi: 10.1002/ps.1964
- Potter, M.F., & Hillery, A.E. (2002). Exterior-targeted liquid termiticides: an alternative approach to managing subterranean termites (Isoptera: Rhinotermitidae) in buildings. *Sociobiology*, 39: 373-405.
- Quarcoo, F.Y., Hu, X.P., & Appel, A.G. (2012). Effects of non-repellent termiticides on the tunneling and walking ability of the eastern subterranean termite (Isoptera: Rhinotermitidae). *Pest Management Science*, 68: 1352-1359. doi: 10.1002/ps.3302
- Ripa, R., Luppichini, P., Su, N.-Y., & Rust, M. K. (2007). Field evaluation of potential control strategies against the invasive eastern subterranean termite (Isoptera: Rhinotermitidae) in Chile. *Journal of Economic Entomology*, 100: 1391-1399. doi: 10.1093/jee/100.4.1391
- Rust, M. K., & Saran, R. K. (2006). Toxicity, repellency, and transfer of chlorfenapyr against western subterranean termites (Isoptera: Rhinotermitidae). *Journal of Economic Entomology*, 99: 864-872. doi: 10.1093/jee/99.3.864
- Rust, M. K., & Su, N.-Y. (2012). Managing social insects of urban importance. *Annual Review of Entomology*, 57: 355-375. doi: 10.1146/annurev-ento-120710-100634
- Saran, R. K., & Rust, M. K. (2007). Toxicity, uptake, and transfer efficiency of fipronil in western subterranean termite (Isoptera: Rhinotermitidae). *Journal of Economic Entomology*, 100: 495-508. doi: 10.1093/jee/100.2.495
- SAS Institute. (2016). JMP version 13.1.0. Cary, NC: SAS Institute.
- Sayre, N. F. (2003). Recognizing history in range ecology: 100 years of science and management on the Santa Rita Experimental Range. In M. P. McClaran, P. F. Folliott & C. B. Edminster (Eds.), *Santa Rita Experimental Range: 100 years (1903 to 2003) of accomplishments and contributions* (pp. 1-15). Ogden, UT: US Department of Agriculture, Forest Service.
- Shelton, T. G. (2013). The Influence of Fipronil on *Reticulitermes flavipes* (Isoptera: Rhinotermitidae) Feeding Beyond Treated Plots. *Journal of Economic Entomology*, 106: 2160-2166. doi: 10.1603/EC12443
- Shelton, T. G., Fye, D., & Ulyshen, M. (2014). US Department of Agriculture-Forest Service Termiticide Report for 2013. *Pest Management Professional*, 82: 42-52.
- Shelton, T.G., Mulrooney, J.E., & Wagner, T.L. (2006). Transfer of chlorfenapyr among workers of *Reticulitermes flavipes* (Isoptera: Rhinotermitidae) in the laboratory. *Journal of Economic Entomology*, 99: 886-892. doi: 10.1093/jee/99.3.886
- Spomer, N. A., Kamble, S. T., Warriner, R. A., & Davis, R. W. (2008). Influence of temperature on rate of uptake and subsequent horizontal transfer of [14C] fipronil by eastern subterranean termites (Isoptera: Rhinotermitidae). *Journal of Economic Entomology*, 101: 902-908. doi: 10.1093/jee/101.3.902
- Su, N.-Y. (2005). Response of the Formosan subterranean termites (Isoptera: Rhinotermitidae) to baits or nonrepellent termiticides in extended foraging arenas. *Journal of Economic Entomology*, 98: 2143-2152. doi: 10.1093/jee/98.6.2143
- Su, N.-Y., & Lees, M. (2009). *Biological Activities of a Bait Toxicant for Population Management of Subterranean Termites Pesticides in Household, Structural and Residential Pest Management* (Vol. 1015, pp. 87-96): American Chemical Society.
- Su, N.-Y., & Scheffrahn, R. H. (1990). Economically important termites in the United States and their control. *Sociobiology*, 17: 77-94.
- Treacy, M., Miller, T., Black, B., Gard, I., Hunt, D., & Hollingworth, R. M. (1994). Uncoupling activity and pesticidal properties of pyrroles. *Biochemical Society Transactions*, 22: 244-247. doi: 10.1042/bst0220244
- Vargo, E. L., & Parman, V. (2012). Effect of fipronil on subterranean termite colonies (Isoptera: Rhinotermitidae) in the field. *Journal of Economic Entomology*, 105: 523-532. doi: 10.1603/EC11155
- Ying, G. G., & Kookana, R. S. (2006). Persistence and movement of fipronil termiticide with under-slab and trenching treatments. *Environmental Toxicology and Chemistry: An International Journal*, 25: 2045-2050. doi: 10.1897/05-652R.1