International Journal of Pest Management

ISSN: 0967-0874 (Print) 1366-5863 (Online) Journal homepage: http://www.tandfonline.com/loi/ttpm20

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To cite this article: Les Greenberg, Michael K. Rust, SaraJean Wright & Dong-Hwan Choe (2017): Argentine ant control around homes: efficacy of treatments and urban runoff, International Journal of Pest Management, DOI: 10.1080/09670874.2016.1278085

To link to this article: http://dx.doi.org/10.1080/09670874.2016.1278085

Published online: 17 Jan 2017.

INTERNATIONAL JOURNAL OF PEST MANAGEMENT, 2017
http://dx.doi.org/10.1080/09670874.2016.1278085

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Argentine ant control around homes: efficacy of treatments and urban runoff

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ABSTRACT

Pest management professionals in California receive more customer complaints about Argentine ants than for any other urban ant pest. Fipronil, applied as a 30 × 30 cm band around the house foundation, has become the preferred treatment used to control these ants. Unfortunately, fipronil is now showing up in urban waterways at levels that are toxic to aquatic invertebrates. Our recent studies are aimed at mitigating insecticide runoff while still controlling the ant infestations. A high priority is preventing fipronil runoff from the driveway to the street, where it can flow into drains and from there to urban waterways. In this paper, two related studies address these issues. Not treating driveways with fipronil reduced by two to three orders of magnitude its runoff when compared with earlier studies. However, not treating the driveway can reduce efficacy of treatments. Granular bifenthrin, indoxacarb, botanicals, and a thiamethoxam ant bait were tested as supplemental treatments. The gel bait showed the best result as a supplement, but only after 8 weeks. We have reduced fipronil runoff while maintaining efficacy of the ant treatments.

ARTICLE HISTORY
Received 7 April 2016
Accepted 2 December 2016

KEYWORDS
Linepithema humile; urban pesticide runoff; fipronil; bifenthrin; indoxacarb; thiamethoxam; ant bait

1. Introduction

In California, surveys indicate that Argentine ants are the most common pest ants encountered by pest management professionals (PMPs) (Knight & Rust 1990), and make up 85% of the ants collected at service accounts of the largest pest control firm in San Diego (Field et al. 2007). It is not uncommon for ant visits to bait stations around homes to exceed 0.5 million during 24 h (Reierson et al. 1998). There are a couple of important considerations in controlling Argentine ants, *Linepithema humile* (Mayr), around homes. On the one hand, we wish to achieve the best possible outcome in reducing ant numbers (Rust et al. 2003; Klotz et al. 2007; Klotz et al. 2008; Silverman & Brightwell 2008; Klotz et al. 2009; Klotz et al. 2010). On the other hand, regulatory agencies want PMPs to minimize the runoff of insecticides into urban waterways. Pyrethroids and fipronil commonly found in ant control products have been detected in these waterways at levels that could be lethal to aquatic invertebrates which are important in aquatic food chains (e.g. Gan et al. 2012; Jorgenson et al. 2012; Ensminger et al. 2013; Weston et al. 2013; Weston & Lydy 2014). Mitigation of pesticide runoff while maintaining control of ants is a challenging problem. Current labels for fipronil use recommend a 30 × 30 cm band spray going up the wall and out from the wall of the house, including at the garage door and driveway. Driveway applications are usually done for ant control because ants frequently walk along edges at the garage door/driveway interface and may make nests in driveway cracks. In the two related studies presented here, we seek to satisfy mitigation and efficacy requirements by applying ant control products where they are less likely to run off (i.e. not on the driveway), while supplementing the standard treatments with additional products to maintain efficacy. We chose supplements that are less toxic to aquatic invertebrates or are less likely to run off. For the current studies, we only report water runoff for the fipronil and its degradates since these are currently a high priority for the funding agency (California Department of Pesticide Regulation) and the analysis procedures are well established. We have previously also analyzed pyrethroid runoff (Greenberg et al. 2010, 2014).

A previous study showed that after outdoor house treatments for Argentine ants, significant amounts of fipronil and pyrethroids could be collected in water running down the driveway (Greenberg et al. 2010). One finding was that careful application of bifenthrin granules away from the driveway gave very little runoff down the driveway, while spray applications of fipronil and bifenthrin that included the driveway at the garage door gave much greater runoff. In another study (Greenberg et al. 2014), it was shown that applying fipronil in the expansion joint at the garage door significantly reduced its runoff when compared to a narrow band application on the concrete at the same location. In this manuscript, we describe two related studies, one done in 2011 and the other in 2013, where

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we did not apply fipronil on the driveway so as to reduce its runoff. To compensate for the reduced use of fipronil, we supplemented the treatment with other products to enhance effectiveness of the treatment. In one study, we used bifenthrin granules as a supplement, and in the other we supplemented with three other insecticides. Our goal was to compare the efficacy of the new treatment protocols and to measure the fipronil runoff.

2. Methods and materials

2.1. Sugar water ant monitoring

Efficacy of ant treatments was calculated from a reduction in ant foraging, based on adjusted weight loss from monitoring vials of sugar water before and after treatment, rather than based on numbers of ants counted or trapped. Ten 15-ml polypropylene tubes (Falcon® screwcap vials) filled with about 13 ml of 50% (wt/vol) sucrose were placed around each structure for about 24 hours. To prevent spills, the open end of the vial was placed on a wooden Lincoln Log (K-NEX, Hatfield, PA), 41 mm long × 18 mm thick, which has a convenient notch in the middle that elevates the vial and reduces side-to-side rolling. All houses are different, but we placed two monitors on each of the shorter house dimensions, and three monitors on each of the longer dimensions. Monitors were placed in the same location every week. In 2011, another 10 vials were placed around the backyard perimeter about every 7 m. All vials were covered with an inverted plastic 15.24-cm flower pot to prevent sprinklers from diluting the sugar water and animals from disturbing them. After 24 hours, the vials were sealed and returned to the laboratory and weighed. We selected houses with large Argentine ant infestations, and in those situations, we rarely find other ant species going to the vials (although such instances are noted). It is also rare to find other insects in the vials. The homes were monitored 1 week before and 1, 2, 4, and 8 weeks after the treatment.

Loss of liquid (i.e. weight) from the tubes was corrected for evaporation of the liquid. The adjusted weight loss value made it possible to estimate the number of ant visits per station, and to map areas of greatest foraging. There is a direct relationship between amount of sugar water taken, and the number of foraging ants in the area (Reierson et al. 1998; Klotz et al. 2007, 2008, 2009, 2010; Greenberg et al. 2010, 2014). Lower numbers of visits represent lower overall ant numbers. The number of ant visits was calculated by dividing the consumption (g) by 0.0003 g/visit, a single Argentine ant consuming 0.0003 g of sucrose water per visit (Reierson et al. 1998). One advantage of such monitoring is that it reflects long-term foraging (i.e. 24 h) and does not depend on singular momentary observations that may vary greatly with time of day. We chose homes in which there was an average of at least 6 ml taken per vial (~20,000 ant visits per vial).

2.2. Spray treatments

The fipronil sprays were applied using a 15-liter backpack sprayer (Birchmeier Co., Switzerland). The sprays were applied as a pin stream (5.1 cm wide) at the interface of the structure and the ground. No spray was applied on the driveway at the garage door and a 30.5 cm (1 ft) buffer was left between the driveway and the rest of the building.

2.3. Granular treatments

Weighed samples of bifenthrin granules were put into plastic bags and then manually dispensed at the product's label rate. None of the granules were allowed to touch the driveway. The granules were applied around bushes, trees, and lawns where ants were seen in the front and back of each house. The granules did not overlap with the spray treatments at the base of the foundation.

2.4. Study completed in 2011

Fipronil treatments were done using ≈1.8 L of a solution of 0.06% Termidor® SC (BASF Corporation, Research Triangle Park, NC) around the house foundation. Granular bifenthrin treatments were done around lawns and bushes in the front and back of the house using Talstar® PL and Talstar® EZ with Verge (FMC Corporation, Agricultural Products Group, Philadelphia, PA). Since bifenthrin is also acutely toxic to aquatic invertebrates, we chose a granular formulation because a previous study had shown it had much lower runoff than bifenthrin sprays (Greenberg et al. 2010). The PL formulation uses a sand grain matrix, while the Verge matrix consists of tiny clay balls. The application rate was ≈1.04 kg per 92.9 square meters (2.3 lbs per 1000 ft^2). One-hundred gram quantities of the granular products, sufficient to cover 9.29 m^2 (100 ft^2), were pre-weighed in baggies and the granules were manually tossed to cover the required area. The actual amounts used (mean ± SE) depended on the size of the residence and the treatment area and were 560 ± 81.2 g for the Talstar PL and 860 ± 128.8 g for the Talstar Verge. The treatments around the backyard perimeter did not include fipronil, although the house foundation in the backyard was treated. One series of monitoring vials were placed around the backyard perimeter. There were five houses ($N = 5$) for each of the three treatments.

Figure 1. Photo of the water dam on a driveway in Riverside, CA. Each side of the dam consists of two 2 × 4s joined with a metal bracket and each half of the dam is attached to a hinge in the middle.

2.5. Study completed in 2013

Fipronil treatments were done as mentioned above. The first supplement was EcoPCO® WP-X, a wettable powder botanical insecticide (now available in soluble pouches, Central Garden & Pet Company, Schaumburg, IL). It consists of 3% 2-phenethyl propionate, 5% thyme oil, and 0.5% pyrethrins. Approximately 3.8 L of 0.025% solution was applied at each residence to the driveway as a crack and crevice treatment, as well as to adjoining sidewalks and flower beds. Arilon® is a water-dispersible granular concentrate containing indoxacarb (Syngenta Crop Protection, LLC, Greensboro, NC). Approximately 3.8 L per residence of a 0.1% solution was applied to the driveway as a crack and crevice treatment, as well as to adjoining sidewalks and flower beds. Finally, Optigard® Ant Gel Bait (Syngenta Crop Protection, Inc., Greensboro, NC), containing 0.01% (wt/wt) thiamethoxam as the active ingredient, was used in the study. The gel matrix is highly attractive, probably due to the presence of sugar compounds. Six bait stations, each containing 5 ml (1.2 g) of gel bait, were used at each house, three on either side of the driveway. The bait station consisted of a 15-ml Falcon tube (Fisher Scientific) that was placed in a hole in the turf adjacent to the driveway so that the cap was flush with the surface of the soil. A small hole (3 mm diameter) was drilled in the cap to permit ant entry and to prevent water and larger animals from entering. If the bait in the station was reduced by 50% or more, a new station was put in its place. Over all time intervals (8 weeks), a total of 85.35 ml of bait was consumed at the five houses. There were five houses ($N = 5$) for each of the four treatments.

2.5.1. Collection of water samples for analysis

Water samples were collected to measure insecticide runoff from five homes treated with fipronil as a 2.54 × 2.54 cm (1 × 1 inch)-wide pin stream band applied around the house foundation but not within 30 cm of the driveway or garage door. We constructed a water dam (Figure 1) out of four 2 × 4 wooden beams, each 96.5 cm long. To make one-half of the dam, two of the beams were connected lengthwise with non-flexible metal brackets. Then, the two halves of the dam were connected with a hinge so that it could be folded in half for transport or unfolded into a V-shaped dam almost 3.6 m wide for placing on the driveway. Five and one-tenth cm (2 inch) thick bands of memory foam were glued to the bottom of the 2 × 4s. Before sample collection, the dam was wrapped with clean 0.02 mm (0.8 mil) plastic shrink wrap. The dam was then placed foam side down on the driveway and five bricks were placed along the top of the dam so as to make a water-resistant seal between the cement and the dam. To collect a sample, we flushed the driveway with a hose from the garage door towards the dam. As the water collected in the center of the dam, a 1-L amber bottle was filled using a 60-mL aquatic glass pipette (Bioquip, Rancho Dominguez, CA). The driveway was flushed with just enough water to collect the sample. A RainWave gauge (Rain Wave, Brampton, ON, Canada) was attached to the hose to measure the volume of water used. Samples were returned to the laboratory and kept at 4 °C until analyzed for insecticide residues in the laboratory of Dr Jay Gan. In the current study, water samples were collected pre-treatment and 1-day post-treatment.

2.5.2. Chemical analysis

Each collected water sample (1000 mL) was extracted with methylene chloride (60 mL) for three consecutive times using glass separatory funnels. The combined solvent phase was dehydrated by passing through a funnel filled with glass wool and anhydrous sodium sulfate (approximately 30 g). The extract was concentrated to approximately 1 mL on a vacuum rotary evaporator. For analysis of fipronil and its metabolites, the residue was recovered in hexane:acetone (9:1 by volume; three 1 mL aliquots), and subjected to a cleanup using a 10-mL solid-phase extraction cartridge packed with 2 g activated Florisil. Prior to sample loading, the cartridge was conditioned with hexane (7 mL). The extract (approximately 4 mL) was then passed through the conditioned cartridge and eluted with hexane:acetone (9:1 by volume; 6 mL) at a flow rate of 1 mL min^{-1}. The volume of the eluate was further reduced to about 0.5 mL under a gentle nitrogen stream and reconstituted to 1.0 mL in hexane:acetone (9:1 by volume). An aliquot of the final sample was taken for gas chromatography (GC) analysis.

3. Statistics

All statistics were done with Systat (2009). For the 2011 protocol, statistical comparisons at the house foundation and in the backyard were analyzed independently. Initially, for both 2011 and 2013 data sets, a repeated measures ANOVA (RM ANOVA) was done with the insecticide treatments as the "Between Subjects" variable, and "Weeks" and "Weeks × Treatments" as the "Within Subjects" variables. RM ANOVAs provide several useful statistics. First, the Between Subjects (treatments in this case) analysis is a test of whether the grand means over time of each treatment are significantly different. The Within Subjects (weeks) analysis tests for any trend over time of the different treatments. Finally, the Weeks × Treatment interaction term tells us whether there is a significant difference in these trends over time between the treatments. For example, if ants recover more quickly from one treatment than another, there may be a significant interaction term. The data used for these analyses were the percent reduction in ant numbers for each of the post-treatment weeks in the study. Using the percent reduction reduces the importance of the initial ant numbers around houses. For both years, as a follow-up to the main RM analysis, percent reductions in ant numbers for each week were used to do simple comparisons within the two main effects.

Simple comparisons of the non-replicated treatments (treatments within each of the weekly time periods) were done for each time period. These simple comparisons were followed with multiple comparisons of the treatments within each time period using Tukey's HSD test so as to maintain the alpha-level at 0.05 for each time period.

Simple comparisons of the replicated treatments (the percent reduction in ant numbers over time for each treatment) were done by comparing the pre-treatment number against each of the post-treatment numbers (weeks 1, 2, 4, and 8). These comparisons of the replicated treatments were done for each of the three treatments tested in 2011 or the four treatments tested in 2013. All simple comparisons were followed with corrections for multiple comparisons as described subsequently. Statistical tests within weeks for a treatment (pre-treatment vs. each post-treatment week) are valuable because each of the five houses in each treatment is serving as its own control over time. For the comparisons of the replicated treatments, we did Dunnett one-tailed tests to see whether each post-treatment value was significantly lower than the pre-treatment number. We then did a Bonferroni correction on these probabilities to account for the fact that four comparisons were done (pre-treatment vs. week 1, 2, 4, and 8).

For all simple comparisons in these experiments, we used the non-pooled error term for each comparison instead of the pooled error term of the main analysis. This approach is the more conservative analysis because it uses fewer degrees of freedom for the error term (Keppel 1991, p. 383–384).

4. Results

4.1. Study completed in 2011

4.1.1. At the house

4.1.1.1. Highlights. Figure 2 shows the percent reduction in ant numbers at each time period at the house and Table 1 shows the corresponding tests for significance when comparing the pre-treatment values with each post-treatment value for each treatment. During weeks 1, 2, and 4, the fipronil + Verge treatment had more significant reductions in ant numbers than the fipronil + PL or the fipronil alone (Table 1).

4.1.1.2. Detailed analysis. The RM ANOVA of the treatments main effect shows no significant differences over all time periods ($F = 0.97$; df = 2, 12; $P = 0.4$). On the other hand, the within treatments main effect (weeks) was significant ($F = 7.2$; df = 3, 36; $P < 0.001$) and the interaction main effect of Weeks × Treatment was significant ($F = 2.7$; df = 6, 36; $P = 0.0275$). The simple comparison of treatment means during week 8 (see Figure 2) showed that the

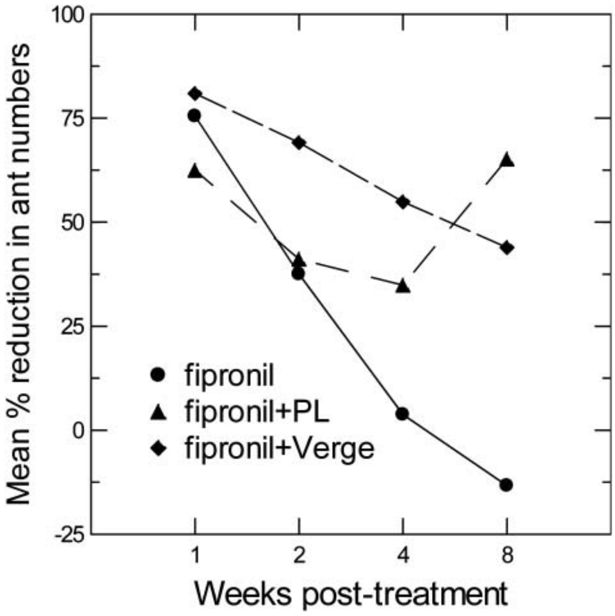

Figure 2. Mean % reductions in ant numbers near homes during 2011. See text for description of treatment protocols. Negative values are increases in ant numbers. $N = 5$ houses per treatment.

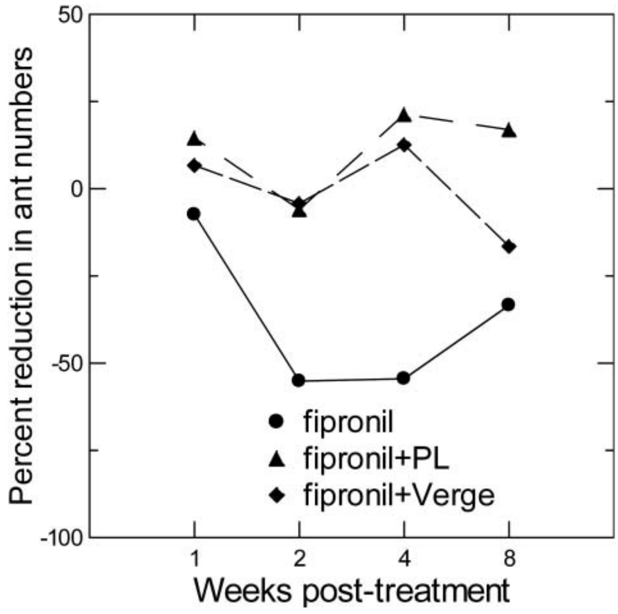

Figure 3. Mean % reductions in ant numbers away from homes during 2011. See text for description of treatment protocols. Negative values are increases in ant numbers. $N = 5$ houses per treatment.

fipronil + Talstar PL had a significantly greater reduction in ants than the fipronil alone (Dunnet one-tailed test, $P < 0.05$).

4.1.2. The backyard

4.1.2.1. Highlights. Figure 3 shows the percent reduction in ant numbers at each time period in the backyard and Table 2 shows the corresponding tests for significance when comparing the pre-treatment values with each post-treatment value for each treatment. Table 2 shows that none of the treatments significantly reduced ant numbers from pre-treatment values. Ant control in the backyard was minimal compared to the control around the house. However, both the bifenthrin PL and bifenthrin Verge treatments had fewer ants than the fipronil alone treatment (Figure 3).

4.1.2.2. Detailed analysis. The RM ANOVA of treatments was significant ($F = 5.3$; df = 2, 12; $P = 0.0224$). Within treatments (weeks) and the interaction term Treatments × Weeks were not significant ($F = 1.4$; df = 3, 36; $P = 0.3$ and $F = 0.9$; df = 6, 36; $P = 0.5$, respectively). The simple comparison of treatments within week 2 was significant ($F = 4.3$; df = 2, 12; $P = 0.039$; see Figure 3) and the fipronil alone treatment had significantly more ants than the fipronil + Verge (Dunnet one-tailed tests, $P < 0.05$). The simple comparison of treatments within week 4 also was significant ($F = 6.9$; df = 2, 12; $P = 0.01$; see Figure 3) with the fipronil + PL and the fipronil + Verge both having significantly greater reductions in ant numbers than the fipronil alone (for both, $P < 0.05$, Dunnet one-tailed test).

Table 1. The 2011 study showing tests of percent reduction in ant numbers at each time period for fipronil treatments near the home.

Week	Fipronil[a]	Fipronil[a] + bifenthrin PL[b]	Fipronil[a] + bifenthrin Verge[c]
1	75.5*	62.5ns	80.9**
2	37.5ns	41.1ns	69.1**
4	3.7ns	34.9ns	54.9*
8	−13.3ns	65.2*	43.9ns

Each data point is the mean % reduction from the pre-treatment values for five homes. *$P < 0.05$; **$P < 0.01$; ns = not significant.
[a]Termidor® SC.
[b]Talstar® PL.
[c]Talstar® EZ with Verge.

4.2. Study completed in 2013

4.2.1. Efficacy of treatments

4.2.1.1. Highlights. Figure 4 shows the percent reduction in ant numbers at each time period at the house foundation and Table 3 shows the corresponding tests for significance when comparing the pre-treatment values with each post-treatment value. The most

Table 2. The 2011 study showing tests of percent reduction in ant numbers for fipronil treatments away from the home.

Week	Fipronil[a]	Fipronil[a] + bifenthrin PL[b]	Fipronil[a] + bifenthrin Verge[c]
1	−7.4ns	14.5ns	6.7ns
2	−55.2ns	−6.0ns	−4.2ns
4	−54.5ns	21.3ns	12.6ns
8	−33.4ns	16.9ns	−16.5ns

Each data point is the mean % reduction from the pre-treatment values for five homes. ns = not significant.
[a]Termidor® SC.
[b]Talstar® PL.
[c]Talstar® EZ with Verge.

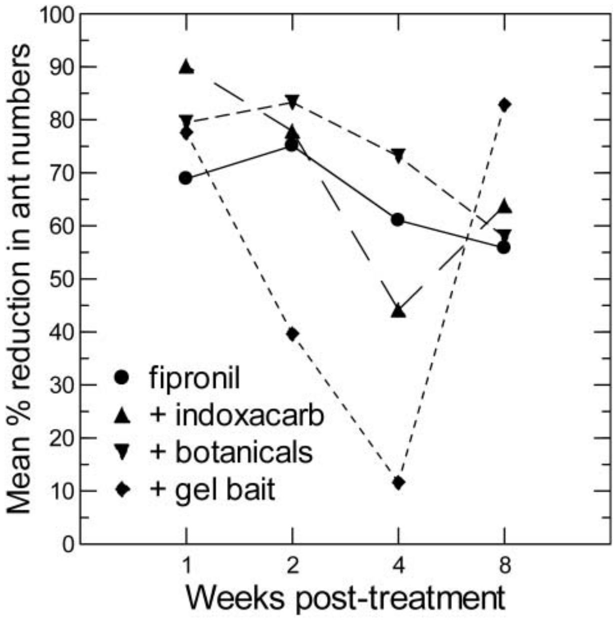

Figure 4. Mean % reductions in ant numbers near homes comparing four different treatment protocols in 2013. All houses received the pin stream fipronil treatment. In addition, three of the four groups of houses also received one of the supplemental treatments shown in the legend. $N = 5$ houses per treatment.

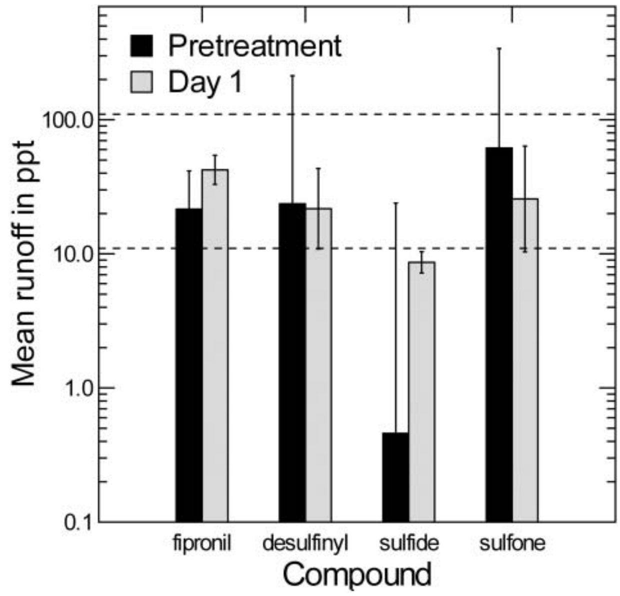

Figure 5. Runoff of fipronil and its degradates from four houses treated with a 2.54 × 2.54 cm band (pin stream) in 2013. Upper dashed line is the acute aquatic benchmark (110 ppt) for invertebrates while the lower dashed line is the chronic aquatic benchmark (11 ppt).

significant reduction in ant numbers for week 1 was for the fipronil + indoxacarb; for weeks 2 and 4, it was fipronil + botanicals; for week 8, it was fipronil + indoxacarb (see Table 3).

4.2.1.2. Detailed analysis. The RM ANOVA on percent reduction in ant number shows no significant differences between treatments ($F = 1.5$; df = 3, 16; $P = 0.2$). On the other hand, within treatments (weeks) was significant ($F = 16.0$; df = 3, 48; $P < 0.001$) and the interaction term of Weeks × Treatment was also significant ($F = 7.9$; df = 9, 48; $P < 0.001$).

There were significant simple comparisons among treatments within a time period for week 2 ($F = 4.4$; df = 3, 16; $P = 0.019$; see Figure 4) and week 4 ($F = 7.1$; df = 3, 16; $P = 0.003$; see Figure 4). In both cases, the fipronil had a significantly greater reduction in ant numbers than the fipronil + ant gel bait (Dunnet one-sided test, $P < 0.05$ for both).

Table 3. The 2013 study showing tests of percent reduction in ant numbers at each time period near the home.

Week	Fipronil[a]	Fipronil[a] + botanicals[b]	Fipronil[a] + indoxacarb[c]	Fipronil[a] + thiamethoxam[d]
1	68.9**	79.5**	90.2***	77.6**
2	75.1**	83.3***	77.9**	39.6ns
4	61.0*	73.1**	44.2*	11.6ns
8	55.8**	57.9**	63.8***	82.8**

Each data point is the mean % reduction from the pretreatment values for five homes.
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns = not significant.
[a]Termidor® SC.
[b]EcoPCO® WP-X.
[c]Arilon®.
[d]Optigard® Ant Gel Bait.

4.2.2. Water runoff of fipronil and aquatic benchmarks

Invertebrate aquatic benchmarks are based on toxicity values reviewed by the US EPA (2016). They are used for risk assessments developed as part of the decision-making process for pesticide registration. They define "acute" invertebrate toxicity as the lowest 48- or 96-hour LC_{50} (lethal concentration to kill 50% of test organisms) in a standardized test with invertebrates such as daphnids or midges, multiplied by the LOC (level of concern) of 0.5. For example, if the LC_{50} for an invertebrate is 200 μg/L, the benchmark would be 100 μg/L. The "chronic" invertebrate benchmark is defined as the lowest NOAEC (no-observed-adverse-effects concentration) multiplied by the LOC of 1. The NOAEC is from a life-cycle test with invertebrates. With respect to our studies, these benchmarks are used to decide when pesticide runoff is potentially harmful to aquatic invertebrates and therefore in need of mitigation. Fipronil and its breakdown products have similar benchmarks.

We can see from Figure 5 that mean pre-treatment and day 1 post-treatment runoff values for fipronil and its degradates are all below the acute benchmark of 110 μg/L (ppt), although some are above the chronic benchmark. The mean fipronil value for the four houses 1-day post-treatment was ≈40 μg/L, but ≈20 μg/L was already present in the pre-treatment reading. A fifth fipronil-treated house had a painted driveway and is not included in this analysis. However, the fipronil runoff for the painted driveway was much higher than that of the mean runoff for the other four houses: 514 μg/L vs. 43.1 ± 4.9 μg/L (mean ± SE), respectively.

5. Discussion

In southern California and elsewhere, the invasive Argentine ant is a major pest around urban houses (Field et al. 2007). These infestations are frequently treated either by homeowners or by PMPs (Rust et al. 2003; Silverman & Brightwell 2008). Fipronil is one of the preferred ant treatments used by PMPs in CA and is sprayed at the wall/ground interface around the entire house, including the corresponding garage door/driveway interface (see Section 2 for details). Although these treatments are very effective against these ants (e.g. see Klotz et al. 2008, 2009; 2010; Greenberg et al. 2010; Greenberg et al. 2014), environmental regulators are finding fipronil in urban waterways at levels that could be toxic to aquatic invertebrates (see Section 1).

Aquatic life benchmarks for the insecticides used in these two studies are, in order of decreasing acute toxicity to aquatic invertebrates (in μg/L): permethrin, 10.6; fipronil, 110; bifenthrin, 800; pyrethrin, 5800; thiamethoxam, 17,500; and indoxacarb, 300,000 (US EPA 2016). The benchmark charts do not show any values for the other botanical components of the EcoPCO product. Our supplemental treatments were either less toxic than the fipronil, or less likely to run off, as is the case with the granular bifenthrin products. Permethrin was the exception, but was only a minor component in the EcoPCO product.

Because the driveway is the main conduit to the street for insecticides running off from the house due to rain or of irrigation, our first goal in these studies was to reduce fipronil's runoff by not treating the driveway and by leaving a 1-ft untreated buffer zone between the driveway and the rest of the house. The day 1 runoff (Figure 5) for fipronil and its breakdown products is two to three orders of magnitude lower than those obtained in earlier studies (Greenberg et al. 2010, 2014) where the driveway at the garage door received treatments. Not doing fipronil treatments on the driveway is an important mitigation technique.

After reducing fipronil runoff, our second goal was to maintain efficacy of treatments by supplementing the fipronil with other products. In our current studies, we have shown that adding other products that do not have a serious runoff problem can help to maintain efficacy of treatments. In the 2011 study, we supplemented the fipronil treatments with granular bifenthrin products which we have shown to have low runoff potential compared to liquid bifenthrin sprays (Greenberg et al. 2010). Of the granular products, the bifenthrin Verge formulation had more significant reductions in ant numbers at the house than the bifenthrin PL formulation (Table 1). Both products contain the same percentage of active ingredients, suggesting that the clay substrate of the Verge has some advantages over the sand substrate of the PL in controlling ants. Possible factors are their duration at the site and which formulation contacts more ants.

The 2011 study also showed that fipronil was more effective around the house than in the backyard (Tables 1 and 2). The mode of action of fipronil may help explain these different results. Fipronil is spread among ants by lateral transfer of the insecticide by ants that have contacted it (Soeprono & Rust 2004). These ants tend to follow interfaces such as those where a building foundation meets the ground. Spraying the fipronil at the interface is likely to contact many foraging ants, followed by lateral transfer to others on the trail or in the nest. On the other hand, ants in the backyard are more likely to be tending homopterans on plants and may not be readily exposed to the fipronil spray. Although the typical foraging ranges of Argentine ants can be up to 61 m from structures and feeding sites (Vega & Rust 2003), they will probably not move that far if they have a closer food source. The ants in the backyard most likely encountered only the bifenthrin granules.

In our 2013 study, we supplemented treatments with botanical pesticides, indoxacarb, and ant gel baits. These products all increased efficacy, although for the gel bait it took 8 weeks and it then had the highest reduction in ant numbers of 82.8% (Table 3). Ant baits in bait stations are a promising solution to insecticide runoff issues. For ant baits to be effective, they need to have delayed toxicity to allow ants to collect the toxicant and spread it around the entire colony (Rust et al. 2004). Also, because the bait is in a very attractive matrix, it may initially pull in more ants from surrounding areas, leading to an increase in ant numbers at monitors and an apparent reduction in control. Our data suggest that, by week 8, the bait has passed the equilibrium point and is killing more ants than it is attracting. Welzel and Choe (2016) also tested the ant gel bait against Argentine ants, both with and without the ant's trail pheromone added to the bait. They found that ant numbers with the pheromone-assisted bait increased at 1-week post-treatment before going down in subsequent periods, showing some similarity to our findings. Bait stations require maintenance and secure dispensers resistant to children and pets. A cost analysis indicated that a standard industry treatment involving sprays or scatter baits cost 40% less than baiting with bait stations (Klotz et al. 2009). However, with increased scrutiny of pesticide residues in urban waterways, bait stations may become a necessary part of the treatment protocol.

A new experimental development in ant baits is the use of polyacrylamide hydrogels as a matrix to store sucrose water and toxicants (Boser et al. 2014; Buczkowski et al. 2014a, 2014b; Rust et al. 2015). These gels, in the form of small hard round crystal balls, are sometimes put into potting soil to help maintain moisture in the soil and are readily available (e.g. Miracle-Gro Water-Storing Crystals, The Scotts Company LLC, Marysville, OH). When experimentally used for ant control, these gels absorb sugar solutions with toxicants and then slowly release their contents to feeding ants. These baits can be scattered or put into bait stations. They are effective in controlling Argentine ants and may reduce runoff if used in bait stations. Thiamethoxam has been the toxicant used in early trials, but other toxicants may also work with the gels.

Jones et al. (2016) did runoff studies using either indoor concrete slabs or an outdoor test facility consisting of lots with front walls, yards, and driveways. Pyrethroids were applied to the concrete surfaces both indoors and outdoors followed by artificial rain. They found that the indoor runoff results could not always predict the outdoor runoff and they emphasize that washoff research needs to be conducted together with efficacy testing of the products. We agree with their recommendations and our current and previous studies (Greenberg et al. 2010, 2014) used real houses to simultaneously monitor efficacy of treatments to control ants and measure insecticide runoff from those treatments. We expect our results will help mitigate runoff by improving how ant products are labeled for use around houses.

Acknowledgments

We thank Kevin Welzel for helping to set up the ant gel bait stations. We also thank Kathleen Campbell for doing many of the treatments. We thank Fred Ernst for his assistance in constructing the water dam and in collecting samples. We also thank Dr Jay Gan (Environmental Sciences, UC Riverside) for doing the pesticide analysis in his laboratory. In particular, we thank Kean Goh and Mike Ensminger of DPR for their support of our research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported in part by the California Department of Pesticide Regulation [grant number 14-C0102] and by a US EPA Assistance Agreement [grant number X8-83512101-0].

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References

Boser CL, Hanna C, Faulkner KR, Cory C, Randall JM, Morrison SA. 2014. Argentine ant management in conservation areas: results of a pilot study. Monogr West N Am Nat. 7:515–560.

Buczkowski G, Roper E, Chin D. 2014a. Polyacrylamide hydrogels: an effective tool for delivering liquid baits to pest ants (Hymenoptera: Formicidae). J Econ Entomol. 107:748–757.

Buczkowski G, Roper E, Chin D, Mothapo N, Wossler, T. 2014b. Hydrogel baits with low-dose thiamethoxam for sustainable Argentine ant management in commercial orchards. Entomol Exp Appl. 153:183–190.

Ensminger MP, Budd R, Kelley KC, Goh KS. 2013. Pesticide occurrence and aquatic benchmark exceedances in urban surface waters and sediments in three urban areas of California, USA, 2008–2011. Environ Monit Assess. 185:3697–3710.

Field HC, Evans WE, Hartley R, Hansen LD, Klotz JH. 2007. A survey of the structural ant pests in the southwestern U.S.A. (Hymenoptera: Formicidae). Sociobiology. 49:1–14.

Gan J, Bondarenko S, Oki L, Haver D, Li JX. 2012. Occurrence of fipronil and its biologically active derivatives in urban residential runoff. Environ Sci Technol. 46:1489–1495.

Greenberg L, Rust MK, Klotz JH, Haver D, Kabashima JN, Bondarenko S, Gan J. 2010. Impact of ant control technologies on insecticide runoff and efficacy. Pest Manage Sci. 66:980–987.

Greenberg L, Rust MK, Richards J, Wu X, Kabashima JN, Wilen C, Gan J, Choe D-H. 2014. Practical pest management strategies to reduce pesticide runoff for Argentine ant (Hymenoptera: Formicidae) control. J Econ Entomol. 107:2147–2153.

Jones RL, Trask JR, Hendley P, Cox MJ, Chepega JC, Harbourt CM, Davidson PC. 2016. Effects of formulation on transport of pyrethroids in residential settings. Environ Toxicol Chem. 35:340–347.

Jorgenson BC, Wissel-Tyson C, Young TM. 2012. Factors contributing to the off-target transport of pyrethroid insecticides from urban surfaces. J Agric Food Chem. 60:7333–7340.

Keppel G. 1991. Design and analysis: a researcher's handbook. 3rd ed. Englewood Cliffs (NJ): Prentice Hall.

Klotz JH, Rust MK, Field HC, Greenberg L, Kupfer K. 2008. Controlling Argentine ants in residential settings (Hymenoptera: Formicidae). Sociobiology. 51:579–588.

Klotz JH, Rust MK, Field HC, Greenberg L, Kupfer K. 2009. Low impact directed sprays and liquid baits to control Argentine ants (Hymenoptera: Formicidae). Sociobiology. 54:101–108.

Klotz JH, Rust MK, Greenberg L, Field HC, Kupfer K. 2007. An evaluation of several urban pest management strategies to control Argentine ants (Hymenoptera: Formicidae). Sociobiology. 50:391–398.

Klotz JH, Rust MK, Greenberg L, Robertson MA. 2010. Developing low risk management strategies for Argentine Ants (Hymenoptera: Formicidae). Sociobiology. 55:779–786.

Knight RL, Rust MK. 1990. The urban ants of California with distribution notes of imported species. Southwest Entomol. 15:167–178.

Reierson DA, Rust MK, Hampton-Beesley J. 1998. Monitoring with sugar water to determine the efficacy of treatments to control Argentine ants, *Linepithema humile* (Mayr). In: Proceedings of the 1998 National Conference on Urban Entomology; 1998 Apr 26–28; San Diego, CA. p. 78–82.

Rust MK, Reierson DA, Klotz JH. 2003. Pest management of Argentine ants (Hymenoptera: Formicidae). J Entomol Sci. 38:159–169.

Rust MK, Reierson DA, Klotz JH. 2004. Delayed toxicity as a critical factor in the efficacy of aqueous baits for controlling Argentine ants (Hymenoptera: Formicidae). J Econ Entomol. 97:1017–1024.

Rust MK, Soeprono A, Wright S, Greenberg L, Choe D-H, Boser CL, Cory C, Hanna C. 2015. Laboratory and field evaluations of polyacrylamide hydrogel baits against Argentine ants (Hymenoptera: Formicidae). J Econ Entomol. 108:1228–1236.

Silverman J, Brightwell RJ. 2008. The Argentine ant: challenges in managing an invasive unicolonial pest. Annu Rev Entomol. 53:231–252.

Soeprono A, Rust MK. 2004. Effect of horizontal transfer of barrier insecticides to control Argentine ants (Hymenoptera: Formicidae). J Econ Entomol. 97:1675–1681.

Systat. 2009. Statistics, version 13.1. Chicago (IL): Systat Software.

US EPA. 2016. Aquatic life benchmarks for pesticide registration; [updated 2016 July 12; cited 2016 Aug 15]. Available from: https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/aquatic-life-benchmarks-pesticide-registration

Vega SY, Rust MK. 2003. Determining the foraging range and origin of resurgence after treatment of Argentine ant (Hymenoptera: Formicidae) in urban areas. J Econ Entomol. 96:844–849.

Welzel KF, Choe D-H. 2016. Development of a pheromone-assisted baiting technique for Argentine Ants (Hymenoptera: Formicidae). J Econ Entomol. 109:1303–1309.

Weston DP, Lydy MJ. 2014. Toxicity of the insecticide fipronil and its degradates to benthic macroinvertebrates of urban streams. Environ Sci Technol. 48:1290–1297.

Weston DP, Ramil HL, Lydy MJ. 2013. Pyrethroid insecticides in municipal wastewater. Environ Toxicol Chem. 32:2460–2468.