*Journal of Economic Entomology*, XX(XX), 2021, 1–7
https://doi.org/10.1093/jee/toab244
Research

ENTOMOLOGICAL SOCIETY OF AMERICA
SHARING INSECT SCIENCE GLOBALLY

OXFORD

Household and Structural Insects

# Reduced Susceptibility Towards Commercial Bait Insecticides in Field German Cockroach (Blattodea: Ectobiidae) Populations From California

**Shao-Hung Lee,[1,2] Dong-Hwan Choe,[1,] Michael K. Rust,[1] and Chow-Yang Lee[1,2,]**

[1]Department of Entomology, University of California, 900 University Avenue, Riverside, CA 92521, USA, and [2]Corresponding authors, e-mail: slee228@ucr.edu; chowyang.lee@ucr.edu

Subject Editor: Claudia Husseneder

Received 26 October 2021; Editorial decision 19 November 2021

## Abstract

Gel bait insecticides have been extensively used to manage the German cockroach, *Blattella germanica* (L.) (Blattodea: Ectobiidae), but issues with reduced effectiveness of such formulations are becoming increasingly common. We collected five field strains of German cockroaches in California and evaluated them against five commercial bait products [Maxforce FC Magnum (0.05% fipronil), Maxforce Impact (1% clothianidin), Advion Evolution (0.6% indoxacarb), Optigard (0.1% emamectin benzoate) and Siege (2% hydramethylnon)]. Increased survivorship and incomplete mortality towards all baits were recorded in the field strains. We assessed susceptibility to the active ingredients fipronil, clothianidin, indoxacarb, abamectin, hydramethylnon, and deltamethrin using topical bioassays with diagnostic doses ($3 \times LD_{95}$ and $10 \times LD_{95}$) developed from the UCR susceptible strain. Low mortality was registered when tested with the $3 \times LD_{95}$'s of deltamethrin (0%), fipronil (0–3%), and clothianidin (13–27%); low to moderate mortality when treated with the $3 \times LD_{95}$ of indoxacarb (13–63%), and moderate to high mortality after treatment with the $3 \times LD_{95}$ of abamectin (80–100%) and hydramethylnon (70–83%). The mortality of all strains remained low after treatment with the $10 \times LD_{99}$ of deltamethrin (0–20%) and low to moderate with fipronil (20–70%). We found negative correlations ($P < 0.05$) between Advion Evolution mean survival time and indoxacarb $10 \times LD_{95}$ mortality and between Maxforce Impact and clothianidin $10 \times LD_{95}$ mortality. These findings demonstrate multiple resistance towards all tested commercial bait insecticides except Optigard, suggesting the effectiveness of avermectin products in resistance management programs.

**Key words:** deltamethrin, fipronil, indoxacarb, abamectin, insecticide resistance

The German cockroach, *Blattella germanica* (L.) (Blattodea: Ectobiidae), is one of the most prevalent pests within urban buildings such as restaurants and low-income housing (Lee and Wang 2021). Issues with German cockroach infestations range from psychosocial impacts to direct health consequences of allergen production and pathogen transmission (Mollet et al. 1997, Menasria et al. 2014, Schal and DeVries 2021). Because of their quick action, low cost, and availability, insecticides have been the most preferred approach to cockroach management. However, after decades of continued use, insecticide resistance has become a perpetual obstacle to German cockroach management (Chai and Lee 2010, Hu et al. 2020, Scharf and Gondhalekar 2021).

For the past two decades, conventional indoor cockroach management programs have shifted away from reliance on residual spray insecticides to incorporate baiting as standard cockroach control tools (Wang et al. 2004, Gondhalekar et al. 2011, Tee and Lee 2014, Ko et al. 2016). Baiting provides many advantages over residual sprays, including simplicity of application, reduced contamination, increased target specificity, increased chance of lethal exposure, and has been widely successful in dampening the overall severity of cockroach infestations (Miller and Meek 2004, Miller and Smith 2020, Appel and Rust 2021). Although baits continue to be ubiquitous in cockroach management (Gondhalekar et al. 2011, Wang et al. 2019), multiple cases of resistance towards baits have been reported throughout the past decade (Gondhalekar and Scharf 2012; Ko et al. 2016; Wu and Appel 2017; Fardisi et al. 2019; Hu et al. 2020, 2021), with Fardisi et al. (2019) also demonstrating the ineffectiveness of rotation and mixture strategies thought to preempt resistance development.

Given the prolific evolution of physiological resistance in German cockroaches and historical abandonment of many classes of insecticides due to loss of efficacy (Cochran 1995), novel approaches will be necessary to preserve the usefulness of bait technology. Endeavors of this nature are contingent on a holistic understanding of the status and nature of insecticide resistance towards contemporary products. There is a current lack of this data on German cockroaches from California despite the many metropolitan areas and growing structural pest control industries. The last survey on insecticide resistance occurred more than 30 yrs ago with limited testing of a single insecticide (chlorpyrifos) and before the widespread adoption of bait insecticides (Rust and Reierson 1991).

In this study, we responded to pest management professionals (PMPs) and housing authority personnel about the reduced performance of cockroach treatments at residential sites across several Californian cities. We collected five field strains of cockroaches and tested them against five commercial baits with different insecticide modes of action in a laboratory bioassay. The topical activity of the active ingredients from the baits was evaluated for each strain. We also included deltamethrin in our evaluation due to the prevalence of pyrethroid products in the market and the well-documented history of pyrethroid resistance in this species (Lee and Rust 2021). The association between the performance of baits and their respective active ingredients was calculated to estimate the contribution of physiological and behavioral factors towards bait susceptibility.

## Materials and Methods

### Insects

Five strains of German cockroaches were collected from separate residential sites in California from 2018 to 2020 (Table 1). Apart from one strain's (CDR) location, all sites had ongoing or previous cockroach control programs utilizing various commercial products. A susceptible laboratory strain (UCR) was used in this study to determine the baseline toxicity of insecticides and served as a standard for comparison. The UCR strain was established from the Orlando normal strain over 40 yrs ago and has never been exposed to insecticides. All strains were reared separately in 121-liter garbage bins equipped with electrical barriers (Wagner et al. 1964) at 24 ± 2°C, ambient RH (30–50%), and a 12-hour photoperiod. Dog food (Purina Dog Chow, Nestlé Purina Petcare, St. Louis, MO), a water source, and corrugated cardboard harborages were provided ad libitum.

Adult males were selected for all experiments because of uniform sizes (about 50 mg) and physiological states (Appel et al. 1983, Abd-Elghafar et al. 1990), and removal of males from breeding colonies has a minor impact on rearing. Furthermore, adult males are the most susceptible stage in bait bioassays due to their high foraging activity (Metzger 1995). If baits are unable to kill the adult males in arenas, they will not be able to control the females and immature stages.

### Insecticides

Analytical or technical grade insecticides were used to determine the baseline toxicity: fipronil (≥ 95%, Sigma Aldrich Corporation, St. Louis, MO), clothianidin (≥ 98%, Sigma Aldrich Corporation, St. Louis, MO), indoxacarb (≥ 95%, Sigma Aldrich Corporation, St. Louis, MO), abamectin (≥ 90%, Sigma Aldrich Corporation, St. Louis, MO), hydramethylnon (98%, Chung Hsi Chemical Industries, Hsinchu, Taiwan), and deltamethrin (≥ 98%, Sigma Aldrich Corporation, St. Louis, MO). Five commercial bait formulations were evaluated: Maxforce FC Magnum (0.05% fipronil, Bayer Environmental Science, Research Triangle Park, NC), Maxforce Impact (1% clothianidin, Bayer Environmental Science, Research Triangle Park, NC), Advion Evolution (0.6% indoxacarb, Syngenta Corporation, Wilmington, DE), Optigard (0.1% emamectin benzoate, Syngenta Corporation, Wilmington, DE), or Siege (2% hydramethylnon, BASF Corporation, Research Triangle Park, NC).

### Bait Evaluation

Two days before each trial, ten adult males were allowed to acclimate in an arena (27.5 × 20 × 9 cm) with dog food, water, a cardboard harborage (inverted paper cup (5 oz.) with a piece of corrugated cardboard inside), and filter paper covering the bottom. The walls of the arena were coated with a thin layer of fluon (BioQuip Products Inc., Rancho Dominguez, CA) to prevent insects from escaping. At the start of the trial, 0.3 g of insecticide bait was introduced to the arena on a small weigh boat with one quadrant cut off to prevent the raised edges from blocking access to the bait. Cockroaches were allowed to feed freely on bait or dog food during the trials, and exact consumption of either bait or dog food was not measured. Insects were considered dead when they were unable to walk or right themselves when gently probed with forceps. Mortality was recorded every 2 h for the first 24 h, then every 12 h up to 14 d. Dead individuals were removed from the arena. Control replicates were prepared in an identical manner but without the addition of bait. Each experiment was replicated 3 times.

### Baseline Toxicity of Insecticides and Diagnostic Dose Assays

Stock solutions of insecticide were made by diluting either analytical or technical grade insecticides in acetone (w/v%),

**Table 1.** Information on the susceptible and field-collected German cockroach strains used in this study

| Name | Collection location | Type of building | Collection date | Treatment history/other information |
|---|---|---|---|---|
| UCR | - | - | - | Laboratory susceptible strain, no insecticide exposure. |
| WM | Los Angeles, CA | Public housing | September 2018 | Products containing deltamethrin, imidacloprid, beta-cyfluthrin, and lamda-cyhalothrin. |
| RG386 | Los Angeles, CA | Public housing | August 2019 | Products containing indoxacarb and chlorfenapyr. |
| Ryan | San Jose, CA | Apartment | 2020 | Products containing fipronil, dinotefuran, methoprene, pyriproxyfen, novaluron, and pyrethroids. Received from Dr. Ryan Neff of MGK. |
| CDR | Vista, CA | Apartment | November 2019 | No treatment history at the collection site. |
| SY | San Diego, CA | Apartment | November 2019 | Products containing chlorfenapyr, indoxacarb, hydroprene, pyriproxyfen, and novaluron. |

followed by serial dilutions to create ranges of doses achieving ~10–90% mortality in the UCR susceptible strain. All selected compounds were active ingredients in the baits used for the bait evaluations except for abamectin (used in this study as the representative macrocyclic lactone to investigate Optigard [0.1% emamectin benzoate] resistance) and deltamethrin (absent in baits, but commonly found in many residual insecticide spray products).

Adult males of the UCR strain were briefly anesthetized with $CO_2$, and 0.5 µl of insecticide solution was applied to the first and second abdominal sternites with a microapplicator (Burkard Manufacturing Co Ltd, Rickmansworth, England). Dog food, water, and cardboard harborages were provided to the treated cockroaches, and mortality was recorded at 72 h post-treatment (120 h for hydramethylnon). Controls were treated with acetone only. A total of 7–9 doses were used and each was replicated 4–21 times. The data obtained from this study was used to generate the $LD_{50}$ and $LD_{95}$ for each insecticide (Table 2).

The diagnostic dose of 3 × $LD_{95}$ was used to screen for resistance based on the presence of survivors after treatment (Robertson et al. 2017). Additionally, to conserve adult males for bait studies and still estimate the degree of resistance, each strain was tested with the 10 × $LD_{95}$ for each insecticide (except for hydramethylnon due to the insolubility of the technical material at high concentrations). Ten adult males of each cockroach strain were briefly anesthetized with $CO_2$ and treated with 0.5 µl of insecticide solution on the abdominal sternites with a microapplicator. Treated cockroaches were provided dog food, water, and cardboard harborages. The proportion of dead individuals was recorded after 72 h (120 h for hydramethylnon). Each dose was replicated 3 times.

### Data Analyses

The impact of the baits on survivorship was analyzed with Kaplan-Meier analysis, and survivorship curves were compared with that of the UCR strain using log-rank tests in SPSS Statistics version 28.0 (IBM Corporation, Armonk, NY). Data obtained in baseline toxicity tests on the UCR strain were pooled and subjected to probit analysis using PoloPlus (LeOra Software LLC, Petaluma, CA). The significance of resistance of field-collected strains at the 3 × $LD_{95}$ and 10 × $LD_{95}$ levels was determined by comparing them to the UCR strain through Mantel-Haenszel tests using R version 3.5.1. Control mortality below 20% was used to correct for treatment mortality using Abbott's formula (Abbott 1925). Spearman's correlation was calculated between the mean survival time in bait assays and percent mortalities from diagnostic dose treatments (10 × $LD_{95}$ for fipronil, clothianidin, indoxacarb, and abamectin; 3 × $LD_{95}$ for hydramethylnon) using R version 3.5.1.

## Results

### Bait Evaluation

Maxforce FC Magnum, Advion Evolution, and Siege showed reduced performance when tested against field-collected strains compared to the UCR strain based on log-rank tests (Fig. 1A, C, and E; Supp Table S1 [online only]). Total mortality differed amongst baits, with Maxforce FC Magnum, Advion Evolution, and Siege causing 50–80%, 80–100%, and 60–93.3% mortality at 14 d, respectively (Table 3). Ryan was the least susceptible strain to all baits (except Optigard) with the longest mean survival times, although overlap of 95% CI's and insignificant differences in survivorship were found at both the upper and lower ends of response for all baits (Fig. 1A–E; Table 3). Mortality trends with Maxforce Impact varied greatly, with WM having no significant difference in survivorship versus UCR (Fig. 1B) whereas Ryan failed to exceed 50% mortality at 14 d (Table 3). Marginal increase in survivorship against Optigard was found in all strains with RG386, CDR, and SY being insignificantly different from UCR (Fig. 1D). Final mortality was 93.3–100%, and mean survival times were uniform with overlapping 95% CI's between all field strains (Table 3).

### Diagnostic Dose Assays

All strains were topically resistant to deltamethrin with 0% mortality after treatment with the 3 × $LD_{95}$ and ≤ 20% mortality from the 10 × $LD_{95}$ (Fig. 2; Supp Table S2 [online only]). All strains were resistant to both Diagnostic doses of fipronil, with mortality ranging from 20% to 70% at the higher dose. Resistance towards clothianidin and indoxacarb varied between strains, with high mortality at the 10 × $LD_{95}$ of clothianidin for WM and CDR (100% and 87%, respectively), and at the 10 × $LD_{95}$ of indoxacarb for RG386 and CDR (87% and 97%, respectively). Other strains ranged between 53–83% for both clothianidin and indoxacarb. Total mortality across all strains occurred from the treatment of the 10 × $LD_{95}$ of abamectin and ≥ 80% mortality from the 3 × $LD_{95}$. All strains were found to be resistant to hydramethylnon at the 3 × $LD_{95}$ level with mortality between 70–83%.

### Correlation Between Bait Survival and Contact Resistance

Significant negative correlations were found between Advion Evolution survival time and indoxacarb 10 × $LD_{95}$ mortality (Spearman's correlation: $\rho = -0.94$, $P < 0.01$), as well as Maxforce Impact survival time and clothianidin 10 × $LD_{95}$ mortality (Spearman's correlation: $\rho = -0.93$, $P = 0.017$). Insignificant correlations were found between Maxforce FC Magnum survival time and fipronil 10 × $LD_{95}$ mortality as well as Siege survival time and hydramethylnon 3 × $LD_{95}$ mortality ($\rho = -0.83$, $P = 0.058$; $\rho = -0.75$,

**Table 2.** Toxicity of insecticides against the susceptible UCR strain at 72 h (120 h for hydramethylnon)

| Insecticide | *n* | $LD_{50}$ (95% CI) (µg/insect) | $LD_{95}$ (95% CI) (µg/insect) | Slope | SE | $\chi^2$(df) |
|---|---|---|---|---|---|---|
| fipronil | 620 | 0.0013 (0.0011–0.0014) | 0.0036 (0.0031–0.0048) | 3.595 | 0.424 | 4.806 (6) |
| clothianidin | 630 | 0.0199 (0.0142–0.0260) | 0.3036 (0.2123–0.4994) | 1.390 | 0.138 | 5.771 (7) |
| indoxacarb | 610 | 0.1100 (0.0890–0.1330) | 0.7480 (0.5340–1.2190) | 1.976 | 0.149 | 4.0003 (4) |
| abamectin | 600 | 0.0053 (0.0041–0.0062) | 0.0155 (0.0126–0.0221) | 3.505 | 0.375 | 4.275 (5) |
| hydramethylnon | 600 | 3.3260 (2.2760–4.2550) | 14.1890 (10.7930–22.1740) | 2.611 | 0.246 | 5.576 (4) |
| deltamethrin | 820 | 0.0046 (0.0039–0.0052) | 0.0113 (0.0093–0.0149) | 4.204 | 0.301 | 8.4798 (5) |

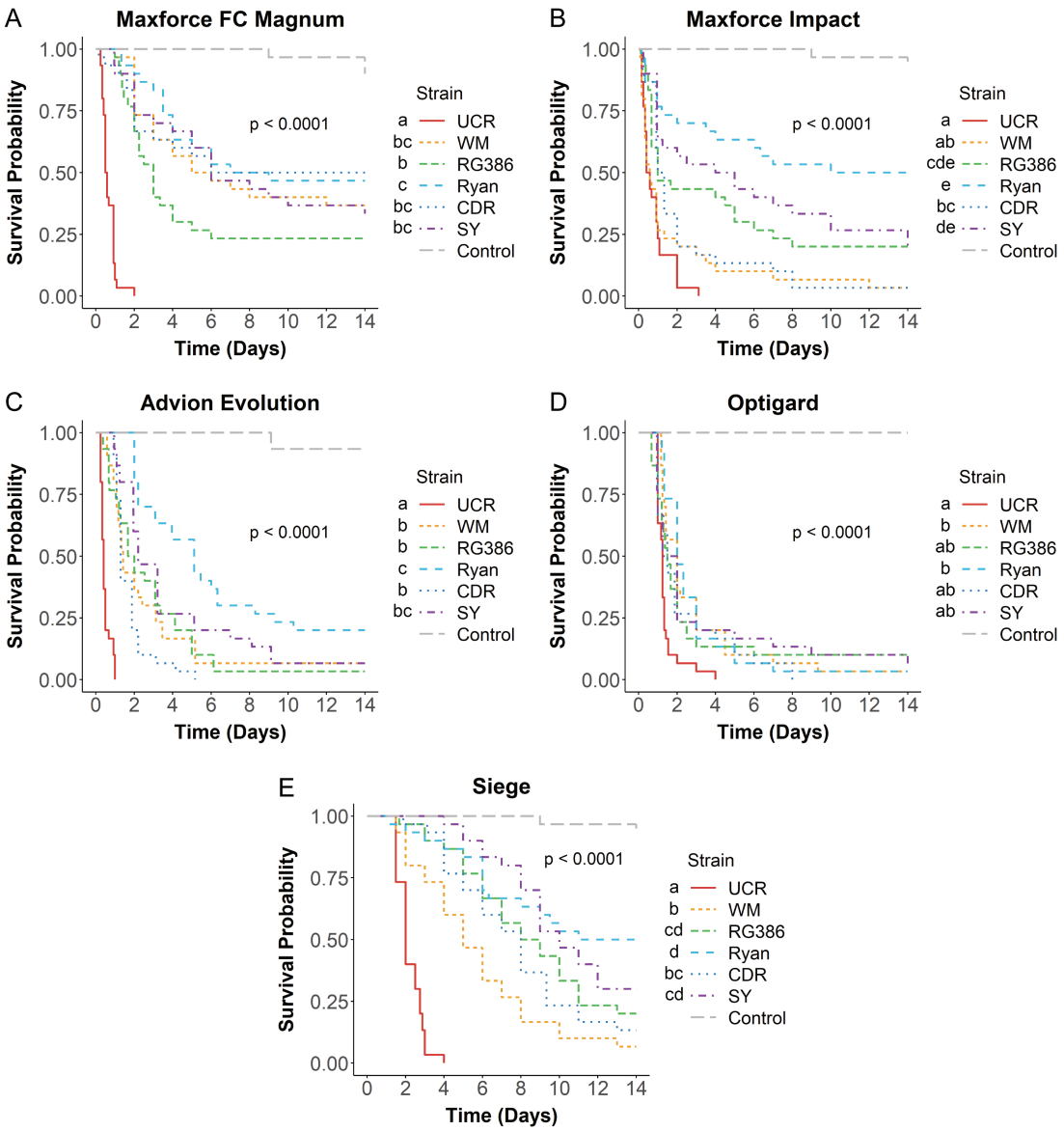


**Fig. 1.** Survivorship of cockroach strains in bait evaluation tested with (A) Maxforce FC Magnum (0.05% fipronil), (B) Maxforce Impact (1% clothianidin), (C) Advion Evolution (0.6% indoxacarb), (D) Optigard (0.1% emamectin benzoate), and (E) Siege (2% hydramethylnon). Log-rank tests were performed to determine differences amongst strains ($\alpha = 0.01$). *P*-values indicate differences between all strains and strains with different lower-case letters are significantly different from one another.

$P = 0.084$, respectively). No result was calculated for Optigard because all responses from the 10 × $LD_{95}$ of abamectin were 100%.

## Discussion

Resistance towards most insecticide classes found across all surveyed populations is indicative of broad-spectrum resistance in current infestations of German cockroaches in California. This likely explains the reduced efficacy of treatments at their respective field sites. Insecticide resistance is a sign of prolonged treatment exposure across multiple generations (Yu 2014). However, all field-collected strains were found to be resistant to insecticides absent from their control programs. This may imply any or a combination of the following: prior exposure that resulted in the development of stable resistance mechanisms (e.g., homozygosity of mechanisms with minimal fitness cost), presence of broad-spectrum resistance mechanisms (e.g., mixed-function oxidase activity), or cross-resistance occurring in any mechanism (Liang et al. 2017). In particular, the deltamethrin resistance found in all strains suggests that cross-resistance towards baits may be occurring as a result of metabolic detoxification activity (Hu et al. 2020, 2021).

Furthermore, many baits failed to kill all test insects from the field-collected strains after 14 d; only Advion Evolution and Optigard caused 100% mortality in the CDR strain while all other strains had mortalities ranging from 50% to 96.7% (Table 3). The presence of survivors observed in most of the trials suggests the potential of further resistance development in similar populations due to the inadvertent selection for less susceptible individuals. It should be noted, however, that bait reapplication did not occur during the experiments, while field treatment programs with follow-up applications every 2–4 wks theoretically improve control efficiency (Appel and Rust 2021). Additionally, survival can be due to the reduced appeal or function of aged bait applications instead of inherently lower susceptibilities of the remaining cockroaches, but this will require a

more extensive procedure to elucidate. Because cockroaches were not forced to feed on the baits, palatability and the choice of dog food as an alternative resource act as additional factors affecting overall insecticide exposure. Regardless of the reason, survivorship in field populations is a sign of ineffective treatment and would contribute towards the perpetuation of infestations.

Behavioral resistance towards baits in German cockroaches is a well-known phenomenon that often manifests as an aversion towards bait ingredients and theoretically can be the main contributor to increased time-to-kill (Silverman and Bieman 1993, Appel and Rust 2021). Although we did not explicitly investigate strain-specific interactions towards each bait formulation and active ingredient, the forced contact dosing method with topical applications functions as an indirect way to gain insight into the involvement of physiological resistance towards insecticides. Statistical significance found in the diagnostic dose data (Fig. 2; Supp Table S2 [online only]) for most strains and insecticides provide evidence that bait resistance from the bait bioassay is unlikely to be solely caused by avoiding lethal exposure. In particular, the strong negative correlation between Advion Evolution survival time and indoxacarb diagnostic dose mortality and between Maxforce Impact survival time and clothianidin diagnostic dose mortality suggests that in these strains, the reduced

**Table 3.** Mean survival times and total mortality of cockroach strains in bait evaluation

| Bait (% active) | Strain | Mean survival time (days) | 95% CI | Std. error | % Mortality at 14 days |
|---|---|---|---|---|---|
| Maxforce FC Magnum (0.05% fipronil) | UCR | 0.669 | 0.541–0.798 | 0.066 | 100.0 |
| | WM | 7.633 | 5.741–9.526 | 0.965 | 66.7 |
| | RG386 | 5.232 | 3.458–7.006 | 0.905 | 80.0 |
| | Ryan | 8.717 | 6.871–10.563 | 0.942 | 53.3 |
| | CDR | 8.304 | 6.217–10.391 | 1.065 | 50.0 |
| | SY | 7.831 | 5.931–9.730 | 0.969 | 66.7 |
| Maxforce Impact (1% clothianidin) | UCR | 0.813 | 0.551–1.074 | 0.133 | 100.0 |
| | WM | 1.906 | 0.719–3.092 | 0.605 | 96.7 |
| | RG386 | 4.521 | 2.663–6.379 | 0.948 | 80.0 |
| | Ryan | 8.469 | 6.352–10.586 | 1.080 | 50.0 |
| | CDR | 2.331 | 1.257–3.404 | 0.548 | 96.7 |
| | SY | 6.040 | 4.029–8.051 | 1.026 | 80.0 |
| Advion Evolution (0.6% indoxacarb) | UCR | 0.478 | 0.391–0.565 | 0.044 | 100.0 |
| | WM | 2.783 | 1.606–3.960 | 0.600 | 96.7 |
| | RG386 | 2.815 | 1.848–3.783 | 0.494 | 96.7 |
| | Ryan | 6.328 | 4.752–7.904 | 0.804 | 80.0 |
| | CDR | 1.647 | 1.275–2.019 | 0.190 | 100.0 |
| | SY | 3.885 | 2.625–5.144 | 0.643 | 93.3 |
| Optigard (0.1% emamectin benzoate) | UCR | 1.364 | 1.136–1.591 | 0.116 | 100.0 |
| | WM | 2.889 | 1.901–3.877 | 0.504 | 96.7 |
| | RG386 | 2.878 | 1.505–4.251 | 0.700 | 96.7 |
| | Ryan | 2.858 | 1.986–3.731 | 0.445 | 96.7 |
| | CDR | 2.382 | 1.654–3.110 | 0.371 | 100.0 |
| | SY | 3.265 | 1.806–4.725 | 0.745 | 93.3 |
| Siege (2% hydramethylnon) | UCR | 2.217 | 1.991–2.443 | 0.115 | 100.0 |
| | WM | 5.867 | 4.619–7.115 | 0.637 | 93.3 |
| | RG386 | 8.656 | 7.321–9.990 | 0.681 | 80.0 |
| | Ryan | 10.101 | 8.535–11.668 | 0.799 | 60.0 |
| | CDR | 7.844 | 6.593–9.095 | 0.638 | 86.7 |
| | SY | 10.200 | 9.067–11.333 | 0.578 | 70.0 |

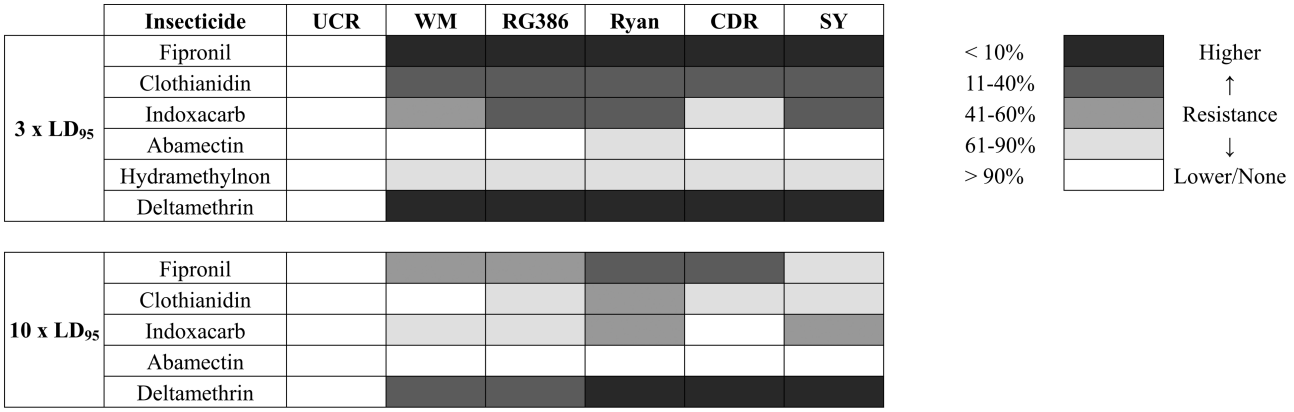


**Fig. 2.** Mortality of cockroach strains at 72 h post-treatment with diagnostic doses (120 h for hydramethylnon).

susceptibility is predominantly caused by physiological resistance towards the active ingredient itself and less influenced by other factors such as bait palatability/aversion due to similar trends observed from the forced exposure (topical) and non-forced exposure (bait assay) methods. In contrast, the insignificant correlation between Maxforce FC Magnum and fipronil as well as Siege and hydramethylnon posits a strain-level disparity in behavioral response towards these baits or insecticides. From these results, behavioral and physiological factors may contribute to bait resistance and their magnitudes will vary depending on strain and insecticide.

Optigard and abamectin performed comparatively well amongst all insecticides with the highest overall bait mortalities (Table 3), lack of significant survivorship deviation in 3 of 5 field strains (Fig. 1D), and complete mortality from the 10 × $LD_{95}$ of abamectin (Fig. 2). This finding of relatively low levels of resistance towards macrocyclic lactones is reflected in the lack of documented substantial physiological resistance towards abamectin reported thus far (Wang et al. 2004, Fardisi et al. 2017). While these data may suggest the advantage of avermectins in managing otherwise resistant German cockroaches, there is evidence showing the rapid decrease of abamectin susceptibility in low-resistance populations once these products are introduced into their treatment programs, so field efficacy must be interpreted with caution (Fardisi et al. 2019). Furthermore, Optigard performed slower than Maxforce FC Magnum, Maxforce Impact, and Advion Evolution on the UCR strain, and despite the minimal resistance in the field-collected strains, failed to outperform Maxforce Impact for WM and CDR and Advion Evolution for WM, RG386, and CDR based on mean survival times (Table 3). Only when higher levels of resistance were present in the field-collected strains did Optigard have a temporal advantage (e.g., Ryan across all baits), so its viability may be limited to treating populations with high resistance towards other insecticides or those which tend towards higher proportions of survivors after treatment.

Despite the sparse documentation of hydramethylnon resistance in field-collected populations of German cockroaches (Ko et al. 2016, Fardisi et al. 2017), Siege gel bait is no longer sold in the United States, nor did any of the field sites report the use of hydramethylnon products. The resistance found in the Siege bioassays and incomplete mortalities at the 3 × $LD_{95}$ of hydramethylnon in all field-collected strains suggest a common occurrence of low-level resistance in many field populations of cockroaches. Coupled with this being the slowest performing bait on the susceptible UCR strain (mean survival time = 2.217 d versus 0.478–1.364 d for other baits [Table 3]), these factors can possibly explain the diminished presence of hydramethylnon in the market.

In summary, our study confirms the presence of multiple insecticide resistance towards contemporary gel bait products and active ingredients in recently collected field populations of German cockroaches from California. Along with the ubiquitous resistance towards deltamethrin, this poses foreseeable problems for selecting effective insecticides in the field if such resistance profiles become widespread. In the absence of controlled dosing, bait insecticides are perceived as inherently more potent than contact insecticides due to oral exposure being the primary mode of entry. This circumvents the need for toxicants to penetrate through the cuticle, and cockroaches may acquire doses far greater than the minimum for mortality if the bait matrix is highly palatable and active ingredient concentration is sufficient (Gondhalekar et al. 2011, Appel and Rust 2021). Although baits have been used in successful management programs thus far, this may be due to the aforementioned effects acting as a buffer to prevent significant resistance development through saturation. Consistent exposure to excessive lethal doses in this manner can increase the potential of high resistance levels, and as evidenced by Fardisi et al. (2019), judicious use of cockroach insecticides can result in further overall resistance development even if populations begin with minimal resistance. The heterogeneous response in strain susceptibility and potential behavioral mechanism involvement adds additional complexity to selecting an appropriate treatment due to the lack of a universally effective approach. More research into areas such as accessible methods to screen for insecticide resistance in the field to improve product selection, the incorporation of insecticide synergists to improve the efficiency of individual insecticides, or other novel strategies to combat resistance will be vital for the continued reliance on cockroach baits.

## Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

## Acknowledgments

We thank the Public Housing Authorities of Los Angeles, Jim Panknin (ExCimex, CA), and Ryan Neff (MGK Company) for their assistance with the collection of German cockroach strains; Chung Hsi Chemical Plant Ltd, Taiwan, for providing technical grade hydramethylnon, and BASF Corporation (NC) for providing Siege gel bait; and UC Riverside Urban Entomology Endowed Chair Research Fund for partial support of this study.

## References Cited

**Abbott, W. S. 1925**. A method of computing the effectiveness of an insecticide. J. Econ. Entomol. 18: 265–267.

**Abd-Elghafar, S. F., A. G. Appel, and T. P. Mack. 1990**. Toxicity of several insecticide formulations against adult German cockroaches (Dictyoptera: Blattellidae). J. Econ. Entomol. 83: 2290–2294.

**Appel, A. G. and M. K. Rust. 2021**. Management using baits, pp. 213–230. *In* C. Wang, C.-Y. Lee, and M. K. Rust (eds.), Biology and management of the German cockroach. CSIRO Publishing, Clayton South, Victoria, Australia.

**Appel, A. G., D. A. Reierson, and M. K. Rust. 1983**. Comparative water relation and temperature sensitivity of cockroaches. Comp. Biochem. Physiol. 74A: 357–36.

**Chai, R. Y., and C. Y. Lee. 2010**. Insecticide resistance profiles and synergism in field populations of the German cockroach (Dictyoptera: Blattellidae) from Singapore. J. Econ. Entomol. 103: 460–471.

**Cochran, D. G. 1995**. Insecticide resistance, pp. 171–192. *In* M. K. Rust, J. M. Owens, and D. A. Reierson. 1995. Understanding and controlling the German cockroach. Oxford Univ. Press, New York.

**Fardisi, M., A. D. Gondhalekar, and M. E. Scharf. 2017**. Development of diagnostic insecticide concentrations and assessment of insecticide susceptibility in German cockroach (Dictyoptera: Blattellidae) field strains collected from public housing. J. Econ. Entomol. 110: 1210–1217.

**Fardisi, M., A. D. Gondhalekar, A. R. Ashbrook, and M. E. Scharf. 2019**. Rapid evolutionary responses to insecticide resistance management interventions by the German cockroach (*Blattella germanica* L.). Sci. Rep. 9: 8292.

**Gondhalekar, A. D., and M. E. Scharf. 2012**. Mechanisms underlying fipronil resistance in a multiresistant field strain of the German cockroach (Blattodea: Blattellidae). J. Med. Entomol. 49: 122–131.

**Gondhalekar, A. D., C. Song, and M. E. Scharf. 2011**. Development of strategies for monitoring indoxacarb and gel bait susceptibility in the German cockroach (Blattodea: Blattellidae). Pest Manag. Sci. 67: 262–270.

**Hu, I.-H., S.-M. Chen, C.-Y. Lee, and K.-B. Neoh. 2020**. Insecticide resistance and its effects on bait performance in field-collected German cockroaches (Blattodea: Ectobiidae) from Taiwan. J. Econ. Entomol. 113: 1389–1398.

**Hu, I.-H., H.-Y. Tzeng, M.-E. Chen, C.-Y. Lee, and K.-B. Neoh. 2021**. Association of *CYP4G19* overexpression with gel bait performance in pyrethroid-resistant German cockroaches (Blattodea: Ectobiidae) from Taiwan. J. Econ. Entomol. 114: 1764–1770.

**Ko, A. E., D. N. Bieman, C. Schal, and J. Silverman. 2016**. Insecticide resistance and diminished secondary kill performance of bait formulations against German cockroaches (Dictyoptera: Blattellidae): insecticide resistance and cockroach secondary kill. Pest Manag. Sci. 72: 1778–1784.

**Lee, C.-Y., and M. K. Rust. 2021**. Chemical control methods, pp. 165–212. *In* C. Wang, C.-Y. Lee, and M. K. Rust (eds.), Biology and management of the German cockroach. CSIRO Publishing, Clayton South, Victoria, Australia.

**Lee, C.-Y., and C. Wang. 2021**. German cockroach infestations in the world and their social and economic impacts, pp. 1–16. *In* C. Wang, C.-Y. Lee, and M. K. Rust (eds.), Biology and management of the German cockroach. CSIRO Publishing, Clayton South, Victoria, Australia.

**Liang, D., J. McGill, and J. E. Pietri. 2017**. Unidirectional cross-resistance in German cockroach (Blattodea: Blattellidae) populations under exposure to insecticidal baits. J. Econ. Entomol. 110: 1713–1718.

**Menasria, T., F. Moussa, S. El-Hamza, S. Tine, R. Megri, and H. Chenchouni. 2014**. Bacterial load of German cockroach (*Blattella germanica*) found in hospital environment. Pathog. Glob. Health. 108: 141–147.

**Metzger, R. 1995**. Behavior, pp. 49–76. *In* M. K. Rust, J. M. Owens, and D. A. Reierson. 1995. Understanding and controlling the German cockroach. Oxford Univ. Press, New York.

**Miller, D. M., and F. Meek. 2004**. Cost and efficacy comparison of integrated pest management strategies with monthly spray insecticide applications for German cockroach (Dictyoptera: Blattellidae) control in public housing. J. Econ. Entomol. 97: 559–569.

**Miller, D. M., and E. P. Smith. 2020**. Quantifying the efficacy of an assessment-based pest management (APM) program for German cockroach (L.) (Blattodea: Blattellidae) control in low-income public housing units. J. Econ. Entomol. 113: 375–384.

**Mollet, J. A., L. D. Vailes, D. B. Avner, M. S. Perzanowski, L. K. Arruda, M. D. Chapman, and T. A. E. Platts-Mills. 1997**. Evaluation of German cockroach (Orthoptera: Blattellidae) allergen and seasonal variation in low-income housing. J. Med. Entomol. 34: 307–311.

**Robertson, J. L., M. M. Jones, E. Olguin, and B. Alberts. 2017**. Bioassays with arthropods, 3rd ed. CRC Press, Boca Raton, FL.

**Rust, M. K., and D. A. Reierson. 1991**. Chlorpyrifos resistance in German cockroaches (Dictyoptera: Blattellidae) from restaurants. J. Econ. Entomol. 84: 736–740.

**Schal, C., and Z. C. DeVries. 2021**. Public health and veterinary importance, pp. 17–52. *In* C. Wang, C.-Y. Lee, and M. K. Rust (eds.), Biology and management of the German cockroach. CSIRO Publishing, Clayton South, Victoria, Australia.

**Scharf, M. E., and A. D. Gondhalekar. 2021**. Insecticide resistance: perspectives on evolution, monitoring, mechanisms and management, pp. 231–255. *In* C. Wang, C.-Y. Lee, and M. K. Rust (eds.), Biology and management of the German cockroach. CSIRO Publishing, Clayton South, Victoria, Australia.

**Silverman, J., and D. N. Bieman. 1993**. Glucose aversion in the German cockroach, *Blattella germanica*. J. Insect Physiol. 39: 925–933.

**Tee, H.-S., and C.-Y. Lee. 2014**. Sustainable cockroach management using insecticidal baits—formulations, behavioural responses and issues, pp. 65–85. *In* P. Dhang (ed.), Urban insect pests—future management practices. CABI International, Oxfordshire, United Kingdom.

**Wagner, R. E., W. Ebeling, and W. R. Clark. 1964**. An electric barrier for confining cockroaches in large rearing or field-collecting cans. J. Econ. Entomol. 57: 1007–1009.

**Wang, C., M. E. Scharf, and G. W. Bennett. 2004**. Behavioral and physiological resistance of the German cockroach to gel baits (Blattodea: Blattellidae). J. Econ. Entomol. 97: 2067–2072.

**Wang, C., A. Eiden, R. Cooper, C. Zha, and D. Wang. 2019**. Effectiveness of building-wide integrated pest management programs for German cockroach and bed bug in a high-rise apartment building. J. Integr. Pest Manag. 10: 1–9.

**Wu, X., and A. G. Appel. 2017**. Insecticide resistance of several field-collected German cockroach (Dictyoptera: Blattellidae) strains. J. Econ. Entomol. 110: 1203–1209.

**Yu, S. J. 2014**. The toxicology and biochemistry of insecticides, second edition. CRC Press, Boca Raton, FL.