Ineffectiveness of Over-the-Counter Total-Release Foggers Against the Bed Bug (Heteroptera: Cimicidae)

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ABSTRACT   Field-collected bed bugs (*Cimex lectularius* L.) showed little, if any, adverse effects after 2-h direct exposure to the aerosolized pyrethroid(s) from three over-the-counter total-release foggers ('bug bombs' or 'foggers'); Hotshot Bedbug and Flea Fogger, Spectracide Bug Stop Indoor Fogger, and Eliminator Indoor Fogger. One field-collected population, EPM, was an exception in that there was significant mortality at 5–7 d when bugs out in the open had been exposed to the Spectracide Fogger; mortality was low when these bugs had access to an optional harborage, a situation observed for all field-collected populations when exposed to the three foggers. Even the Harlan strain, the long-term laboratory population that is susceptible to pyrethroids and that served as an internal control in these experiments, was unaffected if the bugs were covered by a thin cloth layer that provided harborage. In residences and other settings, the majority of bed bugs hide in protected sites where they will not be directly contracted by the insecticide mist from foggers. This study provides the first scientific data supporting the position that total-release foggers should not be recommended for control of bed bugs, because 1) many field-collected bed bugs are resistant to pyrethroids, and they are not affected by brief exposure to low concentrations of pyrethrins and/or pyrethroids provided by foggers; and 2) there is minimal, if any, insecticide penetration into typical bed bug harborage sites. This study provides strong evidence that Hotshot Bedbug and Flea Fogger, Spectracide Bug Stop Indoor Fogger, and Eliminator Indoor Fogger were ineffective as bed bug control agents.

KEY WORDS   bug bomb, *Cimex lectularius*, fogger, pyrethroid, resistance

During the past decade, bed bugs (*Cimex* spp.) have become increasingly commonplace worldwide (Harlan et al. 2008). The bed bug, *Cimex lectularius* L., is adapted for temperate climates and is the dominant species in the United States, whereas the tropical bed bug, *Cimex hemipterus* (F.), is adapted for semitropical to tropical climates (Usinger 1966). Bed bugs are temporary ectoparasites that feed exclusively on blood from humans and other warm-blooded animals. Bed bugs are recognized at the federal level as public health pests (EPA 2002, CDC and EPA 2010). They are largely nocturnal and spend most of their time hiding in cracks and crevices (Usinger 1966, Romero et al. 2010, Reis and Miller 2011).

Pyrethroid resistance is well documented and widespread in field-collected bed bugs and has been implicated in the resurgence and challenge of bed bug control (Romero et al. 2007, Zhu et al. 2010, Bai et al. 2011). Additionally, the re-emergence of bed bugs as human pests is associated with factors such as increased international travel and commerce, changes in pesticide availability and pest management practices, and the public's lack of awareness of bed bugs and the ease in which they are spread (Hwang et al. 2005, Eddy and Jones 2011).

A dramatic increase in consumer products marketed for bed bug control has accompanied the bed bug resurgence. Over-the-counter (OTC) total-release foggers, commonly known as 'bug bombs' or 'foggers,' are marketed as consumer products for the control of many types of crawling and flying household insects. Decades ago, annual sales of foggers amounted to more than one per household (Greenberg 1963). The most recent estimate from the U.S. Environmental Protection Agency (EPA) is that ≈50 million foggers are used annually (http://epa.gov/oppfead1/cb/csb_page/updates/2010/new-foggers.html). Foggers often are used by consumers as a low-cost alternative to professional pest control services; they typically are easy to use and require little effort.

Most foggers contain pyrethrins, pyrethroids, or both, as active ingredients. Foggers act by broadcasting an insecticide mist by way of an aerosol propellant. The directions typically indicate that the can is to be shaken well and positioned on a table or stand in the center of the room then activated by depressing or removing a tab at the top center of the can; people and pets are to vacate the area during the treatment period, usually 2 h. The can's contents are entirely de-

pleted as aerosol insecticide droplets are rapidly released upwards into the airspace, where they remain suspended then gradually settle onto exposed surfaces.

Foggers generally are not recommended for control of household pests because of concerns that 1) there is minimal insecticide penetration into pest harborage sites, which renders them ineffective as control agents; 2) the broadcast insecticide application leaves pesticide residues on exposed surfaces and objects; and 3) the aerosol propellants may be highly flammable, capable of causing fires and explosions (Potter 1999). Foggers have been implicated in human injury and illnesses, often because of misuse of the products by consumers. The U.S. Centers for Disease Control and Prevention (CDC) reported a total of 466 cases of acute, pesticide-related illness or injury associated with exposure to total-release foggers in eight states between 2001 and 2006 (Wheeler et al. 2008). In terms of the severity of these cases, 80% were classified as low, 18% were moderate, and 2% were high; health effects typically were temporary and most commonly involved the respiratory system. Additionally, the Washington State Department of Health classified the death of a female infant as "suspicious," because she was found dead the morning after her apartment had been treated with three foggers. Another CDC report highlighted illnesses associated with bed bug treatments in seven states between 2003 and 2010; one fatality was associated with multiple factors including misuse of two fogger products (Jacobson et al. 2011).

The most common factors contributing to insecticide exposure from foggers include inability or failure to vacate before discharge of the fogger, unintentional fogger discharge, premature re-entry, excessive number of foggers, and failure to notify others nearby (Wheeler et al. 2008). In an effort to minimize misuse caused by failure to follow label instructions, EPA has required manufacturers to make a number of labeling changes by 30 September 2011, to enhance clarity and draw increased attention to critical information (http://epa.gov/oppfead1/cb/csb_page/updates/2010/new-foggers.html).

The few available peer review publications regarding the efficacy of foggers pertain to the German cockroach, *Blattella germanica* (L.), (Moore 1977, Kardatzke et al. 1982, Ballard et al. 1984) and the cat flea, *Ctenocephalides felis* (Bouché) (Osbrink et al. 1986). There are no published data regarding the efficacy of foggers against bed bugs. In this study, we evaluated three foggers against recently field-collected populations of bed bugs as well as a long-term laboratory strain to gain insights into the efficacy of these OTC products.

Materials and Methods

Insects. Five bed bug populations (EPM, King, Kingry, Marcia, and Pointe) were collected between July 2010 and March 2011 from residences in Columbus, OH, and they subsequently were maintained under ambient conditions in the laboratory (22 ± 2°C,

40 ± 15% RH). In addition, the Harlan strain, which is a pyrethroid-susceptible population (Zhu et al. 2010) initially collected in 1973 from Ft. Dix, NJ, and laboratory reared thereafter with no known insecticide exposure, was used as an internal control. Each bed bug population was housed in a glass jar (13 cm high × 7 cm dia; narrow-mouth Mason pint jar, Ball Corp., Broomfield, CO) containing filter paper strips for harborage, with an organza fabric and filter paper covering held in place with a screw-on metal ring.

Bed bugs were reared in situ on a diet of warmed sodium-heparinized chicken blood using the Hemotek 5W1 system (Discovery Workshops, Accrington, England) with Parafilm as the membrane. Approximately every 7–14 d, each bed bug population was offered a bloodmeal until a majority of the bugs were replete.

Study Site. All experiments were conducted in three rooms in a vacant office building on the Ohio State University campus, Columbus, OH. In each of the test rooms, 6 mil plastic sheeting (Blue Hawk, Grand Prairie, TX) was installed to cover the drop ceiling, outlets, and vents to prevent dispersion of the insecticide into adjacent areas. The volume of the two treatment rooms was 32.5 m^3 (1,190 ft^3) and 35.0 m^3 (1,280 ft^3), and the control room was 36.3 m^3 (1,330 ft^3).

Foggers. Three OTC indoor foggers, all obtained from a nationwide retailer, and all from United Industries Corp., St Louis, MO, were evaluated: Hotshot Bedbug and Flea Fogger (0.05% pyrethrins, 0.1% esfenvalerate, 0.1% piperonyl butoxide, 0.167% MGK 264, 0.1% nylar) (Spectrum Group, St. Louis, MO), Spectracide Bug Stop Indoor Fogger (0.1% tetramethrin, 0.6% cypermethrin) (Spectrum Group), and Eliminator Indoor Fogger (0.515% cypermethrin) (Chemisco, St. Louis, MO). A can of each fogger treats 54.6 m^3 (2,000 ft^3) of unobstructed area. Only Hotshot Fogger is specifically labeled for use against bed bugs; the other two foggers are labeled for use against flying and crawling pests in homes. However, the latter two products can be used against bed bugs in many states, whose regulatory requirements are that only the site (e.g., indoors) has to be specified by the label, not the particular pest.

Experimental Units. Test arenas consisted of petri dishes (100 × 15 mm; Fisherbrand, Pittsburgh, PA) or cylindrical plastic containers (50 × 37 mm; Pioneer Plastics Inc., North Dixon, KY) whose sides had been coated with Fluon (Insect-a-Slip Insect Barrier, BioQuip Products, Rancho Dominguez, CA) to prevent bed bug escape. After arenas were provisioned with bed bugs, replicates then were randomly distributed inside a 114-cm dia wading pool (General Foam Plastic Corp., Norfolk, VA) whose inner walls also had been coated with Fluon. Two pools were prepared per room so that two exposure conditions could be simultaneously evaluated for each fogger or its control. A fogger can was positioned on a crate between the two pools such that it was ≈30 cm above the floor and ≈30 cm from each pool edge. As specified by the directions, the fogger was activated for a 2-h treatment period, then the room was opened and allowed to ventilate for
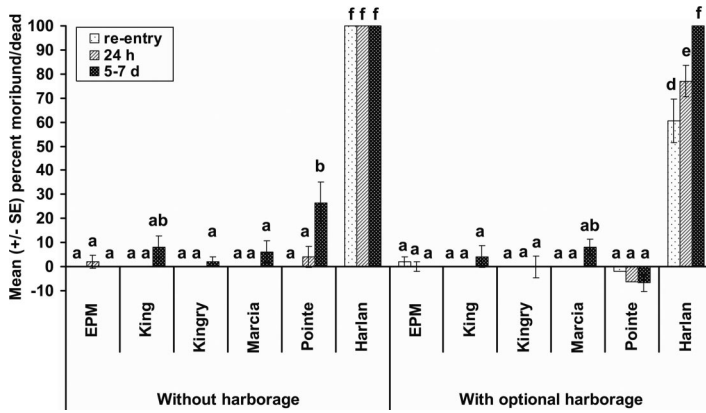
Fig. 1. Cumulative percentage corrected mortality (average ± SE) at re-entry (30 min), 24 h, and 5–7 d for bed bugs from six populations exposed to Hotshot Fogger in either an open petri dish or one containing a piece of paper that served as an optional harborage ($N = 10$ replicates per mean [5 replicates consisting of 5 mixed-sex adults and 5 consisting of 5 mixed-stage nymphs]). Bars with different letters are significantly different based on Tukey's HSD test ($P < 0.05$).

30 min. A control room was similarly configured but without the fogger.

The condition of bed bugs was assessed upon re-entry (30 min) and then again at 24 h and 5–7 d. Bed bugs were examined using a dissecting microscope as necessary. Each bug's condition was assessed based on its behavioral response when probed:

- Healthy: The bed bug moves quickly and in a co-ordinated manner to avoid stimulus.
- Sluggish: reacts slowly, but makes coordinated movements to avoid stimulus.
- Ataxic: unable to coordinate movements to avoid the stimulus. Ataxic bugs can right themselves after falling.
- Moribund: incapable of locomotion and exhibiting movement only of appendages or other body parts.
- Dead: no movement whatsoever.

Direct Exposure Versus Optional Harborage Experiments. All three foggers were evaluated against bed bugs in these bioassays. Bed bugs were either directly exposed in open, unprovisioned petri dishes, or they were placed in petri dishes provisioned with a 80 mm dia filter paper disc (Whatman no. 1, Whatman International Ltd., Maidstone, England) that bed bugs could hide underneath (optional harborage). The Hotshot Fogger was evaluated against all six populations of bed bugs, and both the Spectracide Fogger and Eliminator Fogger were evaluated against three bed bug populations (EPM, Marcia, and Harlan). For the Hotshot Fogger, 10 replicates, 5 consisting of 5 mixed-sex adults and 5 consisting of 5 mixed-stage nymphs, were established for each of 24 treatments: 6 bed bug populations × 2 harborage conditions × 2 treatments (fogger and control). Hence, a total of 1,200 bed bugs was used in this set of bioassays to evaluate the Hotshot Fogger. For both the Spectracide Fogger and the Eliminator Fogger, 10 replicates were similarly established for each of 12 treatment combinations (3 populations × 2 harborage conditions × fogger and control), providing a total of 600 bed bugs per product.

Direct Exposure Versus Forced Harborage Experiments. Only the Hotshot Fogger was evaluated in these bioassays, and two test conditions were compared. In direct exposure tests, each cylindrical plastic container with bed bugs was kept uncovered; in forced harborage tests, each container was covered with a single layer of light-weight cotton broadcloth fabric (Joann Fabrics, Columbus, OH) held in place by a rubber band. Two bed bug populations (EPM and Harlan) were exposed to the Hotshot Fogger; 10 replicates (5 consisting of 10 mixed-sex adults and 5 consisting of 10 mixed-stage nymphs) were established for each of eight treatment combinations (2 populations × 2 harborage conditions × fogger and control). Hence, 800 bed bugs in total were used in this set of bioassays.

Data Analysis. The numbers of moribund plus dead bed bugs were pooled for analysis of bed bug mortality. Treatment data were corrected for control mortality using Abbot's formula (Abbott 1925). Adults and nymphs were combined for analysis. Data were subjected to a repeated-measures analysis of variance (ANOVA) using Statistica 6.1 (StatSoft Inc. 2002), with observation time as the repeated-measures factor and population and harborage as categorical predictor variables. Tukey's honestly significant difference (HSD) test was used for post hoc comparison of means for significant main effects and interaction effects. When overall mean control mortality at an observation time exceeded 15%, all data for that observation were considered unreliable and were not analyzed.

Results

Hotshot Fogger. *Optional Harborage.* All five field-collected bed bug populations showed little, if any, adverse effects after 2 h of direct exposure to aero-solized pyrethroids from the Hotshot Fogger (Fig. 1). Significantly high mortality was observed consistently only for the Harlan strain, the long-term laboratory population that is susceptible to pyrethroids and that
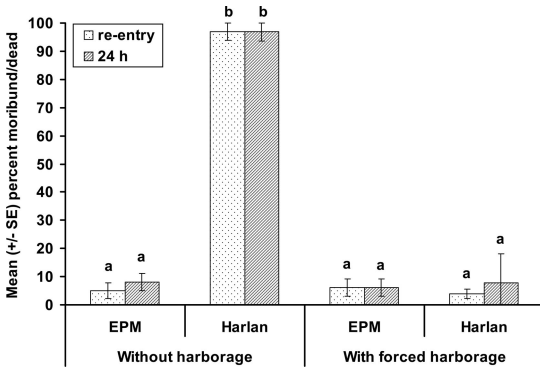
Fig. 2. Cumulative percentage corrected mortality (average ± SE) at re-entry and 24 h for bed bugs from two populations exposed to Hotshot Fogger either in an open container or in a forced harborage wherein each container was covered with thin cotton fabric ($N = 10$ replicates per mean [5 replicates consisting of 10 mixed-sex adults and 5 consisting of 10 mixed-stage nymphs]). Bars with different letters are significantly different based on Tukey's HSD test ($P < 0.05$).

served as an internal control in these experiments. When Harlan bed bugs were directly exposed in open containers, all bugs were moribund or dead at re-entry, but when this population was provided an optional harborage, mortality was significantly lower at re-entry but progressed over time (Fig. 1).

Population ($F = 625.31$; df = 5, 108; $P < 0.001$), harborage ($F = 28.38$; df = 1, 108; $P < 0.001$), and observation time ($F = 22.23$; df = 2, 216; $P < 0.001$) were significant main effects. The full interaction effect (population × harborage × observation time) was significant ($F = 8.19$; df = 10, 216; $P < 0.001$) primarily because of high, but variable, mortality in the susceptible Harlan strain (Fig. 1); field-collected bed bug strains typically exhibited low mortality regardless of observation time. When Harlan bed bugs were directly exposed in open containers, 100% mor-

tality was evident at re-entry, but when they were provided an optional harborage, mortality was time dependent, with 62% mortality at re-entry, 78% at 24 h, and 100% at 5–7 d. In all other treatment and control groups, mortality averaged 2.1% and was nonsignificant, with two exceptions (at 5–7d, Pointe bugs without a harborage exhibited 28% mortality after exposure to the fogger and Harlan control bugs without a harborage had 24% mortality).

Forced Harborage. Figure 2 shows that the field-collected EPM population was unaffected by the Hotshot Fogger regardless of whether bugs were directly exposed or inside a harborage, but more importantly, the susceptible Harlan strain was unaffected if the bugs were covered by a thin cloth layer that provided harborage. The main effects of population ($F = 156.34$; df = 1, 36; $P < 0.001$) and harborage ($F = 166.66$; df = 1, 364; $P < 0.001$) were significant, but observation time (re-entry and 24 h) ($F = 0.36$; df = 1, 36; $P = 0.55$) was not. Because of high control mortality (16.5%), data for the 5–7 d observation were excluded from analysis. The two-way interaction, population × harborage, was significant ($F = 157.83$; df = 1, 36; $P < 0.001$) because only Harlan bugs exposed to the Hotshot Fogger without a harborage experienced significantly higher average mortality (97%) than controls (2.4%) and the EPM bugs (7.5%).

Spectracide Fogger. *Optional Harborage.* When exposed to the Spectracide Fogger, the mortality trend among populations was Harlan > EPM > Marcia (Fig. 3). The main effects of population ($F = 307.2$; df = 2, 54, $P < 0.001$), harborage ($F = 13.72$; df = 1, 54; $P < 0.001$), and observation time ($F = 30.10$; df = 2, 108; $P < 0.001$) were significant (Fig. 3).

The three-way interaction of population × harborage × observation ($F = 11.15$; df = 4, 108; $P < 0.001$) was significant, because at re-entry, Harlan bed bugs experienced significantly higher mortality in open dishes (100%) than when they had access to a harborage (69%); mean mortality further increased to
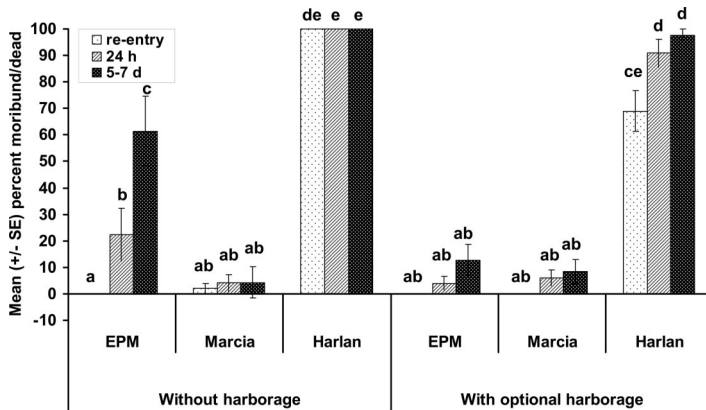

Fig. 3. Cumulative percentage corrected mortality (average ± SE) of bed bugs from three populations exposed to Spectracide Fogger in either an open petri dish or one containing a piece of paper that served as an optional harborage when observed at re-entry, 24 h, and 5–7 d ($N = 10$ replicates per mean [5 replicates consisting of 5 mixed-sex adults and 5 consisting of 5 mixed-stage nymphs]). Bars with different letters are significantly different based on Tukey's HSD test ($P < 0.05$).

91% at 24 h and to 98% at 5–7 d. Additionally, EPM bugs in open dishes had a significant increase in mortality from 0% (re-entry) to 24% (24 h) to 66% (5–7 d). However, when EPM bugs had access to a harborage, their mortality was very low, equivalent to controls.

Eliminator Fogger. *Optional Harborage.* In bioassays with the Eliminator Fogger, the paper harborage curled, resulting in partial or complete escape of bed bugs in some replicates, and thus harborage could not be evaluated as a main effect. Additionally, control mortality at 5–7 d was quite high (37.8%); hence, this observation time was omitted from analysis.

Bed bugs from two field-collected populations, EPM and Marcia, exhibited no significant adverse effects at re-entry and 24 h after being exposed in open containers to the Eliminator Fogger. Overall mortality was quite low for controls (6%) as well as for Marcia (8%) and EPM (3%) exposed to the fogger. Significantly high mortality was observed only for the susceptible Harlan strain. The main effect of population ($F = 564.5$; df = 2, 27; $P < 0.001$) was significant and affected bed bug mortality whereas observation time did not (re-entry and 24 h) ($F = 1.7$; df = 1, 27; $P = 0.2$). The population × observation interaction was significant ($F = 7.2$; df = 2, 27; $P = 0.003$) because Marcia mortality was significantly lower at re-entry (2%) than at 24 h (14%) whereas EPM was similar at re-entry (2%) and 24 h (8%). In contrast, the long-term laboratory population, Harlan, had consistently high mortality at re-entry (100%) and 24 h (100%).

Discussion

Field-collected bed bugs typically were not affected by direct exposure for 2 h to the aerosolized pyrethroid(s) emanating from any of the three total-release foggers (Figs. 1–3), with the exception of EPM, which experienced significantly high mortality at 5–7 d when bugs out in the open had been exposed to the Spectracide Fogger but not when these bugs had access to a harborage (Fig. 3). In contrast, the Harlan strain, the long-term laboratory population that is susceptible to pyrethroids, experienced significantly high mortality when directly exposed to any of the three foggers (Figs. 1–3). Hence, pyrethroid resistance appears to play a role in the foggers' failure to kill bed bugs.

Subsequent genotyping of bed bugs used in our study indicated that all five field-collected populations possessed both known kdr mutations for pyrethroid resistance, V419L and L925I (A.T.H., S.C.J., J.L.B., and O. M. unpublished data), but the Harlan strain possessed none, which is in agreement with the findings of Zhu et al. (2010). The dual compliment of kdr mutations is the most commonly encountered bed bug haplotype in Ohio (A.T.H., S.C.J., J.L.B., and O. M. unpublished data), and it appears to be very prevalent in Ohio as well as throughout much of the United States (Zhu et al. 2010). Furthermore, it is highly unlikely that any field population would be as susceptible as the Harlan strain. Because resistance is widespread in field-collected bed bug populations (Romero et al. 2007, Zhu et al. 2010, Bai et al. 2011), it is likely that pyrethrin- and pyrethroid-based foggers will have little, if any, impact on modern-day bed bug infestations. Note also that Hotshot Fogger was ineffective against field-collected bed bugs despite the presence of piperonyl butoxide, an insecticide synergist that has been shown to somewhat improve product efficacy in pyrethroid-resistant bed bugs (Romero et al. 2009a).

A very important finding was that a forced harborage negated any fogger effects on the susceptible Harlan strain (Fig. 2). Furthermore, having access to a paper harborage resulted in delayed mortality in pyrethroid-susceptible Harlan bugs (Figs. 1 and 3) and significantly reduced mortality for EPM bugs exposed to Spectracide (Fig. 3). Hence, our research supports the view that total-release foggers lack the ability to penetrate into typical harborages used by many household insects, therefore rendering these products ineffective as control agents. Our findings provide support for Osbrink's et al. (1986) suggestion that reduced mortality of cat fleas on disks of carpet versus filter paper was likely because of the carpet providing a refuge for cat fleas to avoid the mist from foggers.

In residences and other settings, the majority of bed bugs hide in protected sites during photophase. Reis and Miller (2011) observed that ≥80% of bed bugs remain in harborages during the day regardless of their feeding status. They found that unfed, rather than fed, bed bugs leave their harborages at night to search for a bloodmeal. It could be suggested that setting off foggers during nighttime rather than day, perhaps, would impact more bed bugs (e.g., hungry bugs searching for a host), but there would be no host cues to stimulate searching behavior because the area has to be vacated when the fogger is activated. The innate behavior of bed bugs to remain in tight, inaccessible harborages for a prolonged period of time has important implications for fogger efficacy against bed bug populations. Because of bed bugs' propensity for hiding sites, the majority of the population will not be directly contracted by the insecticide mist from total-release foggers, hence rendering these products ineffective.

Another serious concern is that fogging can actually acerbate problems with some insects. For example, German cockroaches prematurely released their oothecae, resulting in an increase in newly hatched nymphs, in response to fogging with pyrethrins (Kardatzke et al. 1982) or dichlorvos (Ballard et al. 1984). Furthermore, German cockroaches moved from fogged units to adjacent units in 50% of apartments, with increased catches of cockroaches the night after the fogger treatment (Ballard et al. 1984). In fact, pyrethroids, the active ingredients of foggers tested here, have been shown to increase locomotor activity of bed bugs upon contact with dry deposits (Romero et al. 2009b). This potential behavioral effect of foggers on bed bugs needs to be evaluated as it may increase the difficulties associated with bed bug control. Bed bugs are notoriously difficult to control in multi-unit buildings (Wang et al. 2009, Harlan et al.

2008, Eddy and Jones 2011), and any product that further disperses the bed bugs to adjacent units is of grave concern.

All three total-release foggers claim "kills on contact" yet all field-collected bed bugs were unaffected upon re-entry. Furthermore, 5–7 d later, most of these bugs remained unaffected, which suggests that these pyrethroid-based foggers lack delayed toxicity and have no long-term residual efficacy against field populations of bed bugs (Figs. 1 and 3).

The public is ill-served when products do not perform in accordance with labeling and use directions claims. The use of ineffective insecticide products means that people are wasting money, and they are delaying effective treatment of insect pests whose populations are ever increasing in their residence and likely spreading to others. Furthermore, insecticides are unnecessarily being introduced into the environment, and people (and insects) are being exposed to insecticide residues, while further reinforcing insecticide resistance in insects. Despite the widespread use of OTC foggers, there is only limited research on these products, and the data suggest that pyrethrin- and pyrethroid-based foggers are ineffective against diverse household insect pests. For example, Osbrink et al. (1986) found that foggers containing 0.5% pyrethrins failed to control cat fleas, but those containing an insect growth regulator (IGR) provided flea control for up to 60 d. Moore (1977) found that the least effective total-release aerosols for German cockroach control were 0.25% resmethrin-tetramethrin.

In conclusion, our study provides strong evidence that Hotshot Bedbug and Flea Fogger, Spectracide Bug Stop Indoor Fogger, and Eliminator Indoor Fogger were ineffective as bed bug control agents. The low concentrations of pyrethrins, pyrethroids, or both, and the brief exposure provided by these total-release foggers had little impact on modern-day bed bugs. Our data also support the position that currently marketed total-release foggers should not be recommended for treating bed bug infestations because these products provide no residual and they allow for minimal, if any, insecticide penetration into typical bed bug harborage sites.

Acknowledgments

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