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Research

Special Collection: Perspective on Biology and Management of Bed Bugs

Comparative Efficacy of Superheated Dry Steam Application and Insecticide Spray Against Common Bed Bugs Under Simulated Field Conditions

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Abstract

The common bed bug, *Cimex lectularius* L., is a difficult urban pest to control. A simulated field study was conducted to compare the efficacy of steam application and an insecticide mixture spray (0.05% acetamiprid and 0.06% bifenthrin mixture) against *C. lectularius*. Three types of furniture (desk chair, upholstered armchair, and wooden table) were treated in the laboratory. The efficacy of the treatments was evaluated by visual inspection and placement of interceptor traps under the legs of the furniture. One hundred mixed stages of an insecticide-resistant population of *C. lectularius* were released onto each furniture item. After a 10-day acclimation period, each furniture item received steam treatment, insecticide spray, or no treatment. The second application of treatment was conducted 14 d later. Bed bug counts from interceptors and visual inspections were recorded at 13 d and 28 d after the initial treatment. At 28 d, the mean (± SE) live bed bug count in the steam, spray, and control group was 1 ± 0, 2 ± 1, and 83 ± 10, respectively. Both treatment methods were highly effective in controlling bed bugs on furniture. The mean bed bug count from interceptors in the steam, spray, and control groups were 0.3 ± 0.2, 11 ± 7, and 47 ± 9, respectively. There was no significant difference in the efficacy between steam and spray treatments based on either visual inspection or bed bug counts from interceptors. However, based on interceptor counts, the steam treatment caused faster bed bug population reduction than insecticide sprays.

Key words: bed bug, control, steam application, insecticide spray

Since the late 1990s, the common bed bug, *Cimex lectularius* L. (Hemiptera: Cimicidae), has once again become a common urban pest in the U.S. and many other countries (Meek 2003, Potter 2006, Potter et al. 2015, Wang et al. 2016a, Doggett et al. 2018). An inspection of 2,372 low-income apartment units in four New Jersey cities found that infestation rates ranged from 3.8 to 29.5% among 43 buildings (Wang et al. 2016a). Bed bug bites can cause pain, various cutaneous reactions, loss of sleep, and mental distress (Goddard and deShazo 2009, Susser et al. 2012) and are considered challenging urban pests to control due to their widespread insecticide resistance, their hiding behavior, and small size (Romero et al. 2007, Yoon et al. 2008, Zhu et al. 2010, Adelman et al. 2011, Gordon et al. 2014, Romero and Anderson 2016). Compared to German cockroaches (*Blattella germanica* L.), which can be effectively controlled by the application of gel baits (Appel and Rust 2021), there is not a comparable insecticide that is both highly effective against bed bugs and can be applied to all areas where bed bugs hide nor that capitalizes on the foraging and feeding behavior, as baits do with cockroaches. Eliminating bed bug infestations usually requires a combination of several methods and multiple services. It often involves the need to overcome challenges in eliminating bed bugs within harborages associated with complex furniture (i.e., upholstered furniture). The median number of services using insecticide-based treatment programs and heat-based treatment programs to control bed bugs was 2.6 and 1.3, respectively (Potter et al. 2015).

Insecticide treatment is the most popular method used by professionals (Potter et al. 2015) and residents alike (Wang et al. 2016a). Insecticide sprays and dusts may offer residual protection compared to nonchemical methods such as laundering or steam application. In the U.S., the most commonly used classes of insecticides for bed bug control by professionals include pyrethroids, neonicotinoids, pyrroles (chlorfenapyr), inorganic materials (diatomaceous earth dust, silica gel), and insecticide mixtures (pyrethroid + neonicotinoid) (Potter et al. 2015). Insecticide mixtures are generally more effective than pyrethroid sprays (Wang et al. 2016b). Despite this widespread use of insecticides, few studies have evaluated their efficacy under field or semi-field conditions (Wang et al. 2007, Moore and Miller 2009, Potter et al. 2012, Potter et al. 2013, Potter 2014). In a 2015 field study, Wang et al. (2015) found that insecticide mixture treatments, when combined with nonchemical management methods (encasements, steam, and laundering), resulted in significantly higher population reduction after eight weeks than using nonchemical methods alone.

Nonchemical methods are often used to manage bed bug infestations, perhaps due to concerns of human exposure to insecticide residues and to combat the development of insecticide resistance by bed bugs. Common nonchemical methods include reduction of harborage sites (decluttering, sealing cracks and holes), physical removal (by hand, trapping, vacuuming, or disposal of infested items), encasing the mattresses and box springs with zippered encasements, applying high temperature (steam, dry heat), and freezing (Olson et al. 2013, Cooper et al. 2015a, Kells 2018). High-temperature treatments can be very effective since all bed bug stages are instantly killed at 50°C (Kells and Goblirsch 2011). Among the high-temperature treatment methods, the steam application is attractive because of the potential for instantons kill and ease of use. Both commercial and consumer-grade steamers (price range US$75–1,259) effectively control bed bugs that are exposed or hiding under fabric or within cracks (Puckett et al. 2013, Wang et al. 2018b). The surface temperature may reach >71°C, ensuring all bed bugs on the surface, hiding in cracks or under the fabric, will be killed. Several field studies have reported steam applications as parts of bed bug management programs (Walker et al. 2008, Wang et al. 2009, Singh et al. 2013, Abbar et al. 2020), but the field efficacy of steam treatment alone has not been well studied.

Steam treatment offers several important advantages over insecticide treatment methods. There are fewer limitations regarding where steam can be applied compared to residual insecticides. Treated items such as bed linens, pillows, clothing, wheelchairs, toys, etc., can be used again immediately after treatment and without risk of human exposure to insecticide residues. Steam may be more effective than insecticides at destroying bed bug eggs contacted during treatment. Despite these potential advantages, the adoption of steam treatment by pest management professionals (PMPs) has been low. Potter et al. (2015) reported that 95% of the surveyed companies used insecticides compared to only 38% used steam treatment. In a more recent survey of 194 pest control companies, 97% reported using insecticides compared to 27% using steam to control bed bugs (Anonymous 2021). In this study, we compared the efficacy of insecticide sprays to that of steam applications for controlling bed bugs under simulated field conditions.

Materials and Methods

Bed Bugs

Individuals used were from the Irvington 624-5G strain *C. lectularius,* collected from an apartment in 2013 in Irvington, New Jersey, and thereafter maintained in the laboratory. A preliminary experiment conducted in 2019 found that bed bugs from this population had high resistance levels (performance ratio = 2,059 based on LC_{50}) to residues of Transport GHP (0.05% acetamiprid + 0.06% bifenthrin, FMC Corporation, Philadelphia, PA) (Ranabhat and Wang, unpublished data). The bed bugs were fed with defibrinated rabbit blood once every two to four weeks before the experiment. Detailed rearing procedures can be found in Ranabhat and Wang (2020).

Furniture

Three furniture types were used for releasing bed bugs: a wooden desk chair with an upholstered cushion, an upholstered armchair, and a wooden table, hereafter referred to as "desk chair", "upholstered chair", and "table", respectively. The upholstered chair was purchased from Amazon.com (Famree fabric armchair). The other furniture items were obtained from the surplus store at Rutgers University. Sizes of the furniture were: desk chair—55 × 50 × 86 mm (W × D × H), upholstered chair—67 × 53 × 72 mm (W × D × H), table—150 × 58 × 72 mm (L × W × H). Each desk chair and upholstered chair were placed in an arena that consisted of a piece of 1.2 × 1.2 m plywood lined with plastic, and each table was placed individually in an arena that consisted of a piece of 1.2 × 2.4 m plywood lined with plastic (Fig. 1). The plywood edges were surrounded by duct tape to prevent bed bugs from escaping. ClimbUp Insect Interceptor traps (Susan McKnight, Inc., Memphis, TN), hereafter referred to as interceptors, were placed under the legs of each furniture item to restrict the movement of bed bugs away from the furniture. These traps also served as a tool for evaluating treatment efficacy. Three different rooms were used for the experiment. Each room contained three arenas, one with a desk chair, one with an upholstered chair, and another with a table. Temperature and relative humidity were recorded in each room during the study period using a HOBO External Temp/RH data logger (Onset Computer Corporation, Bourne, MA). The mean temperatures in the three rooms ranged from 20.7 to 23.3°C, and relative humidity ranged from 36 to 39%. One room did not have windows and included artificial lighting on a 12:12 (L:D) cycle (from 6 am to 6 pm). The other two rooms had windows and natural light; no supplemental artificial

Fig. 1. Experimental laboratory arenas setup to evaluate the efficacy of steam and insecticide spray treatments against a field-collected population of bed bugs (*Cimex lectularius*). Left: an upholstered chair within an experimental arena in the front and a desk chair with an upholstered cushion within one experimental arena in the back. Right: a wooden table within one experimental arena.

lighting was added during the study period (April 16, 2021 to June 29, 2021, sunrise ~6 am–Sunset ~8 pm).

Experimental Design

We used replicated 3 × 3 Latin square design to evaluate the efficacy of steam application (Polti Cimex Eradicator, Polti USA Inc. Los Angeles, CA) and insecticide spray treatment (Transport GHP) against *C. lectularius* (Table 1). The two potential sources of variation in the experiment are furniture type and operator. After the first trial (original experiment) was completed, a second trial (replicate of the original experiment) was conducted using the same methods, furniture types, and operators. In the remainder of the paper, we will refer to the original experiment as the first trial and the replicated experiment as the second trial. The three operators were Ramos, Cooper, and Wang, the authors of this paper.

Treatments and Follow-Up Inspections

We released 100 bed bugs (40 2nd to 3rd instar nymphs, 30 4th to 5th instar nymphs, 15 males, 15 females) on each furniture item. Bed bugs were fed 5 d (first trial) or 9 d (second trial) before being released at four locations on each type of furniture. To estimate egg production during the study, we prepared three jars of 30 female bed bugs and placed them alongside furniture treatments in all three rooms. The number of eggs produced between the time bed bugs were released on furniture until the time of the initial treatment (10 d) was recorded.

Treatments began 10 d after bed bugs were released on furniture to allow for acclimation of the bed bugs and to provide females time to lay eggs. The treatments were: I—Untreated control, II—Steam application, and III—Transport GHP spray (0.05% acetamiprid, 0.06% bifenthrin). Treatments were performed between 9:00, and 11:00 am. All three furniture items in each room were treated by one operator resulting in each operator treating each type of furniture in each of the two trials. The treatment time required for each operator was recorded for each furniture item. Steam was applied to the furniture edges, crevices, seams, ends of legs, around screws, and any place where bed bug eggs or live stages were visually observed. Transport was applied with a one-gallon stainless steel sprayer (Veseris, Edison, NJ) to furniture seams, corners, crevices, and the ends of legs, following the product label directions for use.

To mimic an occupied environment, a 1.2-L insulated thermos (Coleman Company Inc., Wichita, KS) containing approximately 450 g of dry ice was placed on each furniture item in the evening (8 pm) at 3 and 7 d after the initial treatment. The thermos was placed inside a plastic container with a smooth exterior surface and talcum to prevent bed bugs from reaching the jug.

The number of live bed bugs on each piece of furniture and in the interceptors was counted at 13 d after treatment for comparing treatment effectiveness. Since live bed bugs were observed on all furniture items during the visual inspection, an additional treatment was made 14 d after the initial treatment. Operators were assigned the same pieces of furniture and treatment methods as in the initial application of treatment. Treatment of furniture was done between 9:00, and 11:00 am. Before treatment, live bed bugs (≤7 per arena) found in interceptors were placed back on furniture items. In the spray group, the live bugs were placed on the furniture where they were directly treated. The bed bugs were placed on the furniture in the steam group and then directly steamed. This was necessary to expose all visibly accessible bed bugs to each treatment method. An insulated thermos containing approximately 450 g of dry ice was placed on each piece of furniture the day of the re-application of treatment at 8 pm and again at 17 and 20 d after the first application to stimulate bed bug activity.

The total amount of insecticides used in the 1st and 2nd treatment was 93 and 83 ml during the first trial, respectively. The total amount of insecticides used in the 1st and 2nd applications was 83 and 79 ml during the second trial, respectively.

At 28 d, all live bed bugs from the furniture were counted and removed. Bed bugs from interceptors were also counted and removed, and a dry ice trap was placed on the furniture for 2–3 d to detect any additional live bed bugs (Singh et al. 2015). The total number and life stage of bed bugs in the dry ice traps and the interceptors per furniture item were recorded.

Table 1. Latin square design for evaluating the effectiveness of steam and insecticide spray treatment for controlling bed bugs (*Cimex lectularius*)

Room (Operator)	Upholstered chair	Desk chair	Table
1	I	II	III
2	II	III	I
3	III	I	II

I—Untreated control, II—Steam, III—Transport spray.

Data Analysis

The effects of three treatments (steam, spray, control) were compared for five different outcomes or response variables—number of eggs produced by female bed bugs during the first 13 d, number of surviving live bed bugs on furniture after 14 d, and 28 d, and number of beg bugs in interceptors after 13 d and 28 d. The statistical methodology used included fixed-effect linear models of a transformed version of each response (explained in the next paragraph) on operator, furniture, treatment, and trial. Plots of residuals from the linear model showed no significant departures from model assumptions. If the resultant analysis of variance (ANOVA) showed significant treatment differences, a pairwise comparison approach was used to identify the pairs of treatments that were mutually different. A Bonferroni adjustment was made to control the experimental error rate for each set of pairwise comparisons, i.e., the probability of incorrectly declaring at least one pair significant when there is no true difference.

To make the experimental data amenable to linear-model-based analysis, each response was log-transformed after adding one before fitting models. If the original response was Y, the transformed response was log(Y+1). The addition of 1 ensures that the log-transformed values are defined when the response value is zero. The aforementioned linear model and ANOVA based analyses are standard and well-established methodologies for analyzing data from Latin Square Designs (Chapter 13, Oehlert 2000; Chapter 3, Wu and Hamada 2021), as are log transformations (Chapter 6, Oehlert 2000; Chapter 4, Wu and Hamada 2021). All analyses were conducted using R statistical software (R Core Team 2021).

Results

Treatment Time

Supp. Fig. A1 shows a visual comparison of the treatment time. There were strong significant differences in the mean treatment time required for spray and steam treatment (F = 90.2; df = 1, 19; P < 0.001) (Supp. Table A1). In the initial treatment, the mean (± SE) time required for steam and spray application was 8.8 ± 1.0 and

3.4 ± 0.5 minutes, respectively. In the 2nd treatment, the mean time for steam and spray application was 6.9 ± 0.5 and 2.5 ± 0.1 minutes, respectively. Thus, overall, the time required for steam treatment was significantly longer (1.7×) than that for spray treatment.

Bed Bug Egg Production by Auxiliary Females

A visual comparison of the mortality rates of female bed bugs (percentages of dead females in the cohort of 30) during the 10 d acclimation period in the two trials is shown in Supp. Fig. A2. The mortality rate, as well as the egg production, appear to be less in the second trial compared to the first trial. The reduced egg production in the second trial may have been due to differences in feeding status (bed bugs were fed 5 d before the first trial started and 9 d before the second trial started). Although the above comparisons suggest some inherent differences between the two trials, such differences have been taken into account while assessing treatment differences by including trial as a factor in the ANOVA models below.

Bed Bug Counts Based on Visual Inspection

At 13 d after the initial treatment, there were significant differences in the total number of surviving bed bugs between treatments ($F = 20.0$; df = 2, 10; $P < 0.001$) (Fig. 2A, Supp. Table A2). No significant differences were detected between the two trials, the three different furniture types, or the three different operators ($P > 0.05$). The mean bed bug visual count in the steam, spray, and control groups were 2 ± 1, 10 ± 5, and 62 ± 9, respectively. The number of bed bugs was significantly lower for both steam and spray treatment compared to the control (first row, Supp. Table A3).

At 28 d, the mean number of surviving bed bugs in the steam, spray, and control group was 1 ± 0, 2 ± 1, and 83 ± 10, respectively. There were significant treatment differences in the number of surviving bed bugs ($F = 88.5$; df = 2, 10; $P < 0.001$) (Fig. 2B, Supp. Table A4). Five of the 12 treated furniture items (three in spray treatment and two in steam treatment) still had live bed bugs.

At 13 d, the total number of eggs found by visual inspection during the first and second trials were 128 and 3, respectively. Therefore, bed bugs in the first trial laid many more eggs during the study period than the bugs in the second trial. This result is consistent with trial differences in the 30-female cohorts set aside in each room during both trails. Due to the small number of eggs in the second trial, we only considered the first trial data to investigate egg production differences among treatments. The mean number of eggs produced in the steam, spray, and control treatment was 1 ± 1, 16 ± 9, and 26 ± 6, respectively. Because there were only nine observations, instead of an ANOVA, the data were analyzed visually. From a plot of the number of eggs (Supp. Fig. A3) against the treatment, steam treatment yielded a smaller number of eggs with a much smaller dispersion than spray or control.

Bed Bug Counts Based on Interceptors

At 13 d after the initial treatment, the mean number of bed bugs in the steam, spray, and control groups were 3 ± 1, 20 ± 4, and 24 ± 5, respectively. These numbers were significantly different ($F = 14.2$; df = 2, 10; $P = 0.001$) (Fig. 2B, Supp. Table A5). No significant differences were detected between the two trials, the three furniture types, and the three operators. The pairwise comparison (third row, Supp. Table A3) shows steam treatment resulted in a significantly lower number of bed bugs than the control at an experimental error rate of 5%. In contrast, no significant difference is detected between control and spray.

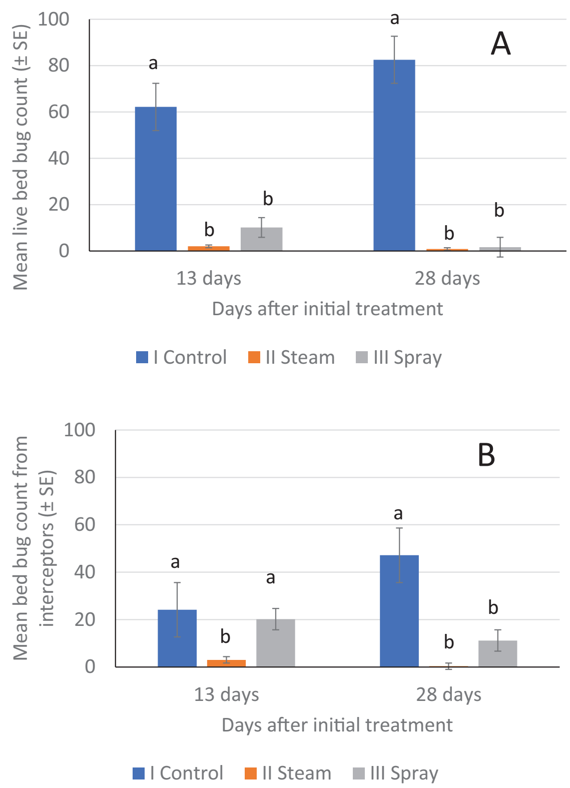

Fig. 2. Efficacy of steam and insecticide spray treatment for controlling the common bed bug (*Cimex lectularius*). A) total number of surviving bed bugs recovered from furniture and off furniture after treatment with steam (Steam), an insecticide spray (Spray), or nothing (Control); B) total number of surviving bed bugs recovered from ClimbUp interceptors placed under furniture legs. At each observation period, bars with different letters indicate significant differences (ANOVA with Bonferroni adjustment for pairwise comparison, $P < 0.017$).

At 28 d, the mean number of bed bugs in interceptors in the steam, spray, and control groups were 0.3 ± 0.2, 11 ± 7, and 47 ± 9, respectively. The ANOVA of the counts (Supp. Table A6) shows a significant difference between treatments ($F = 26.0$; df = 2, 10; $P < 0.001$) as well as between the two trials ($F = 10.4$; df = 1, 10; $P = 0.01$). The pairwise comparisons revealed significant differences at an experimental error rate of 5% between the pairs (control, steam) and (control, spray), but not between steam and spray (last row, Supp. Table A3).

Discussion

This study evaluated and compared the efficacy of a chemical and a nonchemical treatment for eliminating bed bugs on furniture. Both methods were highly effective in eliminating bed bugs or reducing bed bugs to very low numbers within the 28-d trial period. Steam treatment resulted in faster bed bug reductions than spray treatment with 0.05% acetamiprid + 0.06% bifenthrin mixture. Additionally, in the first trial conducted, the mean number of eggs recovered from furniture items treated with steam was much lower than that recovered from furniture treated with spray treatment (1 vs. 16). Lower egg production among bed bugs on furniture treated with steam versus spray may be associated with the instantaneous mortality of adults exposed to lethal temperatures, as compared to the slower modes of action associated with the active ingredients in insecticide tested (acetamiprid and bifenthrin) (Wang et al. 2016b).

This and other differences in control between steam and spray may be more obvious under field conditions where hosts are present, blood meals are available, bed bug egg production is continuous, and insecticide resistance may exist. Additional experiments may reveal further bed bug egg production differences between these two treatment methods. Although the steam application does not have a residual effect, it has better penetration than liquid spray into narrow crevices compared to insecticide spray.

Advantages of insecticide treatments in bed bug management programs include low material cost and ease of application. However, there are some obvious concerns associated with insecticides as bed bug management tools. When applying chemicals to furniture, insecticide droplets may easily be deposited on nontarget surfaces, such as exposed areas of furniture and flooring around furniture items, potentially violating label use directions and leading to unintended pesticide exposure events. Despite our efforts to avoid spraying to the point of runoff (care taken to reduce the sprayer's pressure and to apply the insecticide sparingly), dripping from treated surfaces immediately after application was common during our treatments. Runoff from treated surfaces may be especially likely when spraying wooden or metal areas of furniture and fabrics treated by the manufacturer with stain and moisture resistant products. Since the use of tank sprayers or handheld sprays are extremely common among PMPs and consumers, many applications are likely to leave significant insecticide residues in the treated environment. In German cockroach-infested apartments, the mean insecticides residue concentration in kitchen floor dust wipe samples was 11.9 ng/cm^2 (Wang et al. 2019). Although data is limited, insecticide residues from total release foggers (DeVries et al. 2019) and the ineffectiveness of total release foggers for bed bug management (Jones and Bryant 2012) have been documented. Insecticide resistance is another concern. Significant resistance by bed bugs to a neonicotinoid insecticide occurred after only one generation of selection (Gordon et al. 2014). High resistance to neonicotinoids has already been reported by Romero and Anderson (2016). Any insecticide product will eventually experience lowered efficacy against bed bug infestations after repeated insecticide applications. Another concern associated with insecticides for bed bug control is speed of control. Reducing bed bug populations quickly provides relief to residents in infested environments. Though insecticide applications were just as effective as steam treatments at reducing bed bug numbers over the entire study period, steam provided faster control and was significantly more effective than an insecticide spray at 13 d. While we did not measure the reduction in bed bug numbers before 13 d post-treatment, it is likely that the decrease in the number of bed bugs on furniture treated with steam was immediate, given the instant mortality associated with steam treatments.

Bed bugs often hide in cracks and crevices as well as beneath pleats and folds of furniture items (Cooper 2010). Effective delivery of insecticides into bed bug harborages associated with upholstered furniture is another potential concern since upholstered items may often be treated with stain-resistant materials that repel liquids, therefore, reducing spray penetration (Wang et al. 2018b). This challenge would not be expected for a steam treatment, but this difference was not investigated in this study. The fabric on the upholstered furniture items used in our study lacked pleats and folds and was not treated with stain-resistant materials.

As compared to insecticides, advantages of using steam in the management of bed bugs include its lack of toxicity, the ability to treat many areas where insecticides cannot be used according to label directions, the ability to effectively penetrate through the fabric and into cracks where bed bugs hide and the ability to kill all bed bug life stages, including eggs. Like any control method, it is not without its disadvantages. Using steam can be more labor-intensive compared to spray applications. On average, we spent 1.7× more time treating furniture items with steam than with an insecticide spray. This additional time required was due to the speed at which the steam application nozzle is moved over treated areas (approximately 10 cm per second) compared to the speed at which an insecticide spray can be applied to similar areas.

Furthermore, areas, where insecticide application was not permitted by the product label (i.e., exposed surfaces of upholstered furniture), were treatable with steam, increasing the potential target area and associated treatment time. In this study, all surfaces of furniture items were treated with steam. Application times for steam could be significantly reduced by limiting treatment to areas where visible evidence of bed bugs exists. The effectiveness of such a reduced treatment protocol was not examined in this study, however, it warrants further exploration. Another disadvantage of steam is the potential to cause damage to veneers, polished surfaces, and fabrics exposed to the steam. Moving the steamer nozzle faster or further from the surface being treated while still ensuring the lethal temperature (50°C, as per Kells and Goblirsch 2011) on treated surfaces could minimize any potential damage to heat-sensitive items reduce the time required for treatment.

According to the manufacturer's internal study, the steamer used in our study uses patented technology to produce superheated dry steam (at least 15°C higher than other steamers) and reduced condensation on treated surfaces as compared to the traditional steamer (https://www.poltieradicator.com/superheated-dry-steam/). Previous studies evaluated four different steamers under laboratory conditions: HAAN HS-20R Handheld Steam Cleaner (HAAN Corporation, Lancaster, PA), Steamfast SF-370WH Multi-Purpose Steam Cleaner (Steamfast, Andover, KS), Amerivap Systems STM-BASIC Steamax Commercial Steam Cleaner (Amerivap Systems, Inc., Dawsonville, GA), and J-4000DM Jiffy steamer (Jiffy Steamer Company, Union City, TN) (Puckett et al. 2013, Wang et al. 2018b). Although all tested consumer and commercial grade steamers were effective for controlling bed bugs, using a steamer that generates higher temperatures may eliminate bed bug infestations more efficiently (i.e., can move the nozzle faster compared to a traditional steamer) since temperature and mortality are positively correlated (Kells and Goblirsch 2011). In addition, less steam condensation during steam treatment may reduce the likelihood of damage to the treated surface due to water condensation from the steam treatment.

Reliance upon pesticides as the primary method of control will promote the development of insecticide resistance among bed bugs, rendering pesticides less effective and resulting in increases in control failures. To date, steam has been a widely underutilized control method among PMPs. However, our results demonstrate the potential effectiveness of steam treatment, especially when considered as an alternative to insecticide sprays. Past field studies have repeatedly demonstrated that a combination of several methods and multiple treatment visits are often needed to eliminate bed bug infestations (Wang et al. 2009, Cooper et al. 2015b, Wang et al. 2018a). The survival of a few bed bugs in five of the 12 treated furniture items after 28 d in our study, which included simple furniture designs and careful treatments by researchers, indicates that it is likely some bed bugs will survive single-tactic control programs whether chemical or nonchemical. Under field conditions where the environment is much more complex, and human hosts are present daily, the effectiveness of either treatment method could be lower.

Acknowledgments

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Supplementary Data

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

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