Journal of Integrated Pest Management, 2017, 8(1): 13; 1–10
doi: 10.1093/jipm/pmx009
Issues

Pest Management Strategies for Bed Bugs (Hemiptera: Cimicidae) in Multiunit Housing: A Literature Review on Field Studies

A. Romero,[1,2] A. M. Sutherland,[3] D. H. Gouge,[4] H. Spafford,[5] S. Nair,[6] V. Lewis,[7] D.-H. Choe,[8] S. Li,[6] and D. Young[9]

[1]Department of Entomology, Plant Pathology and Weed Science, New Mexico State University, Las Cruces, NM 88003 (aromero2@nmsu.edu), [2]Corresponding author, e-mail: aromero2@nmsu.edu, [3]Cooperative Extension and Statewide Integrated Pest Management Program, University of California, Hayward, CA 94544 (asutherl@ucanr.edu), [4]Department of Entomology, University of Arizona, Tucson, AZ 85721 (dhgouge@email.arizona.edu), [5]Plant and Environmental Protection Sciences, University of Hawaii, Manoa, Honolulu, HI 96822 (hspaffor@hawaii.edu), [6]Department of Entomology, University of Arizona, Maricopa, AZ 85138 (nairs@email.arizona.edu; lucyli@email.arizona.edu), [7]Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720 (urbanpests@berkeley.edu), [8]Department of Entomology, University of California, Riverside, CA 92521 (dchoe003@ucr.edu), and [9]Center for Sustainable Integrated Pest Management, Colorado State University, Fort Collins, CO 80523 (djy1830@gmail.com)

Subject Editor: Gregory Beavers

Received 29 November 2016; Editorial decision 21 April 2017

Abstract

Bed bugs (*Cimex lectularius* L.) continue to increase as serious pests in the built environment. These insects are particularly problematic in low-income multiunit housing buildings, where infestations are difficult to control, tend to become chronic, and the locations serve as reservoirs from which bed bugs disperse. This document reviews and reports on published accounts and validations of various methods to detect and manage bed bugs in these urban settings. The analysis demonstrates that programs using IPM approaches for bed bug management can lead to significant reductions in bed bug incidence and density when compared with insecticide-reliant approaches. However, total elimination of bed bugs in multiunit environments remains a challenge and is often reported as unattainable, raising concerns about the effectiveness of strategies for bed bug management used in these environments. Several factors may contribute to the persistence of bed bugs in low-income, multiunit housing situations, including lack of awareness and education of residents and staff about bed bugs, overall building infestation levels, resident lifestyles, reluctance to report infestations, resident abilities to undertake unit preparation required by some pest management companies, and low efficacy of insecticide treatments. Although community-wide and proactive bed bug management programs are shown to be more effective, sustainable, and economically viable in the long term than reactive and insecticide-only programs, general adoption of best practices may be impeded by budget limitations and interest of affordable multiunit housing providers.

Resumen

Los chinches de cama (*Cimex lectularius*) es una plaga que se sigue expandiendo en ambientes urbanos. Estos insectos representan un serio problema en edificaciones multi-residenciales de familias de bajos nivel de ingresos económicos, donde las infestaciones son difíciles de controlar, tienden a volverse crónicas y sirven de reservorios desde donde los chinches se dispersan. Este documento revisa y reporta información publicada de la validación de varios métodos para para detectar y manejar los chinches de cama en estos ambientes urbanos. El análisis mostró que los programas que usan abordajes de Manejo Integrado de Plagas (MIPs) para el control de los chinches de cama pueden reducir de manera significativa la incidencia y densidad de estos insectos, si se compara con los programas donde se utilizan solamente insecticidas. Sin embargo, la erradicación de los chinches de cama en estos ambientes sigue siendo un reto y muchas veces difícil de alcanzar, lo que genera dudas acerca de la eficacia de estos programas para el chinche de cama usados en estos ambientes. Varios factores podrían contribuir a la persistencia de chinches de cama en estas edificaciones, los cuales incluye la escasez de concientización y educación de residentes y personal administrativo acerca del insecto, los altos niveles de infestación de chinches en las edificaciones, los hábitos de vida de los residentes, renuencia a reportar infestaciones, incapacidad para llevar a cabo la preparación de la vivienda exigida por las compañías de manejo de plagas, y baja eficacia de los tratamientos con insecticidas. Aunque los programas de manejo comunitario y proactivo de los chinches de cama son más efectivos, sostenible y económicamente viable a largo plazo, si se compara con los programas reactivos que solo aplican insecticidas, la adopción general de estas prácticas podría dificultarse debido a limitaciones presupuestales y la falta de interés que tienen las empresas proveedoras de vivienda subsidiadas en edificaciones multi-residenciales de bajos recursos.

Key words: bed bug, *Cimex lectularius*, IPM, urban pest, multiunit housing

Incidence of bed bugs (*Cimex lectularius* L.) continues to increase in urban environments throughout the world (Potter et al. 2015, Doggett 2016). Although they are not known to be vectors of human diseases, bed bugs can cause allergic reactions (Goddard and deShazo 2009), significant psychological distress, social stigma (Hwang et al. 2005, Susser et al. 2012, Ashcroft et al. 2015), and an economic burden to sufferers of infestations (Potter 2006). In the United States, infestations are particularly prevalent in affordable housing communities (Sutherland et al 2015, Campbell et al. 2016). Li et al. (2016) report both poverty and renting as significant risk factors for bed bug incidence. Although detailed regional data on the incidence and severity of bed bugs in these settings are lacking, many researchers have reported on the problem. For instance, a recent survey of 114 pest management professionals (PMPs) in the western United States (Sutherland et al. 2015) revealed that 73% of respondents believed the number of bed bug infestations to be increasing. A 2012 survey in Virginia reported that up to 82% of affordable housing communities were infested (Wong et al. 2013), while a comprehensive survey in 43 buildings within New Jersey reported overall infestation rates of 12.3% (Wang et al. 2016). Whole building analysis of five elderly and disabled multiunit housing sites in Arizona documented active infestations in 3–15% of apartments (Gouge et al. 2016).

The ongoing struggles faced by affordable housing communities to remediate bed bug infestations are in part, owing to an overall lack of understanding of bed bug ecology, the social behavior of residents, and limited engagement by the customers (be it the tenant, property owner, and manager) owing to costs associated with bed bug control. Additionally, ineffective pest management practices is frequently associated with limited budgets for pest control within public housing authorities, and other low-income housing providers (Bennett et al. 2015; Fig. 1). Currently, the most common strategy for bed bug control in these environments consists of regular or reactive application of pesticides, especially liquid and aerosol formulations of pyrethroid insecticides (Fig. 2; Potter et al. 2015, Sutherland et al. 2015). This approach may be ineffective in part owing to reported widespread resistance to pyrethroid insecticides (Romero et al. 2007a,b; Zhu et al. 2010). Residents desperate to eliminate bed bug infestations sometimes decide to employ general use insecticide products (Fig. 3), some of which have been identified as contributing to poisonings in recent years (Centers for Disease Control and Prevention [CDC] 2011). A common do-it-yourself method is the use of total-release foggers or "bug bombs," which are proven to be largely ineffective against bed bugs (Jones and Bryant 2012). Furthermore, these products contain pyrethroids, a repellent and neurotoxic insecticide group that stimulates the insect's locomotor activity that promotes relocation or dispersal of individuals to other areas (Romero et al. 2009). For these reasons, insecticide applications, especially of pyrethroids or general use materials, cannot be the sole tactics used for successful bed bug remediation.

Integrated pest management (IPM) is a comprehensive strategy used in part to prevent and mitigate problems associated with insecticide-reliant programs. Integrated pest management was originally developed for use within agricultural settings and involves the use of a combination of compatible strategies to prevent pests and to reduce or maintain pests at levels below those reaching the economic injury level (EIL; Dent 2000). A similar approach has been proposed to manage pest populations in urban environments (Schal and Hamilton 1990). Adapting these terms developed within agricultural environments, proponents of IPM in urban environments have coined the terms aesthetic injury level (AIL) and tolerance threshold (TT), denoting pest levels that do not create obvious problems or health hazards (Schal and Hamilton 1990). Although IPM as a strategy has been recognized as a necessity when dealing with many housing pests, the AIL or TT associated with bed bugs is essentially zero. This applies not only to human populations but also to federal, state, and municipal habitability requirements for providers of rental and public housing (City and County of San Francisco, Department of Public Health 2012; California Assembly AB-551 2016, Rental property: bed bugs). Thus, some PMP companies in the United States have implemented bed bug control programs that include more than simply the application of insecticides (Bennett et al. 2015). These services usually incorporate preventive educational components delivered to residents and staff as well as combinations of chemical and nonchemical management tactics such as mattress encasements, steam, vacuuming, and high temperature treatments (Stedfast and Miller 2014, Bennett et al. 2015, Cooper et al. 2015). Implementation of IPM is essential for the management of bed bugs, particularly in environments where bed bug control has been challenging, such as low-income and multiunit housing buildings. High resident turnover, lack of resources, ease of dispersal, communication barriers, and clutter issues also contribute to chronic infestations (Pinto et al. 2007, Stedfast and Miller 2014, Bennett et al. 2015, Sutherland et al. 2015, Cooper et al. 2016). Given the diversity of tactics now employed in bed bug management, we examined the published information documenting attempts to validate, under field conditions, methods to detect, manage, and prevent bed bugs in challenging environments. As inspecting for and monitoring of bed bug populations are both long-term components of IPM and first steps of establishing a well-planned management, we address these methods within a separate section. Studies that evaluated at least one control method were included. This review is not meant to provide a detailed description of each method in use or proposed for bed bug management, but rather to provide a review of the methods that have been tested and validated for the purpose of evidence-based decision-making by PMPs, housing managers, and residents.

Detection and Monitoring

It has been determined that early detection of infestations followed by expeditious professional treatment is the most effective control

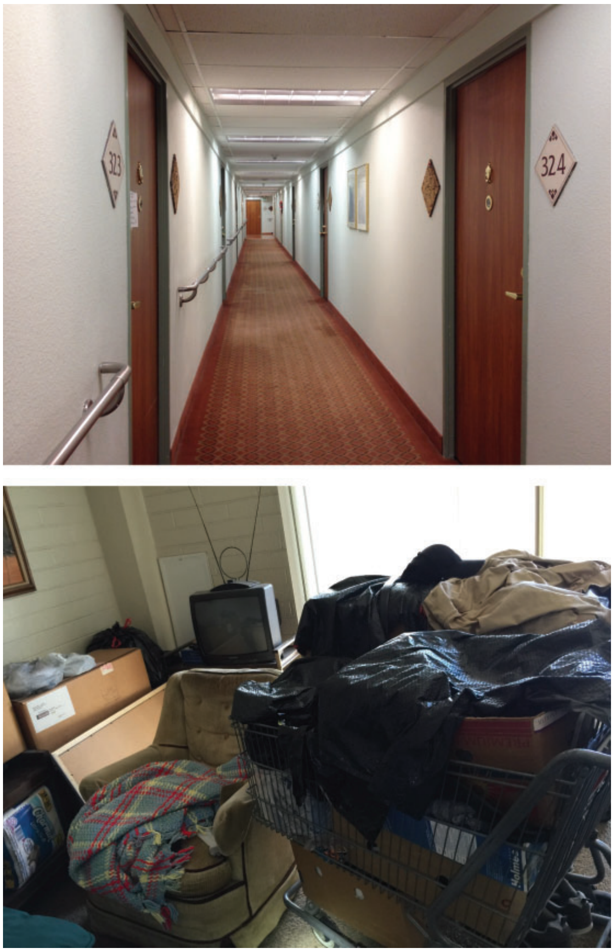

Fig. 1. Multiunit apartments are vulnerable environments to the introduction, spread, and persistence of bed bug infestations (upper). Clutter offers numerous places where bed bugs can hide and is an impediment to control attempts (lower).

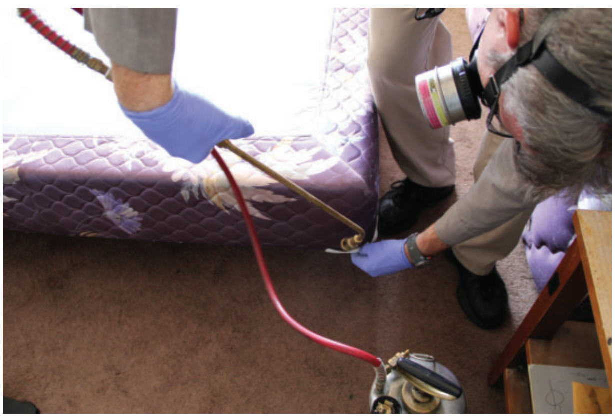

Fig. 2. Insecticide sprays are the most common method used by pest management professionals to control bed bugs.

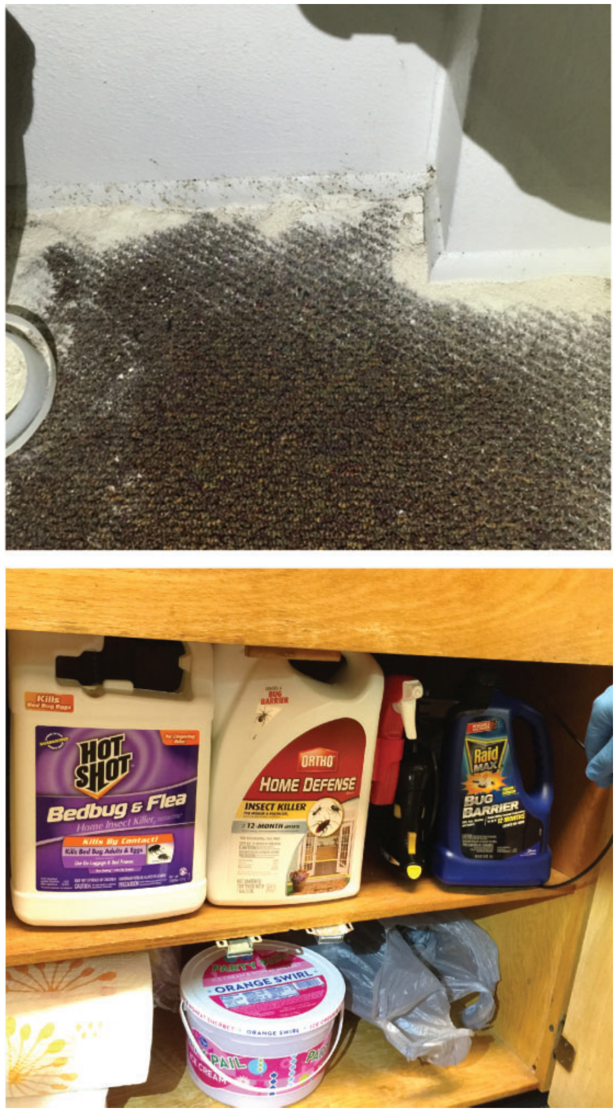

Fig. 3. Residents often apply excessive insecticidal dusts, including diatomaceous earth (upper). Overuse of insecticide by residents is common and can cause harmful effects on human health (lower).

approach for bed bugs (Pinto et al. 2007; Wang et al. 2011, 2016). Furthermore, comprehensive awareness of the extent of bed bug infestation within a building is essential for the PMP to develop an effective treatment plan (Pinto et al. 2007). Early detection provides the best chance of eradication should an infestation be present. In the absence of routine inspection and monitoring, early reporting is dependent upon a resident or housing manager, noticing evidence of a bed bug infestation (dead bugs, blood on sheets, cast skins, etc.). Some research has been conducted regarding the ability of the public to identify a bed bug, although it is generally recognized that there is a need to educate people about what bed bugs are, what they look like, and how they are transported (Anderson and Leffler 2008). Surveys in Europe showed that the ability to identify a bed bug correctly is low among adult citizens of the United Kingdom (10%) and Germany (12.5%), and ability was influenced by factors such as age or previous personal encounters with bed bugs (Reinhardt et al. 2008, Seidel and Reinhardt 2013). A survey of 230 people in Hawaii indicated that 70 (30%) could correctly identify a bed bug (Gerardo 2014). Nineteen of those surveyed self-reported that they had previous encounters with bed bugs and were more likely to correctly identify a bed bug than those who did not have any previous encounter with bed bugs (Gerardo 2014). However, even with this experience, only 13 of the 19 people (68%) could correctly identify a bed bug (Gerardo 2014). These results suggest that overall, very few people will be able to accurately identify a bed bug. This is likely one of several reasons why residents delay reporting a possible infestation to a facility manager or PMP.

Nationwide surveys recently revealed that visual inspection is the most common method used by PMPs to find bed bugs (Fig. 4; Potter et al. 2015, Sutherland et al. 2015). Although this method can be time-consuming and labor-intensive, PMPs report that visual inspection is an accurate way of detecting infestations (Sutherland et al. 2015). However, some devices have proven to be useful in detecting bed bug infestations not apparent during visual inspection (Wang et al. 2011, Lewis et al. 2013; D. H. G., unpublished data). Lewis et al. (2013) showed that several detection devices were effective at catching bed bugs foraging within a simulated field environment arena during a 24-h period. Pitfall-type interceptors (such as the ClimbUp Insect Interceptor, Susan McKnight, Inc., Memphis, TN; Fig. 4) are relatively inexpensive and effective tools for detecting bed bug infestations as well as for evaluating the effectiveness of bed bug management programs (Wang et al. 2011, Cooper et al. 2015). Attractant-based traps have also been proposed for bed bug detection (Anderson et al. 2009; Singh et al. 2012, 2013a, 2015). A few studies have compared the effectiveness of visual inspections with that of bed bug monitoring devices in detecting bed bugs in multiunit housing communities (Wang et al. 2009a, 2011). Research conducted in low-income housing suggested that both passive (interceptors) and active traps (with attractants, e.g., CDC3000 Cimex Sci-ence LLC, Portland, OR; Night Watch, BioSensory Inc., Putnam, CT; SenSci ActivVolcanoTM Bed Bug Detectors with Lures, BedBug Central, Lawrenceville, NJ) were more effective than visual inspections when detecting the presence of small numbers of bed bugs (Wang et al. 2011, 2016; Gouge, unpublished data). Wang et al. (2011) highlighted that simple and relatively inexpensive detection tools, such as home-made dry ice traps and baited interceptors, can be equally effective or even more effective than some costlier commercially available active monitors, making them suitable for use when there is a limited budget for bed bug inspection. However, dry ice (frozen carbon dioxide) sublimates at $-78.5\,^{\circ}$C ($-109.3\,^{\circ}$F) and can be quite hazardous to handle without protective gloves, making its use impractical (Pillay 2013). In most situations, dry ice is not recommended around children, pets, the elderly, or the infirm. Interestingly, field observations have indicated that advanced detection methods, such as interceptors, do not gather information about other bed bug evidences (fecal, blood stains, etc.) and cannot completely replace visual inspections, suggesting that

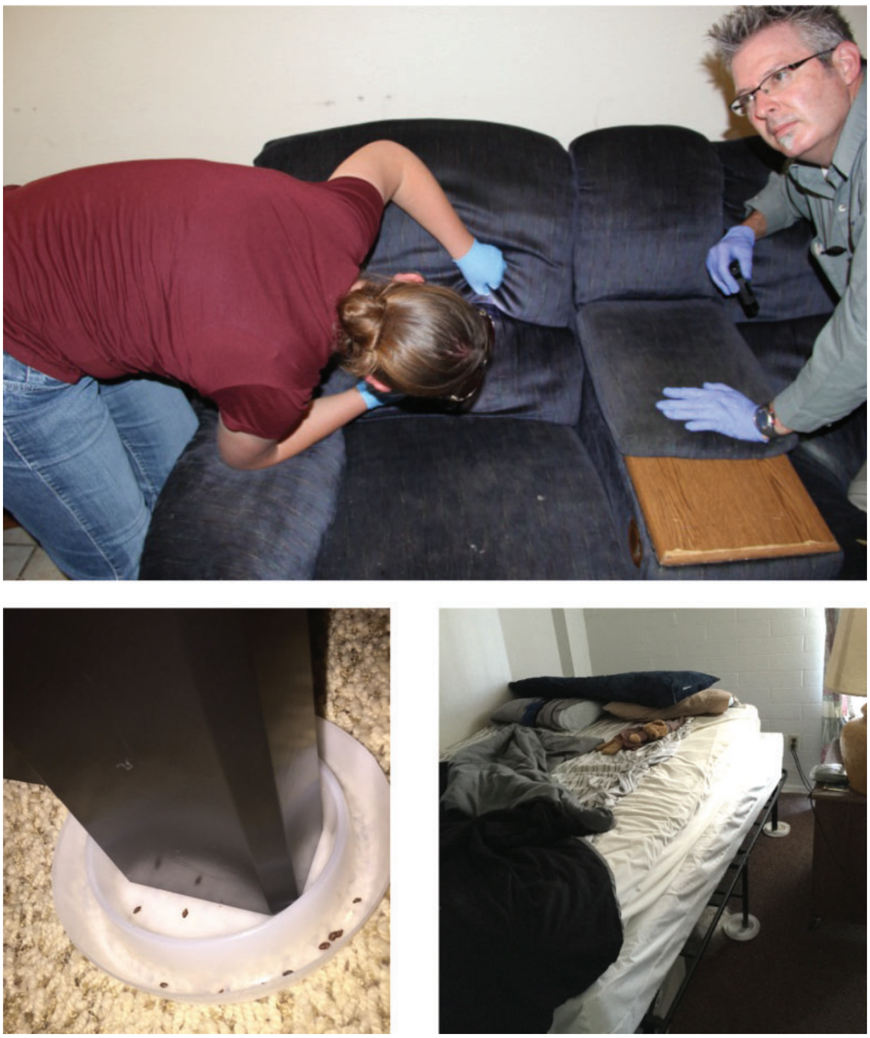

Fig. 4. Visual inspection continues to be the most commonly used method of detection (upper). However, interceptors can be a very effective detection tool when infestations are in the early stages or when used to determine the efficacy of bed bug management programs in housing (lower left). Interceptors can be more effective if beds do not touch walls or bed linens do not hang off and touch the floors (lower right).

incorporation of two or more methods will provide maximum detection sensitivity (D. H. G., unpublished data).

Recently, the simultaneous use of many interceptors has been proposed to eliminate low levels of bed bugs in multifamily housing buildings (Cooper et al. 2016). Massive deployment of pitfall traps eliminated most low-density bed bug infestations (1–10 bed bugs) without any professional treatment over a period of 4–10 mo (Cooper et al. 2016). Such mass trap placement may reduce the number of insecticide applications made in lightly infested places; however, more studies of this type need to be performed before a broad implementation of this tactic is warranted. Furthermore, the time required to eliminate bed bugs using this strategy could be reduced if mass trapping efforts are combined with other management tactics (e.g., insecticides, vacuuming, encasements, heat, or steam vapor). When used alone, however, mass trapping raises ethical issues, as bed bug eradication requires substantial periods of time, and it is not acceptable that residents may continue to be bitten by bed bugs in the meantime.

Within the pest management industry, canine detection is considered by many to be the most accurate and efficient method to detect low-level bed bug infestations in complex environments, such as hotels, theaters, and multiunit housing, and when a large-scale inspection is needed (Fig. 5) (Pfiester et al. 2008, Cooper et al. 2014). However, although evidence shows that canine detection teams perform very well during training exercises, performance vary under field conditions (Cooper et al. 2014). In a field study that evaluated 11 canine detection teams, Cooper et al. (2014) demonstrated high variation in detection accuracy (10–100%) and false-positive rates (0–57%) across the teams. Fatigue of dogs, insufficient handler training, and environmental factors (hot conditions during inspection, presence of other odors) might have affected bed bug detection performance. Although low rate of bed bug detection by dogs (high false-negative alerts) could delay the elimination of a bed bug infestation, high rates of false-positive alerts could result in significant direct treatment costs and unnecessary exposure to pesticides (Cooper et al. 2014). The authors proposed that future research should focus on the effectiveness of the training methods used, evaluation standards, and the associations between training performance and field performance (Cooper et al. 2014).

Nonchemical Methods

Nonchemical methods are always encouraged as important components of a bed bug IPM program to reduce risks associated with chemical methods and to combat insecticide resistance (Kells 2006, Doggett 2007). Recommended methods include general improvements in housekeeping and clutter management; physical removal of bed bugs using vacuums; direct killing of bed bugs using heat, steam, washing and drying clothing and bedding (or freezing); or exclusion of bed bugs using mattress encasements and other barriers (Doggett 2007, Potter et al. 2007, Walker et al. 2008, Pereira et al. 2009, White 2010, Zehnder et al. 2014). The use of nonchemical tools can provide immediate benefits of fewer bed bugs, less debris, and avoidance of pesticide exposure (Potter et al. 2007, Wang and Cooper 2011). However, adoption of only nonchemical bed bug programs is often impractical for low-income housing, as these methods provide no residual efficacy and can be expensive. Wang et al. (2012) reported a study conducted in low-income apartment buildings with low levels of bed bug counts, in which a nonchemical-only program (encasement to mattress and box springs, hot steam, and hand removal of bed bugs using forceps), residual insecticide-only program (Temprid SC [10.5% β-cyfluthrin combined with 21% imidacloprid; Bayer Environmental Science, Research Triangle Park, NC]; Tempo 1% dust [1% β-cyfluthrin; Bayer Environmental Science]; or Mother Earth-D [100% diatomaceous earth; BASF Corporation, St. Louis, MO]), and an IPM program (nonchemical tactics plus Temprid SC, Tempo 1% dust, or Mother Earth-D) were all compared. In this study, the nonchemical program reduced bed bug counts to similar levels observed with the IPM and insecticide-only programs. These results show that significant reduction of low-density bed bug infestations from multiunit housing buildings can be potentially achieved by using only nonchemical methods. However, more work in this area needs to be performed.

Chemical Methods

The application of insecticides is an important and common component of bed bug management protocols in multiunit housing and many other environments (Fig. 2). However, insecticide treatments

Fig. 5. Bed bug detection dog in action (photo credit Richard Cooper).

often are not 100% effective under field conditions, especially when used without nonchemical tactics, and particularly in low-income housing environments where multiple factors (clutter, lack of tenant cooperation, reintroduction of new bed bugs, difficulty to find and treat all individuals, etc.) may hamper attempts to eliminate bed bug infestations (Moore and Miller 2009, Wang et al. 2009b). In addition, the presence of insecticide resistance in bed bug populations could contribute to loss of efficacy of insecticide treatments (Romero et al. 2007a,b). Field studies in bed bug-infested apartments in Cincinnati showed that reduction of bed bug density required several insecticide treatments made in series (Potter et al. 2006). In this study, a combination of two products—a pyrethroid spray (4.75% deltamethrin; Suspend SC, Bayer Environmental Science) and an insecticidal dust (1.0% pyrethrins, 9.7% piperonyl butoxide, 40.0% amorphous silica gel; Drione, Bayer Environmental Science)—reduced bed bugs to nondetectable levels (after 12 wk) from 10 of the 13 apartments after two to five treatments (Potter et al. 2006). Lack of tenant and manager cooperation, clutter that makes it difficult to find hidden aggregations, and low susceptibility of bed bugs to insecticides were reported as possible causes of treatment failure in the three apartments (Potter et al. 2006). Later, a similar study was conducted by Wang et al. (2007) in Indianapolis to evaluate the effectiveness of Suspend SC and Tempo 1% dust against eight bed bug-infested apartments with varying levels of infestations (range: 3–425). In this study, bed bugs were reduced to nondetectable levels in six of the eight infested apartments after 8 wk, with an average of two treatments made per apartment (Wang et al. 2007). The authors of the study suggested that failure to eliminate bed bugs in two of the apartments was most likely owing to the high number of bed bugs detected at the beginning of the study, incomplete insecticide coverage of hiding places, and the presence of pyrethroid resistance in the populations (Wang et al. 2007).

Difficulties experienced when attempting to manage bed bug populations with pyrethroids, owing to reported resistance, has triggered the interest of many research groups to evaluate the efficacy of insecticide formulations with different modes of action. In a field study in Cincinnati, 15 low-income apartments infested with bed bugs were treated monthly with 21.45% chlorfenapyr (Phantom SC termiticide-insecticide; BASF, Research Triangle Park, NC) only. After 5 mo, researchers did not detect bed bugs in 12 of the 15 apartments, but three apartments continued to have bed bugs (Potter et al. 2008). Efficacy of treatment in the three apartments could have been hampered by clutter and lack of tenant cooperation for treatment preparation (Potter et al. 2008).

In search of more effective bed bug treatments, Moore and Miller (2009) evaluated the efficacy of two insecticide treatment regimens for bed bugs in multiunit housing ("traditional treatment" vs. "novel treatment"). Both treatments included multiple products being used by the pest management industry at that time. The "traditional treatment" consisted of maximum label rate applications of pyrethroids, 11.8% β-cyfluthrin (Tempo SC Ultra, Bayer CropScience LP, Montvale, NJ), Suspend SC, as well as the insect growth regulator (IGR) 0.36% (S)-hydroprene (Gentrol Aerosol, Wellmark International, Schaumburg, IL). The "novel treatment" consisted of the application of Phantom Termiticide-Insecticide, a short-lived 60.39% isopropyl alcohol, and 39.20% phenothrin spray (Sterifab; Noble Pines Products Co., Yonkers, NY), a limestone dust formulation (NIC 325; AMC-Texas LLC, Fort Collins, CO), and the IGR Gentrol. At the end of the test period (56 d), treatment regimens significantly reduced the percent of bed bugs (94.4% and 85.7% for traditional and novel treatment, respectively). However, the authors stated that detection of bed bugs after multiple applications was indicative that the insecticides, applied at the label rate, were inadequate for eliminating infestations (Moore and Miller 2009). In the past 6 yr, several dual-action neonicotinoid and pyrethroid combination insecticides have emerged in the U.S. market as options for bed bug control (Potter et al. 2012). According to a 2015 survey of PMPs in the western United States, these dual mode of action insecticides were by far the most widely products used within multiunit housing situations (Sutherland et al. 2015). So far, only a few field studies have evaluated the effectiveness of these insecticide combinations. Potter et al. (2012) evaluated 22 infested apartments treated every 14 d for up to 12 wk with sprays of Temprid SC. Although treatments caused a rapid decline in bed bug numbers (83% reduction after 2 wk), live bed bugs were still found in three units after 12 wk (Potter et al. 2012).

Integrated Methods

Remediation failures in multiunit housing has led research groups and PMPs to embrace an IPM approach incorporating nonchemical methods into pest management programs under evaluation. In a comparative field study, 36 bed bug-infested apartments were treated at least once with one of the following pyrethroid and neonicotinoid combination sprays: 3.5% lambda-cyhalothrin combined with 11.6% thiamethoxam (Tandem, Syngenta Crop Protection, Greensboro, NC); 6% bifenthrin combined with 5% acetamiprid (Transport Mikron, FMC Corporation, Philadelphia, PA); or Temprid SC (Wang et al. 2015). The authors reported an average of 1.4, 1.2, and 1.5 retreatments in units treated with Tandem, Transport Mikron, and Temprid SC, respectively. Nonchemical methods (steam and encasement of mattresses and box springs) were also used in each treatment. After 8 wk, bed bug counts in the apartments treated with Tandem, Temprid SC, or Transport Mikron were significantly lower than in control apartments (nonchemical treatments only; Wang et al. 2015). There were no significant differences in reduction among the three treatments at 8 wk (Wang et al. 2015). Although these results show that mixtures of pyrethroids and neonicotinoids and nonchemical tactics reduced the number of bed bugs in infested apartments after 2 mo, some infestations persisted. Clutter, lack of tenant cooperation, and insecticide resistance issues were the factors that the authors attributed to the persistence of bed bugs in some units after the test period. The above results show that despite the incorporation of nonchemical methods to chemical treatments, the elimination of bed bugs is not always possible, owing to complex human and pest-related factors that are clearly not well understood.

Some researchers have evaluated the use of tactics that reduce human pesticide exposure risk. Wang et al. (2009b) evaluated two IPM protocols for bed bugs in multiunit housing buildings. In both IPM programs, education and outreach efforts were coupled with bed bug removal, steam treatments, mattress encasements, and installation of interceptor traps under legs of beds and furniture. Half of the apartments were treated with diatomaceous earth (Mother Earth-D, Whitmire Micro-GenResearch Laboratories, St. Louis, MO) and half with Phantom SC, both of which are considered to represent reduced risks to humans relative to many other options. The authors reported that both IPM protocols reduced bed bugs to nondetectable levels in 50% of apartments, but places treated with diatomaceous earth reduced significantly more bed bugs than places treated with Phantom SC (Wang et al. 2009b). Additional benefits of these programs included the reduced application of insecticides in sleeping areas, thereby decreasing human exposure (Wang et al. 2009b). The studies highlighted above suggest that the use of reduced risk insecticides can reduce bed bug density, but that reduction of bed bugs to nondetectable levels using such programs may be difficult to achieve. Failure to reduce bed bug populations in the above study was attributed to varying resident abilities to cooperate with protocols, clutter, and the reintroduction of bed bugs (Wang and Cooper 2011). In a subsequent study, Stedfast and Miller (2014) evaluated a proactive bed bug suppression program in low-income, multiunit housing buildings that was based on the use of five nonchemical methods (vacuuming, passive bed bug monitors, mattress- and box spring encasements, and drying clothing) and the perimeter application of diatomaceous earth dust, which was considered practical to apply in these settings and minimally toxic to residents. In addition, the program provided bed bug education and hands-on training for all apartment staff and residents. This proactive approach was mainly designed to limit bed bug spread within the same buildings because this phenomenon was a significant concern in these environments. The program was implemented between January and June of 2012 and the number of whole-unit treatments made in 2011, 2012, and 2013, was recorded. One year after the program was initiated, the authors reported a reduction in the number of new infestations (26.4%) as well as a 2% reduction in the annual costs associated with bed bug management (Stedfast and Miller 2014). In addition, the number of whole-unit treatments made in 2013 was 8.3% lower than in 2012. This finding was indicative of bed bug suppression through implementation of the program. One highlight of this study was the emphasis on bed bug education and hands-on training for all apartment staff and residents.

An IPM program was also evaluated by Singh et al. (2013b) in multiunit housing apartments in which the following tactics were included: education of residents, steam, laundering sheets and linens, placing interceptors under furniture legs and corners of rooms, and applying an aerosol formulation of 0.5% dinotefuran (Alpine aerosol, Whitmire Micro-Gen Research Laboratories, St. Louis, MO) and an insecticidal dust consisting of 0.25% dinotefuran and 95% diatomaceous earth dust (Alpine dust, Whitmire Micro-Gen Research Laboratories, St. Louis, MO). Over a 6-mo period, a 96% reduction in pesticide usage was reported when compared with insecticide-only programs performed previously by Potter et al. (2008) in a similar environment. The IPM program resulted in an average of $96.8 \pm 2.2\%$ reduction in the number of bed bugs. However, reduction of bed bugs to nondetectable levels was only achieved in three lightly infested apartments (Singh et al. 2013b). Lack of complete bed bug control was attributed to the presence of heavy infestations and the scattered distribution of bed bugs in some apartments. Failure to eradicate infestations in multiunit dwellings could lead to the spread of bed bugs into adjoining premises (Wang et al. 2010).

The use of botanically derived products has been proposed to reduce the risks associated with pesticide exposure. Many, but not all, botanically based products are considered "minimum risk pesticides" (pose little to no risk to human health or the environment), according to section 25(b) of the Federal Insecticide, Fungicide, and Rodenticide Act of the United States Environmental Protection Agency (Isman and Paluch 2011), and have become widely available in the general use and professional use marketplaces. Wang et al. (2014) compared the efficacy of products based on essential oils EcoRaider (1% geraniol + 1% cedar oil + 2% sodium lauryl sulfate; EcoRaider, Reneotech, North Bergen, NJ), to that of Temprid SC and a combination of EcoRaider and Temprid SC. All the products were applied to furniture (mattresses, box springs, sofas, chairs, and luggage), floors, cracks near beds or furniture, or any potential harborage that was identified. In all treatment groups, residents were provided with instructions on the use of nonchemical methods such as laundering of bed linens and clothing, and installation of mattress encasements. After 12 wk, all the treatments resulted in >90% bed bug count reduction, with no significant differences among treatments (Wang et al. 2014). However, as in other studies discussed above, bed bugs were reduced to nondetectable levels from only some (22%) of the treated apartments. The authors attributed treatment failures to the presence of heavy bed bug infestations in some apartments, clutter, and lack of resident cooperation in laundering periodically bed sheets. (Wang et al. 2014). Wang et al. (2013) also explored the use of Tempo Dust in a "dust band" treatment technique to reduce the amount of insecticides used in indoor environments. The technique consisted of covering bands of fabric with Tempo Dust (the authors acknowledged a deviation from label rate using this technique), and installing these bands onto furniture legs, thereby delivering the insecticide to any bed bugs crossing the fabric. Interceptors were also installed in association with the dust bands, and Alpine aerosol was applied to live bed bugs found during visits conducted every 2 wk. A second treatment employed an IPM approach that included installation of the "dust bands" described above, a mattress encasement, interceptors, application of hot steam, and application of 1% cyfluthrin dust around the perimeter of the room. In the control group, infested apartments only received monthly insecticide applications made by a pest control company hired by the property management office. Overall, the dust band treatment and the IPM treatment resulted in higher and significant bed bug reductions (95% and 92%, respectively) than insecticide alone applications (85%) during the 12-wk study (Wang et al. 2013). These results are significant in terms of the overall reduction in the use of insecticides, but the persistence of some (5–8%) infestations after 12 wk highlights the challenging nature of these pests in homes.

Community-Wide Bed Bug Management Programs

The integrated studies summarized in this publication show that IPM programs can effectively reduce bed bug incidence and density, but that they sometimes fail to reduce infestations to nondetectable levels. The difficulties highlighted in achieving control of bed bugs within multiunit housing communities have prompted the continued development and adoption of more effective bed bug control strategies. Programs that consider the entire community and attempt to detect infestations before they are reported and before populations spread to multiple units (proactive programs) stand the best chance at succeeding. Wang and Cooper (2011) proposed and implemented (Cooper et al. 2016) a community-wide bed bug management program based on proactive detection using interceptors followed by the use of both nonchemical and chemical methods. The program initially included separate bed bug training modules for staff members and residents to measure the impact of this education on bed bug knowledge and prevention. An eradication protocol was established according to the number of bed bugs caught every 14 d in the interceptors. Although units with bed bug counts fewer than five were nonchemically treated (manual removal was the only control method used), units with >5 bed bugs were treated using a combination of nonchemical and chemical methods. Adoption of this community-wide IPM program resulted in a reduction of incidence from 15% to 2.2% after 12 mo. Furthermore, the program used 90% less insecticide, compared with similar field studies that used an insecticide-only approach. Finally, Cooper et al. (2016) claim that, in addition to being more effective, the community-wide program was more economically viable and sustainable than a reactive approach toward bed bug control. A similar study (Sutherland et al. 2017), recently completed in California, assessed proactive IPM programs for bed bugs over a 1-yr period, comparing them in the end to reactive "conventional" bed bug programs in terms of efficacy, cost, and tenant satisfaction. Educational modules for tenants and regular property-wide monitoring programs (represented by canine detection, interceptors, visual inspections, or some combination of these methods) were instituted at three multiunit housing sites where bed bugs had been historically problematic. Once bed bugs were detected, they were managed using a combination of volumetric heat, mattress encasements, desiccants, and an assortment of registered insecticides. Bed bug incidence was greatly reduced over the course of the 1-yr project; one site began the study with bed bugs detected in 50% of its units and ended, 1 yr later, with bugs detected in only 6.3% (four units) infested, as according to visual inspections and interceptor monitors. Tenant satisfaction was higher during these IPM programs than during the reactive programs in place at the properties beforehand. Finally, and most significantly, costs of these proactive programs were several times more expensive than those in place at these sites in previous years, highlighting serious challenges for implementation of such programs when budgets are limited and value is unappreciated.

In addition to increases in knowledge about bed bug prevention and control that can be imparted to community members during educational programs, the continued involvement, cooperation, and communication of property management and tenants are essential components for effective and sustainable community-wide bed bug management programs. Only a few studies have been conducted to understand the common perceptions and practices used by multiunit housing property managers and their staff for potential or current bed bug infestations. Based on survey responses compiled from 137 property management professionals in California, Campbell et al. (2016) concluded that proactive and unambiguous approaches toward bed bug management have not yet been adopted. For example, most of the property managers surveyed (95% of respondents) manage bed bugs reactively by waiting for complaints to be reported by tenants or their neighbors. Proactive approaches should embrace regular monitoring and unit inspections (with timely tenant notification provided) to find infestations in their infancy when they are easier and less costly to eradicate. Nineteen percent of the respondents in this study indicated that responsibilities for bed bug management costs fall into the realm of "it depends on the situation." The actual instance of ambiguity may be even higher, though, as 14% of respondents chose a combination of responsible entities ("owner and manager," "tenant," or "it depends on the situation"). Campbell et al. (2016) concluded that this ambiguity over financial responsibility would likely discourage tenants from reporting infestations. Clear written definitions of responsibility should motivate responsible parties to become interested and engaged in bed bug control efforts, and may also prove useful in the event of litigation associated with unsuccessful and unacceptable bed bug management programs.

Conclusions

Several field studies have been conducted in low-income, multiunit housing where bed bugs are often difficult to manage. Many of these studies have compared traditional strategies, where there is a high dependency on insecticide treatments, to expanded protocols involving IPM strategies that include chemical, nonchemical methods, and education and outreach. Concerns about indoor insecticide exposure have increased the interest in the use of reduced-risk insecticides such as chlorfenapyr, insect growth regulators, diatomaceous earth, and botanical insecticides, as well as in more frequent use of nonchemical control methods and preventative strategies. Results of the reviewed field studies show that bed bug programs using an IPM approach can result in significant reductions in bed bug incidence and density. However, complete eradication in most places continues to be problematic, especially when the control action is assessed as a terminal effort. This leads us to conclude that a sustained management approach targeting bed bugs is essential in multiunit housing. Several factors contribute to the continued presence of bed bugs, including treatment efficacy, lack of resident and staff awareness, presence of clutter, lifestyle choices, and varying abilities of community members to adequately cooperate with management programs (especially reporting). Often budget limitations have precluded funding for rigorous and sustained IPM services. Community-wide bed bug management programs that incorporate educational components, proactive inspection and monitoring, and the appropriate use of both chemical and nonchemical methods stand to be the most successful at significantly reducing infestations. Considering litigation risks and building closure costs, IPM strategies for bed bugs may well prove to be the only economical option.

Bed bug IPM programs demand significant commitment on the part of housing staff, managers, housing owners, contracted pest management professionals, and educators. Encouraging residents to participate in educational opportunities, take precautions to prevent infestations, communicate effectively, and cooperate with recommendations associated with the management programs may generate additional costs and considerations. Furthermore, public housing authorities and other providers of low-income, multiunit housing need to allocate sufficient funding, negotiate good contracts, enforce good practices, and maintain community-wide proactive programs. Such long-term programs may prove to be the only way to effectively manage bed bugs in these challenging environments, while protecting tenants from the associated health impacts, and housing providers from liability and litigation.

Acknowledgments

This manuscript is based upon collaborative work that is supported in part by a grant from the Western Integrated Pest Management Center, National Institute of Food and Agriculture, U.S. Department of Agriculture. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture.

References Cited

Anderson, A., and K. Leffler. 2008. Bedbug infestations in the news: A picture of an emerging public health problem in the United States. Journal of Environmental Health 70: 24.

Anderson, J. F., F. J. Ferrandino, S. McKnight, J. Nolen, and J. Miller. 2009. A carbon dioxide, heat and chemical lure trap for the bedbug, *Cimex lectularius*. Medical and Veterinary Entomology 23: 99–105.

Ashcroft, R., Y. Seko, L. F. Chan, J. Dere, J. Kim, and K. McKenzie. 2015. The mental health impact of bed bug infestations: A scoping review. International Journal of Public Health 60: 827–837.

Bennett, G. W., A. D. Gondhalekar, C. Wang, G. Buczkowski, and T. J. Gibb. 2015. Using research and education to implement practical bed bug control programs in multifamily housing. Pest Management of Science 72: 8–14.

California Assembly AB-551. 2016. Rental property: Bed bugs. Section 1942.5 of Title 5 of Part 4 of Division 3 of the Civil Code, relating to tenancy.

Campbell, K., A. Sutherland, V. Lewis, and D. H. Choe. 2016. California multi-unit housing managers answer bed bug survey. (https://caanet.org/bed-bug-survey-results/)

(CDC) **Centers for Disease Control and Prevention. 2011**. Acute illnesses associated with insecticides used to control bed bugs–Seven states, 2003–2010. Morbidity and Mortality Weekly Report 60: 1269–1274.

City and County of San Francisco, Department of Public Health. 2012. Director's Rules and Regulations for prevention and control of bed bugs. SFDPH Health Code Article 11.

Cooper, R., C. Wang, and S. Narinderpal. 2014. Accuracy of trained canines for detecting bed bugs (Hemiptera: Cimicidae). Journal of Economic Entomology 107: 2171–2181.

Cooper, R., C. Wang, and N. Singh. 2015. Evaluation of a model community-wide bed bug management program in affordable housing. Pest Management of Science 72: 45–56.

Cooper, R., C. Wang, and N. Singh. 2016. Effects of various interventions, including mass trapping with passive pitfall traps, on low-level bed bug populations in apartments. Journal of Economic Entomology 109: 762–769.

Dent, D. 2000. Insect Pest Management. CAB International. Wallingford, United Kingdom.

Doggett, S. L. 2007. A code of practice for the control of bed bug infestations in Australia, 2nd ed., p. 69. Department of Medical Entomology and The Australian Environmental Pest Managers Association, Westmead Hospital, Sydney, Australia. (http://medent.usyd.edu.au/bedbug/cop_ed2_final.pdf)

Doggett, S. L. 2016. Bed bug survey-Are we biting back? Professional Pest Management Aug/Sep: 28–30.

Gerardo, E. M. 2014. Increasing awareness of and education about bed bugs (*Cimex lectularius*) as a public health issue in Hawaii. MS Thesis. University of Hawaii, Manoa, HI. (http://hdl.handle.net/10125/100320)

Goddard, J., and R. deShazo. 2009. Bed bugs (*Cimex lectularius*) and clinical consequences of their bites. JAMA 301: 1358–1366.

Gouge, D. H., S. Li, S. Nair, M. Wierda, K. Drake, T. Stock, and A. Fournier. 2016. Extreme pesticide use in response to *Cimex lectularius* and *Blattella germanica* infestations, September 25–29, 2016. XXV International Congress of Entomology, Orlando, FL.

Hwang, S. W., T. J. Svoboda, I. J. De Jong, K. J. Kabasele, and E. Gogosis. 2005. Bed bug infestations in an urban environment. Emerging Infectious Diseases 11: 533–538.

Isman, M. B., and G. Paluch. 2011. Needles in the haystack: Exploring chemical diversity of botanical insecticides, pp. 248–265. *In* O. López and J. G. Fernández-Bolaños (eds), Green trends in insect control. Royal Society of Chemistry, Cambridge, London, United Kingdom.

Jones, S. C., and J. L. Bryant. 2012. Ineffectiveness of over-the-counter total-release foggers against the bed bug (Heteroptera: Cimicidae). Journal of Economic Entomology 105: 957–963.

Kells, S. A. 2006. Nonchemical control of bed bugs. American. Entomologist 52: 109–110.

Lewis, V. R., S. E. Moore, R. L. Tabuchi, A. M. Sutherland, D. H. Choe, and N. D. Tsutsui. 2013. Researchers combat resurgence of bed bug in behavioral studies and monitor trials. California Agriculture 67: 172–178.

Li, S., D. H. Gouge, A. Fournier, T. Stock, A. Romero, D. Young, S. Nair, C. Foss, R. Kerzee, D. Stone, et al. 2016. Life quality impacts of bed bug (*Cimex lectularius* L.) infestations. XXV International Congress of Entomology. September 25-29, 2016. Orlando, FL.

Moore, D. J., and D. M. Miller. 2009. Field evaluations of insecticide treatment regimens for control of the common bed bug, *Cimex lectularius* (L.). Pest Management of Science 65: 332–338.

Pereira, R. M., P. G. Koehler, M. Pfiester, and W. Walker. 2009. Lethal effects of heat and use of localized heat treatment for control of bed bug infestations. Journal of Economic Entomology 102: 1182–1188.

Pfiester, M., P. G. Koehler, and R. M. Pereira. 2008. Ability of bed bug-detecting canines to locate live bed bugs and viable bed bug eggs. Journal of Economic Entomology 101: 1389–1396.

Pillay, V. V. 2013. Modern medical toxicology. Jaypee Brothers Medical Publishers (P) Ltd., New Delhi, India.

Pinto, L. J., R. Cooper, and S. K. Kraft. 2007. Bed bugs handbook. The complete guide to bed bugs and their control. Pinto & Associates, Inc., Mechanicsville, MD.

Potter, M. F. 2006. The perfect storm: An extension view on bed bugs. American. Entomologist 52: 102–104.

Potter, M. F., A. Romero, K. F. Haynes, and W. Wickemeyer. 2006. Battling bed bugs in apartments. Pest Control Technology 34: 45–52.

Potter, M. F., A. Romero, K. F. Haynes, and E. Hardebeck. 2007. Killing them softly: Battling bed bugs in sensitive places. Pest Control Technology 35: 24–32.

Potter, M. F., K. F. Haynes, A. Romero, E. Hardebeck, and W. Wickemeyer. 2008. Is there a bed bug new answer? Pest Control Technology 36: 118–124.

Potter, M. F., K. F. Haynes, J. R. Gordon, E. Hardebeck, and W. Wickemeyer. 2012. Dual-action bed bug killers. Pest Control Technology 40: 62–76.

Potter, M. F., K. F. Haynes, and J. Fredericks. 2015. Bed bugs across America. Pestworld November/December 4–14.

Reinhardt, K., J. Hooper, C. Leake-Lyall, A. Harder, and S. Holland. 2008. Who knows the bed bug? Knowledge of adult bed bug appearance increases with people's age in three counties of Great Britain. Journal of Medical Entomology 45: 956–958.

Romero, A., M. F. Potter, and K. F. Haynes. 2007a. Insecticide-resistant bed bugs: Implications for the industry. Pest Control Technology 42–50.

Romero, A., M. F. Potter, D. A. Potter, and K. F. Haynes. 2007b. Insecticide resistance in the bed bug: a factor in the pest's sudden resurgence? Journal of Medical Entomology 44: 175–178.

Romero, A., M. F. Potter, and K. F. Haynes. 2009. Behavioral responses of the bed bug to insecticide residues. Journal of Medical Entomology 46: 51–57.

Schal, C., and R. L. Hamilton. 1990. Integrated suppression of synanthropic cockroaches. Annual Review of Entomology 35: 521–551.

Seidel, C., and K. Reinhardt. 2013. Bugging forecast: Unknown, disliked, occasionally intimate. Bed bugs in Germany meet unprepared people. PLoS ONE 8: 1–6.

Singh, N., C. L. Wang, R. A. Cooper, and C. F. Liu. 2012. Interactions among carbon dioxide, heat, and chemical lures in attracting the bed bug, *Cimex lectularius* L. (Hemiptera: Cimicidae). Psyche 2012: 1–9. doi:10.1155/2012/273613.

Singh, N., C. Wang, and R. Cooper. 2013a. Effect of trap design, chemical lure, carbon dioxide release rate, and source of carbon dioxide on efficacy of bed bug monitors. Journal of Economic Entomology 106: 1802–1811.

Singh, N., C. L. Wang, and R. Cooper. 2013b. Effectiveness of a reduced-risk insecticide based bed bug management program in low-income housing. Insects 4: 731–742.

Singh, N., C. L. Wang, and R. Cooper. 2015. Effectiveness of a sugar-yeast monitor and a chemical lure for detecting bed bugs. Journal of Economic Entomology 108: 1298–1303.

Stedfast, M. L., and D. M. Miller. 2014. Development and evaluation of a proactive bed bug (Hemiptera: Cimicidae) suppression program for low-income multi-unit housing facilities. Journal of Integrated Pest Management 5: E1–E7. doi: http://dx.doi.org/10.1603/IPM14003 last accessed 11/24/2015.

Susser, S. R., S. Perron, M. Fournier, L. Jacques, G. Denis, F. Tessier, and P. Roberge. 2012. Mental health effects from urban bed bug infestation (*Cimex lectularius* L.): a cross-sectional study. BMJ Open 2: e000838. doi:

Sutherland, A., D. H. Choe, V. Lewis, D. Young, A. Romero, H. Spafford, and D. Gouge. 2015. Survey sheds light on bed bugs in multi-unit housing. Pest Control Technology 43: 26–36.

Sutherland, A. M., D. H. Choe, K. Campbell, S. Moore, R. Tabuchi, and V. Lewis. 2017. From the lab to the bedroom: Translating research-based bed bug management strategies to low-income apartment buildings. *In* Proceedings, the 2016 National Conference on Urban Entomology, 22–25 May 2016, Albuquerque, NM. Texas A&M University Press, College Station, TX.

Walker, W., K. Glover, P. Koehler, E. Thoms, and E. Hobelmann. 2008. Fumigation, steam, dusting and labor. Pest Control Technology 36: 40–50.

Wang, C. L., and R. A. Cooper. 2011. Environmentally sound bed bug management solutions, pp. 44–63. *In* P. Dhang (ed.), Urban pest management: An environmental perspective. CABI, Oxon, United Kingdom & Cambridge, United States.

Wang, C., M.M.A. El-Nour, and G. Bennett. 2007. Case study: Controlling bed bugs in apartments. Pest Control Technology 35: 64–70.

Wang, C. L., T. Gibb, G. W. Bennett, and S. McKnight. 2009a. Bed bug (Heteroptera: Cimicidae) attraction to pitfall traps baited with carbon dioxide, heat, and chemical lure. Journal of Economic Entomology 102: 1580–1585.

Wang, C. L., T. Gibb, and G. W. Bennett. 2009b. Evaluation of two least toxic integrated pest management programs for managing bed bugs (Heteroptera: Cimicidae) with discussion of a bed bug intercepting device. Journal of Economic Entomology 46: 566–571.

Wang, C. L., K. Saltzmann, E. Chin, G. W. Bennett, and T. Gibb. 2010. Characteristics of *Cimex lectularius* (Hemiptera: Cimicidae), infestation and dispersal in a high-rise apartment building. Journal of Economic Entomology 103: 172–177.

Wang, C. L., W. T. Tsai, R. A. Cooper, and J. White. 2011. Effectiveness of bed bug monitors for detecting and trapping bed bugs in apartments. Journal of Economic Entomology 104: 274–278.

Wang, C. L., K. Saltzmann, G. Bennett, and T. Gibb. 2012. Comparison of three bed bug management strategies in a low-income apartment building. Insects 3: 402–409.

Wang, C. L., N. Singh, R. A. Cooper, C. F. Liu, and G. Buczkowski. 2013. Evaluation of an insecticide dust band treatment method for controlling bed bugs. Journal of Economic Entomology 106: 347–352.

Wang, C. L., N. Singh, and R. Cooper. 2014. Efficacy of an essential oil-based pesticide for controlling bed bug (*Cimex lectularius*) infestations in apartment buildings. Insects 5: 849–859.

Wang, C. L., N. Singh, and R. Cooper. 2015. Field study of the comparative efficacy of three pyrethroid/neonicotinoid mixture products for the control of the common bed bug, *Cimex lectularius*. Insects 6: 197–205.

Wang, C., N. Singh, C. Zha, and R. Cooper. 2016. Bed bugs: Prevalence in low-income communities, resident's reactions, and implementation of a low-cost inspection protocol. Journal of Economic Entomology 53: 639–646.

Wong, M., N. Vaidyanathan, and R. Vaidyanathan. 2013. Strategies for housing authorities and other lower-income housing providers to control bed bugs. Journal of Housing and Community Development 70: 20–28.

White, J. 2010. Crank up the heat. Pest Management Professional 78: 64–66.

Zehnder, C., M. Schmidt, and A. Hasenböhler. 2014. Thermal treatments for bed bugs, pp. 369–373. *In* G. Müller, R. Pospischil and W. H. Robinson (eds.), Eighth international conference on urban pests, 2014, Zurich, Switzerland. OK-Press.

Zhu, F., J. Wigginton, A. Romero, A. Moore, K. Ferguson, R. Palli, M. F. Potter, K. F. Haynes, and S. R. Palli. 2010. Widespread distribution of knockdown resistance mutations in the bed bug, *Cimex lectularius* (Hemiptera: Cimicidae), populations in the United States. Archives of Insect Biochemistry and Physiology 73: 245–257.