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Citation to Publisher Version: Wang, Changlu & Cooper, Richard. (2011). Environmentally Sound Bedbug Management Solutions. In Partho Dhang (Eds.), *Urban Pest Management: An Environmental Perspective* (44-63). Wallingford: CAB International. http://dx.doi.org/10.1079/9781845938031.0000.

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Chapter 4

Environmentally sound bed bug management solutions

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SUMMARY

Bed bugs have become a serious pest in urban communities throughout the world. These are proving to be one of the most challenging urban pests facing pest management professionals, largely due to lack of effective pesticides and lack of public awareness that has enabled bed bugs to spread at alarming rates. Non-chemical techniques and tools, and integrated pest management strategies are gaining popularity as they impose less environmental impact than pesticide driven programs. This chapter discusses the use of "low-impact" tools and methods. Also, a community-wide bed bug management program for effective bed bug management in the society is explained.

INTRODUCTION

History of Bed Bug Infestation and Control

The bed bug, *Cimex lectularius* L., has been recorded in association with humans for thousands of years (Usinger, 1966). It was a common pest in temperate regions of the world through much of the twentieth century. However, the advent of DDT in the 1940's dramatically reduced bed bug infestations. Leary *et al.* (1946) claimed that "DDT is the most valuable weapon found against bed bugs". Further the U.S. Department of Agriculture called DDT "the perfect answer" to the bed bug problem (Leary *et al.,* 1946). Five percent spray or 10% DDT powder were used to be directly applied on beds, bed frames, walls, baseboard cracks, behind loose wall paper, and to any other hiding places. Eradication was achieved in as little as 48 h. Control could last more than 6 months after only one treatment with DDT. Eventually, bed bugs became widely resistant to DDT and a switch to organophosphates such as malathion became necessary to eliminate DDT resistant populations. The use of DDT and other highly effective insecticides minimized bed bug population in many industrialized countries (Snetsinger, 1997).

Since 2000, bed bug infestations have become increasingly common in the U.S. (Cooper and Harlan 2004, Gangloff-Kaufmann *et al.* 2006, Potter 2008), Canada (Hwang *et al*. 2005), Australia (Doggett *et al.* 2004), and in Europe (Kilpinen *et al*., 2008). An increase in the tropical bed bug, *C. hemipterus* (F.), was also reported along with *C. lectularius* in Australia (Doggett *et al*. 2004). Incomplete data from the New York City Department of Housing Preservation and Development showed bed bug complaints increased from 537 in 2004 to 12,768 in 2010. A survey of management staff from 16 apartment complexes occupied by low income people in New Jersey, USA found 5 percent of all of the housing units experienced bed bug infestations; further, five out of eight complexes reported increase in bed bug infestations from 2008 to 2009 (Wang, unpublished data). The cause of the resurgence of bed bugs remains unclear. One of the more widely accepted theories is that insecticide resistance is one of the factors that led to increased global bed bug activity. Other factors that could have likely to have contributed to the resurgence are increased international travel, lack of effective insecticides, more restricted use of insecticides in homes due to health concerns, and a general lack of awareness in society in many parts of the world where bed bugs were rarely encountered for nearly five decades.

Exclusion of chlorinated insecticides for use inside homes and restricted use of available insecticides due to health concerns could be the reasons for the recent resurgence of bed bugs. Added to this is the fact that bed bud detection is often challenging and when combined with several non-chemicals tools, requires multiple visits to eradicate an infestation (Wang *et al.* 2009a). This makes the process labour intensive and expensive. The cost for professional control in a single home can range from several hundred to thousands of U.S. dollars.

As a counter measure, researchers, government agencies, and the pest management industry are responding to the bed bug resurgence and control difficulties. A book dedicated to bed bug management was published (Pinto *et al.* 2007). Numerous non-refereed articles and web sites about bed bugs have also appeared in recent years and many bed bug management tools are being developed. A number of bed bug management tools have been developed and are being marketed. In spite of this increased focus on bed bugs, infestations continue to increase and spread. Added to this are concerns about safe use of pesticides in the interior environment. This chapter reviews the existing bed bug management methods and discusses how to combine them into environmentally sound practical bed bug management programs. This chapter is not meant to provide detailed description about individual control methods. Rather, it focuses on utility of the techniques, new research findings on bed bug management, and sustainable integrated bed bug control solutions.

INSPECTION AND MONITORING

Detecting the presence of bed bugs is very important in a bed bug management program. In fact, early detection of bed bugs is perhaps the single most important factor in eradicating bed bugs in an efficient and cost effective manner. Residential infestations that are detected early on (within the first month after introduction) tend to be localized and can be eliminated with relative ease. In contrast, the longer an infestation remains undetected, the more widely dispersed the bugs become within the infested structure. Failure to detect early allows bed bugs to start infesting various items in the structure, away from regular sleeping and resting areas. This also makes the work time longer and costly. The failure to detect bed bugs early on also provides the opportunity for bed bugs to spread to other units in multi-occupancy settings (i.e. hotels, apartments, dormitories, hospitals etc.). These can be transferred to residences, places of work, schools, and other public and retail locations within the community through belongings such as back packs, computer bags, handbags, places of work, schools, and other public, and retail locations within the community

Methods of monitoring bed bugs fall into the following categories: visual inspection, client interview, placing monitors, and using specially trained detection dogs. A combination of several methods generally provides better detection than relying on a single method.

Visual Inspection

A thorough inspection by an experienced professional is valuable in determining the presence and distribution of bed bugs, and designing treatment strategies. The inspection should be performed before conducting the initial treatment. Reliability of a visual inspection is limited by experience of the inspector, time spent, accessibility, complexity of the environment, and cooperation of the client. The cryptic and secretive behavior of bed bugs renders visual inspections unreliable when only a few bugs or eggs are present. Many hiding places are difficult, impractical or inaccessible to inspect, especially when clutters obscure potential harborages. Some examples include areas beneath floorboards, under baseboards, behind radiators, inside wall voids or inside mattresses. Visual inspections should include looking for live bed bugs (including eggs), fecal spots, and shed skins. Any signs of bed bug activity in previously un-infested environments are clear indicators of new infestation. The limitations of visual inspections were demonstrated by Wang *et al.* (2009a) where bi-weekly visual inspections in eight apartments found 39 ± 22 bed bugs, whereas an intercepting device placed under furniture legs caught 219 ± 35 bed bugs in the same period.

Client interview

Feedback from clients can be helpful in determining when and how bed bugs may have been introduced, where the location of the infestation is, and how effective the treatment is. Like visual inspection, client interviews are not a reliable method for determining the presence or absence of bed bugs. Interview accuracy is influenced by the client's knowledge, motivation, sensitivity to bed bug bites, and even visual acuity. For example, 50 percent of the residents interviewed in a low-income community were unaware that their apartments were infested (Wang *et al.* 2010). In another study, 30 percent of 474 individuals living in bed bug infested homes indicated that they were not experiencing any bite symptoms (Potter *et al.* 2010a). In one instance, Wang *et al.* (2010) examined an elderly man who had an estimated 10,000 bed bugs present in his apartment. No red welts or scars were found on his arms or neck. In another instance, it was noted that individuals who are aware of infestations will not provide truthful information out of embarrassment, fear of social stigma or concerns that they may be held financially responsible for the infestation. Thus, while client interviews/surveys are strongly recommended, one should not rely solely on the resident's observation to evaluate a site and success of a treatment.

Using Monitors

Monitors designed for bed bugs may be classified as passive or active. Passive monitors do not contain lures for attracting bed bugs, whereas, active monitors contain lures intended to draw bed bugs into the monitor or trap.

Passive monitors

Several passive monitors were developed to help detect bed bugs. To date, the ClimbUp® Insect Interceptor[1] (Susan McKnight, Inc, Memphis, TN, USA) is the only passive monitor

[1] Wang helped develop the ClimbUP Insect Interceptor and was listed on the patent application.

that the authors have found both economical and effective for detecting low levels of infestations. It is used directly under the bed or furniture legs. Despite the fact that the device by itself is passive, the presence of the human host provides this device with the most effective natural lure available. Because they kill bed bugs (by confining them), interceptors can also help reduce the number of bed bugs (Wang *et al*. 2009a, c) as well as provide a degree of relief by reducing feeding activity of bed bugs that are intercepted on route to acquire a blood meal (Pinto *et al.* 2007).

ClimbUp interceptors cannot be placed under the legs of all beds. Some beds frames have legs that are too large for the interceptors. Likewise, platform style bed frames preclude the use of the interception device under legs. Despite the fact that ClimbUp interceptors cannot always be placed under the legs of beds or sofas, interceptors not placed directly under the legs of bed frames and other furniture can still be helpful in the detection of bed bugs. Two interceptors placed beside bed legs in six occupied one bedroom apartments for two weeks collected a median number of seven bed bugs per apartment compared to a median number of 16 bed bugs per apartment when 4 - 12 interceptors were placed under the legs of beds and sofas (Wang, unpublished data). Similarly, Cooper used ClimbUp interceptors to monitor a 360 unit apartment complex for the elderly and was able to identify infestations by placing ClimbUp interceptors adjacent to sleeping areas in units where bed frames were absent (Cooper, unpublished data). The tendency for bed bugs to climb up vertical surfaces (Aboul-Nasr and Erakey 1968) appeared to be a factor in the effectiveness of this monitor. However, ClimbUp interceptors need to be serviced regularly (e.g. every two weeks) by wiping off settled dust and reapplying talcum powder to keep the interior surfaces slippery. Although effective, ClimbUp interceptors are likely to be aesthetically unacceptable to some customers such as hotel managers. Development of interception devices and barriers is currently an area of great interest and new devices are becoming commercially available on a regular basis. Some of the newer devices include the Bed Moat (Canada), Bed Bug Barrier (Australia), and BB Secure Ring (Australia). However, efficacy data are lacking for all of these devices which prevent further interpretation.

Sticky traps (Trapper® Insect Monitor, Bell Laboratories, Inc., Madison, WI. USA), designed for catching crawling insects have not proved effective in detecting bed bugs in our field observations. Several other passive monitors consisting of layered or corrugated cardboard are commercially available. They offer alternative harborages to bed bugs looking for a hiding place. The monitors are placed on or near beds or sofas. Infestations are identified by the presence of bed bugs or their feces and cast skins. These passive monitors rely on bed bugs' harborage seeking behavior. Preliminary field results showed that Catchmaster BDS™ (AP & G Co., Inc., NY. USA) and BB Alert Passive® (Midmos Solutions, Ltd. UK) were much less effective compared to ClimbUp interceptors.

Active monitors

Bed bugs can be attracted and trapped by baited pitfall traps (Anderson *et al.* 2009, Wang *et al.* 2009b). The bait can be carbon dioxide (CO_2), heat, chemical lure, or a combination of these above elements. Because baited traps contain attractants, they can be used both in occupied and vacant rooms and results can often be obtained overnight. CO_2 was the most important lure when compared to heat and chemical attractants. It is believed to be the key attractant in an effective active monitor (Wang *et al.* 2009b). The CO_2 release rate and release time of four active monitors are listed in Table 1.

Table 1. Comparison of CO_2 release rates and release periods of four bed bug monitors.

Monitor	**CO_2 release rate (ml/min)**	**Release period (hours)**
CDC 3000	42	≈10
NightWatch	150 to 200	8
Dry ice trap	737 to 801	10-12
Bedbug Beacon	2 to 11*	48**

* Maximum CO_2 release rate measured at 2 hour after activation.
** After 48 hours, CO_2 release rate was below 2 ml/min.

Comparative studies in apartments of the CDC3000™ (Cimex Science LLC., Portland, OR, USA), NightWatch™ (BioSensory Inc, Putnam, CT, USA), and a homemade dry ice trap showed that all monitors can detect low level bed bug infestations. The dry ice trap was the most effective and NightWatch was the least effective monitor over a 24 h monitoring period. Continuous monitoring over several consecutive days with NightWatch improved detection (Wang *et al.* 2011). CDC3000 and NightWatch utilized CO_2 (emitted from pressured CO_2 cylinders), heat (generated from electric powered component), and chemical attractants to attract bed bugs. The homemade dry ice trap only utilized CO_2 (dry ice as source) to attract bed bugs. Dry ice trap is much more affordable than CDC3000 and NightWatch. However, dry ice is not often readily available and cannot be stored for more than a few days. Dry ice needs to be secured in containers to prevent children and pets from accidental exposure or ingestion.

Bedbug Beacon™ (Packtite/Nuvenco, Laporte, CO, USA) is a new product using a similar principle as the dry ice trap. It utilizes ready-to-mix dry materials to generate CO_2, a concept similar to that explored in mosquito trapping (Kline *et al.* 2006, Xue *et al.* 2008). This source of CO_2 is more convenient and does not require expensive hardware to regulate the release of CO_2. Laboratory experiments in 55.5 × 43.5 cm (L × W) arenas indicated the device can attract approximately 80% of the released bed bugs overnight. The authors tested the utility of the monitor in seven severely infested units (based on visual inspections). One Bedbug Beacon was placed beside the infested bed of each apartment. Four ClimbUp interceptors were placed under the bed legs or beside bed legs in each apartment. Results of these experiment showed that Bedbug Beacon was not effective in detecting bed bugs (Table 2). The ClimbUp interceptors caught an average 16 bed bugs. Most of the bed bugs found in the interceptors were from the outer well of the interceptors, indicating large numbers of bed bugs were present in the rooms and not in the beds. The inconsistency between laboratory results and field results about Bedbug Beacon highlighted the need for conducting field experiments when evaluating bed bug monitoring devices.

Table 2. Relative effectiveness of ClimbUp interceptors and Bedbug Beacon for detecting bed bugs in occupied apartments.

Apartment	Bed bug infestation level	Number of days of placement	Bed bug count	
			Bedbug Beacon	ClimbUp Insect Interceptor
1	Heavy	1	0	11
2	Very heavy	1	1	30
3	Medium	2	2	7
4	Heavy	2	0	36
5	Medium	5	0	9
6	Medium	5	0	13*
7	Medium	5	0	6*

* Interceptors were placed beside bed legs.

Detection dogs

Specially trained dogs to detect bed bugs are used by some pest control companies in the US and elsewhere. However, the only peer-reviewed publication indicating detection dogs as an effective tool to detect the presence of bed bugs was by Pfiester *et al*. (2008). To date, there are no field data confirming the accuracy of the detection dogs in occupied rooms where dead bed bugs and old bed bug feces are present. From our interactions with pest control companies and clients, results from different trained dogs varied significantly. Both environmental and human factors affect the accuracy. In addition, dogs may fail to detect bed bugs if the scent is unavailable to them during the inspection due to the location of the bug(s) and the air flow in the room. Thus, human assistance is needed to allow dogs to sniff inaccessible areas. The cost may not be affordable for individual residents (around $300/hour in the U.S.). Conversely, canine scent inspections are the most efficient and economically practical method for large scale inspections such as entire office buildings, theaters, hotels, dormitories etc. Due to the great degree of variability in the effectiveness of canine scent detection inspections, it is strongly recommended that bed bug activity is verified in areas where dogs have been alerted. In the event that bed bug activity cannot be confirmed, the area in question may be treated by non-chemical measures (i.e. vacuums, heat/steam, etc.) and monitored for several weeks. Pesticides should not be applied unless activity is confirmed by physical evidence. Thus, more studies are needed to evaluate the reliability of detection dogs.

PREVENTION

New bed bug infestations often result from visiting infested rooms, bringing home infested furniture, or receiving visitors with bed bugs in their clothing or personal belongings. In addition, bed bugs migrate from one unit to another in multi-occupancy settings (Doggett *et al*. 2008; Wang *et al*. 2010).

The ease in which bed bugs can be introduced into a previously un-infested environment makes prevention difficult and sometimes impossible. The most important step in the prevention of bed bugs is education and public awareness. Misinformation, misconceptions and a general lack of awareness have been bed bugs' greatest allies enabling the bug to spread in a virtually unrestricted fashion.

There are a number of proactive steps that can be taken to avoid transferring bed bugs from infested environments to previously un-infested locations. The extent that individuals go to avoid introducing bed bugs will vary greatly depending on the amount of exposure that they have to locations where bed bugs are likely to be present and their degree of concern. Following are essential actions which could help prevent infestation and protect individuals from bites.

- People not presently experiencing a bed bug infestation should consider the following preventative measures: 1) Become educated about the life history of bed bugs, how to avoid them, how to inspect for bed bugs and how to recognize the signs and symptoms of an infestation; 2) Exercise caution during travel that involves overnight stays and inspect sleeping quarters; 3) Avoid sitting on furniture or placing personal items near beds and upholstered furniture when visiting places where bed bugs are known to exist; limit personal items (handbags, back packs, etc.) when visiting areas that are known to have bed bug activity; 4) Immediately hot launder or run through a dryer of all suitable items upon returning from areas where bed bugs are likely, or known to be present; and 5) Place items that cannot be laundered or dried into a freezer for at least four days when returning from locations that have bed bugs.
- Property owners/managers of facilities should consider: 1) Educating building occupants about identification, prevention, and control of bed bug infestations; 2) Developing a policy and procedure for dealing with reported or suspected bed bug activity. A suggested policy and procedure for the hospitality industry is available at www.bedbug.org.au. Procedure checklists are also available in Bed Bug Handbook (Pinto et. al. 2007); and 3) Periodically inspecting/monitoring high risk areas of the facility.
- People currently experiencing bed bug infestation in their home should consider the following steps to prevent the further spread of bed bugs: 1) Do not discard infested items without first eliminating as many bugs as possible and then completely wrapping or bagging the item and marking it as a bed bug infested item; 2) Do not relocate items from infested dwellings unless they have been hot laundered, steamed, heat treated, fumigated or otherwise disinfected; 3) Store personal items such as handbags, backpack, computer bags etc. away from sleeping and resting areas in an air tight storage container to prevent infestation of items that will be taken out of the home on a regular basis; and 4) Periodically, hot launder and/or dry clothing and store in bags or an air tight container to prevent clothing that is being worn from becoming infested.
- Repellents available commercially can be used against bed bug bites. Diethyl toluamide (DEET) is a commonly used insect repellent. Kumar (1995) demonstrated

the repellent affect of DEET and N, N-diethylphenylacetamide (DEPA) to *C. hemipterus* over 8 hours under laboratory conditions. Laboratory studies also have demonstrated that filter paper treated with 10% DEET at a rate of 1.26 nmol/cm^2 remained repellent to *C. lectularius* for at least 8 h (Rutgers University, unpublished data). Also, spraying shoes, pants, luggage, and other vulnerable surfaces with repellent containing at least 10% DEET may prove effective in reducing the risk of contracting bed bugs. However more research is necessary to verify if this is an effective measure outside of the lab setting. Rest Easy™ Bed Bug & Insect Control (J T Eaton, Twinsburg, OH. USA) (0.5% permethrin) and Cutter® Advanced™ insect repellent (St. Louis, Mo, USA) (7% picaridin) were not effective in repelling bed bugs in laboratory studies conducted (Wang *et al*., unpublished data).

NONCHEMICAL CONTROL METHODS

Reduction of Harborages

Bed bugs are thigmotactic and prefer to hide in cracks and crevices, and along edges and folds. Also, textured surfaces (i.e. wood, fabric) are preferred to smooth metal, plastic or tiled surfaces. Replacing wooden bed frames with plastic or metal frames, encasing mattresses and box springs, sealing holes and cracks on walls and floor, and removing items around beds and sofas, replacing carpets with solid flooring, and removing skirting are useful measures to reduce the number of harborages. Specially designed encasements are available that are bite proof, escape proof, and entry proof. Encasing mattresses and box springs with bed bug proof encasements will trap existing bed bugs inside where they will starve and die. Encasements prevent additional bed bugs from getting inside mattresses and box springs (Cooper 2007). Also, the smooth exterior of the encasement makes bed bug inspection much easier. In the event that infested beds are discarded, encasements can be used to protect replacement beds from becoming infested by bed bugs still present in other parts of the dwelling.

While the majority of bed bugs are associated with the bed complex (mattress, box spring and bed frame) and upholstered furniture, they can also infest many other items away from the sleeping areas. The closer the item is to the sleeping and resting areas (i.e. beds and sofas), the more likely it is to become infested. Storing items under, on, or next to beds will promote the infestation of personal items that may be difficult to rid of bed bugs.

Sealing holes and harborages on walls should always be considered as part of a proactive measure and may help reduce the probability of bed bugs spreading through common walls of neighboring units; however, the actual effectiveness is unknown. Tapes placed over electric outlets caught bed bugs that were tried to enter the room. However, complete protection from dispersing bed bugs is difficult as bed bugs can also spread through doors and hallways (Wang *et al*. 2010).

Physical removal

Several studies showed that the majority of bed bugs hide on beds, sofas, and other furniture that the occupants spend extensive time each day (Wang *et al*. 2007, Potter *et al*. 2008, Wang *et al*. 2009a). Disposing of infested furniture is the fastest way to remove large numbers of bed bugs from an infested room. Before disposal, furniture should be wrapped in plastic to avoid bed bugs crawl to the handlers or spread to non-infested areas. Disposing furniture should only be recommended if: a) The cost of eliminating the bugs is expected to exceed the cost of replacement; b) The furniture cannot be properly treated using methods such as heat treatment, steam, fumigation or chemical applications, encasements; or c) The owner of the furniture wishes to have it discarded rather than trying to salvage it. Disposal of infested furniture alone is rarely a solution. If infested furniture is being discarded, other control procedures must be done at the same time to address bed bugs in other parts of the dwelling. Replacing discarded furniture with new furniture prior to complete elimination of infestation is likely to result in the replacement furniture becoming infested.

Hand picking the bed bugs found during careful inspection provides immediate relief to inhabitants if only a few bed bugs are present. When the numbers are large, hand picking becomes impractical and the effect is less significant.

Vacuuming with crack and crevice attachments in heavily infested rooms is useful to quickly remove both live and dead bugs as well as shed skins and debris. In areas where large numbers of bed bugs are present, this method can be very efficient but does have limitations. Bed bugs that are protected within cracks or crevices are not easily removed and will often escape vacuuming efforts. Moreover, eggs are not easily dislodged from substrates upon which they have been cemented. The vacuumed areas still need to be treated with other non-chemical or chemical tools such as steam or residual insecticides. In addition, care must be taken to avoid the potential spread of bed bugs to different rooms via infested vacuums and vacuum bags. Vacuum bags should be removed, sealed in an air tight bag and discarded in an outdoor trash receptacle and the interior vacuum housing carefully inspected for bed bugs.

Barrier

The aforementioned ClimbUp Insect Interceptor serves both as a monitor and barrier. After installing the interceptors under the furniture legs and moving the furniture away from the walls, the inhabitants can avoid being bitten by bed bugs in a furniture from the room. However, those bed bugs already in furniture can still bite people. It is necessary to get rid of the bed bugs on the bed first to minimize the likelihood of being bitten. A number of other physical barriers are being developed and will be available in addition to ClimbUp interceptors. Bed bug caster barrier and screw in barrier developed from an Australian company are effective in preventing bed bugs accessing the furniture in our laboratory studies.

Double sided tape, smooth plastic tape, and Vaseline/oil mixture can also serve as effective barriers for preventing bed bug movement between furniture and the floors. Unlike the ClimbUp interceptors, these barriers cannot trap bed bugs. These monitors should only be used for preventing bed bugs from passing the barriers.

Laundering and Drying

Frequent washing or cleaning is an effective and safe method to eradicate bed bugs that are hiding on clothing, bed sheets, pillows, blankets, and other washable fabric materials.

Standard hot washing or drying cycles alone or in combination are effective in killing bed bug eggs and those in mobile stages (Potter *et al*. 2007). Naylor and Boase (2010) found washing at 60^{o}C and tumble drying on a hot cycle > 40^{o}C for at least 30 minutes killed all stages. Moreover clothing should be placed in disposable plastic bags before washing to avoid bed bug spread. Alternatively, dissolvable laundry bags (i.e. Green Clean™ Dissolvable Laundry Bags, Bed Bug Central, Lawrenceville, NJ, USA) can be used to place infested items prior to washing them in the washing machine to reduce the chance of spreading bugs when transferring items to be laundered. Dry cleaning with perchloroethylene was also effective against all stages of bed bugs. However, this method should be used with caution because bed bugs may spread before being killed.

Soaking infested fabric materials in water is lethal to bed bugs but requires extended periods of soaking. A Chinese government study in Hangzhou, Zhejiang province conducted in 1981 tested the effectiveness of 10, 20, 30, and 40 h soaking. Only 40 h treatment killed all bed bugs (unpublished report). Very recently Naylor and Boase (2010) found soaking in water for 24 h killed active stages but had no effect on the eggs.

Heat

Heat has long been used in bed bug control prior to the advent of the modern insecticides (Fox 1925). Boiling water, gasoline torch, and steam were used to treat mattresses, box springs, bed frames, and other harborages. However, the first two methods are not convenient or safe because these can damage the furniture or cause fire. The US army used heated air for treating barracks and was able to eradicate bed bugs. Steam radiators can heat up rooms to > 60°C. Minimum 52-54°C was sufficient to kill bed bug mobile stages and eggs. Six hour exposure time was recommended. Laboratory tests show nearly all bed bugs can be killed after 1 h exposure at 48°C (Benoit 2009).

A growing number of professionals as well as property maintenance staff are using steam machines as a safe and affordable bed bug control method. Hot steam can instantly kill all stages of bed bugs. Users need to adjust the steam flow rate so bed bugs are not blown away before being killed. Steam machines with larger attachments and multiple jet heads reduce the risk of blowing bed bugs away without killing them. The moving speed of the steamer attachment should have the treated surface reaching > 80^{o}C (Kells 2006). Treating upholstered furniture requires a slower speed in order to achieve the lethal temperatures needed to kill bugs that are hiding in folds and pleats. Containerized heat treatment can be performed inside rooms by building custom-made heat chambers using foam boards, oil heaters, and fans (Pereira and Koehler 2009). Portable heating units (PackTite^{TM}) are available for treating a small amount of materials. According to the manufacturer, the temperature inside the unit can reach at least 45^{o}C when connected to electricity. Four hours is recommended to ensure that the center of infested items reaches the minimum lethal temperature.

For homes with a large amount of furniture and other items, heat treatment of the whole house or custom-made heat chambers are used to control bed bugs. Achieving the minimum threshold temperature (50^{o}C) in all areas including piles of clothing and deep inside furniture is essential (Kells, unpublished data). Although highly effective, heat is only as effective as its ability to penetrate. One hundred percent elimination is less likely under cluttered conditions (especially with densely packed clothing) or in structures where concrete construction may serve as a heat sink. This makes it t difficult to achieve lethal temperatures throughout the entire structure. Even under conditions where elimination is not achieved, structural heat treatments can dramatically reduce severe infestations, leaving only a small number of bugs to be eradicated through follow-up services using conventional tools such as vacuums, steam, and insecticides.

Putting infested mattresses or clothing out in the sun or in a parked car in summer can kill some bed bugs. While this method can be helpful, temperatures may not always be sufficient to penetrate the items resulting in survivorship of some bugs or eggs and providing a false sense of security to people trusting in this method. Doggett *et al.* (2006) found out that temperatures were insufficient to cause complete mortality in an experiment with wrapped mattresses. Professionals should not recommend this method as a means of eradicating bed bugs from infested items.

Freeze

Freezing infested items to kill bed bugs in them is effective. Bed bugs die within hours at a temperature of -15°C (Kemper 1936). One hour exposure to -16°C was lethal to adult females (Benoit 2009). Jones and Wang (unpublished data) tested the effect of cold treatment on bed bugs using household freezers (-14 to -15°C). The bed bugs were placed in 4 cm diameter petri dishes along with pieces of paper. Each dish was wrapped with a cotton sock. Two out of the 15 nymphs recovered after 72 h freezing. The recovered bed bugs were able to bite but were not successful in drawing blood and subsequently died. None of the bed bugs (30 eggs, 15 nymphs, and 15 adults) recovered after 96 h freezing. Based on these findings, freezing items in household freezer for 4 days should be sufficient to kill bed bugs. Putting items outside in winter months should not be recommended due to fluctuations in the temperature when infested items absorb solar radiation. So, infested items must be held continuously for more than 5 days at -5°C or below to kill bed bugs (Kells 2006).

Cryonite® technology uses liquid CO_2 to kill bed bugs. Liquid CO_2 coming out from the tank forms a “snow” that immediately lowers the surface temperature well below 0°C in a very short time. There is no field research on the effectiveness of the technology alone. A limited laboratory study in a small aquarium (Insect Investigations Ltd, unpublished data) showed four bursts killed eggs, nymphs, and mostly adults. Under field conditions, bed bugs can be blown away by the high pressure CO_2 during application. For this reason, this technology is not recommended in the Australian bed bug code of practice (Doggett 2010).

CHEMICALS

Insecticides are an important bed bug management tool. Some insecticides do not only kill bed bugs on contact, but also provide residual protection afterwards. Two key factors limit the efficacy and use of insecticides for bed bugs: toxicity and method of application. Chlorinated hydrocarbon insecticides such as DDT and many organophosphates and carbamates are no longer available for bed bug control in many countries. Commonly used liquid insecticides are not very effective when applied alone (Moore and Miller 2008). Even if new and much more effective chemicals are discovered or registered for bed bug control in the future, these may not be affective against bed bug infestations. This was realized with DDT and other early synthetic insecticides that required more restricted application methods in developed countries where bed bug resurgence occurred.

Throughout history, bed bugs have demonstrated the ability to quickly develop resistance to pesticides. DDT resistance was found after only about 3 years of use in a military facility (Johnson and Hill 1948). Lilly *et al.* (2009 a, b) demonstrated the ineffectiveness of pesticides belonging to different chemical classes. In fact resistance to pyrethroids has been well documented. Majority of the current bed bug populations collected in the field were resistant to deltamethrin, a common chemical in the pyrethroid class (Zhu *et al*. 2010). In addition, resistance ratio of four bed bug colonies was > 12,765 (Romero *et al*. 2007). These findings confirmed that the effectiveness of insecticides will continue to be undermined by the bed bug's ability to develop resistance mechanisms. Due to these limitations and concerns about pesticide exposure, incorporating nonchemical methods into bed bug control programs is necessary to obtain satisfactory results.

Organic Insecticide

Several products in the organophosphate and carbamate groups are used to control bed bugs in Australia and Asia. However, the majority of the current residual insecticides registered for bed bugs in Australia (Doggett and Russell 2008), Europe, and U.S. are pyrethroids. While organophosphates and carbamates were more effective than pyrethroids (Lilly *et al.* 2009 a), they are not registered for bed bug control in the US because the US Environmental Protection Agency determined that exposure to these pesticide groups pose potential risks to human health and the environment.

Studies have successfully demonstrated the effect of combining insecticides against bed bugs. A combination of Suspend® SC(0.06% deltamethrin) and Drion® (1% pyrethrin, 10% piperonyl butoxide, 40% silica gel) or DeltaDust® (0.05% deltamethrin) eliminated bed bugs from 10 of 13 apartments after two to five treatments (Potter *et al.* 2006). Later, Wang *et al.* (2007) evaluated the effectiveness of deltamethrin spray and cyfluthrin dust treatment and found out that bed bugs were eliminated in 6 of 8 infested apartments after 8 weeks. An average of two treatments was applied to each apartment. In an experiment involving 15 apartments, chlorfenapyr spray only eliminated bed bugs from 1, 4, and 5 apartments at 4, 8, and 12 weeks, respectively (Potter *et al*. 2008). These studies demonstrated that thorough insecticide treatments can lead to satisfactory results, but complete bed bug elimination is difficult. Also, the lack of resident's cooperation is a contributing factor in the elimination failure (Wang *et al.* 2007).

Meanwhile, pyrethroid sprays were shown to be effective when applied directly on bed bugs, but dry residues were much less effective or ineffective (Potter *et al*. 2007, More and Miller 2006). Dust formulations have been found superior to spray formulations (Potter 2009). It appears advantageous to use dust formulations to control resistant populations. The effectiveness of various dust insecticides varied significantly (Doggett, personal communication). Continuous exposure to Tempo 1% dust (1% cyfluthrin, Bayer Environmental Science, Raleigh, NC, USA) killed 100% of the pyrethroid resistant bed bugs after 24 h. Wang (unpublished data) conducted an experiment in two heavily infested apartments where more than 500 bed bugs were found by visual inspection. One thorough application of Tempo 1% dust eradicated the infestations. In both apartments, the mattresses and box springs were wrapped in plastic, which might have contributed to the success of the eradication. Pyrethroid dusts can be very irritating to the applicator and it requires proper personal protective equipment during application. After application, the excess dust should be vacuumed to minimize human exposure to the dust.

Less toxic chemicals have been researched and used in bed bug management. Hydroprene, a juvenile hormone mimic, is used in combination with pyrethroid sprays by professionals (Potter 2008), but its effectiveness is unknown. Its mode of action is to prevent females from producing viable eggs. Laboratory experiments showed 0.07% hydroprene did not completely stop the treated females from producing viable eggs, although fecundity was reduced by 75 percent (Miller, unpublished data).

There are no indications that organic insecticides made of plant derived materials are effective against bed bugs as residual treatments. In our evaluations, alcohol sprays (70% or 91% alcohol) caused some mortality to bed bugs especially at nymphal stages. However, alcohol sprays do not have residual effect and can be a fire hazard if used excessively near pilot lights or other flammable sources.

Inorganic insecticides

Among the evaluated inorganic insecticide dusts such as diatomaceous earth (DE), boric acid, limestone, only DE demonstrated acceptable efficacy against bed bugs (Potter 2009). DE has the advantage over pyrethroid dust by having low mammalian toxicity, no known resistance in bed bug populations, and long residual activity in a dry environment. Doggett and Russell (2008) achieved 100 percent mortality of adults within 9-15 days of treatment with doses of 1 – 8 g/sq m DE. At a dose of 4 g/sq m, 33 percent of the adults died within 2 days. Also found were first instars to be significantly more susceptible to DE than adults with 99 percent mortality observed 2 days after treatment using the same dose of 4 g/square meter. Similarly, experiments by Potter (2009) show that DE caused > 90 percent bed bug mortality in both nymphs and adults in 10 days.

Fumigants

In some cases, it is necessary to fumigate infested materials when other options are not practical. Vikane® gas (active ingredient: sulfuryl fluoride, Dow AgroSciences, Indianapolis, IN, USA) is registered for treatment of bed bugs and is effective against all stages including eggs. Fumigation is the only method that, when applied correctly, will result in 100 percent elimination of all bed bug stages from infested structures and/or infested items. The fumigation process requires several days. This is often difficult and can be cost prohibitive for large structures (e.g. apartment buildings, hotels, etc.). Finally care must also be taken not to disperse bed bugs to new locations during the temporary relocation of the occupants of the structure that is being fumigated.

Resin strips impregnated with dichlorvos (AMVAC, Los Angeles, CA, USA) are useful for treating small items such as clothing, shoes, and books. Placing a dichlorvos strip in a large trash bag for 1-2 weeks with the infested items killed all stages of bed bugs based on laboratory tests (AMVAC, unpublished data). Also, Potter *et al*. (2010b) demonstrated that 7 - 14 days of exposure to the DDVP vapors was required to achieve 100 percent mortality of bugs and eggs in items like artwork, clocks, and suitcases, while other items like shoes and books still had live bugs or eggs even after 14 days of continuous exposure. These results suggest that the use of DDVP resin strips can be a very useful tool but are not completely reliable method in all situations.

Bed bugs are susceptible to high concentrations of CO_2. In laboratory trials (Wang, unpublished data), 100% CO_2 killed all active stages after 7 h and killed all eggs after 10 h at room temperature (around 24-26^{o}C). To fumigate infested clothing, 1,400 g dry ice (as source of CO_2) was placed in each 158 liter garbage bag filled with clothes (80% full) and sealed the bags for 24 h. The dry ice was placed at the bottom and center of the clothes piles. Thirty bed bugs (adults, nymphs, and eggs) were placed at the bottom, center, and top of the clothes pile. Five bags were tested. All bed bug life stages were killed after 24 h. Using this technique in a ventilated room has little environmental risk and can be easily done by both professionals and residents. Meanwhile CO_2 fumigation is a potentially safe and affordable method to treat non-washable items such as books, CDs, electronics, shoes, clothing, etc. When large amount of materials need to be fumigated, a fumigation bubble or custom made fumigation chamber is necessary. Liquid CO_2 may be needed for fumigating these chambers.

INTEGRATED BED BUG MANAGEMENT

As discussed in the previous section, each method or tool has its limitations. This calls for an integrated pest management (IPM) approach involving multiple methods. This is necessary to minimize the risk of new infestations, discover infestations at their early stage, effectively eradicate existing bed bug infestations, and maintain sustainable control. Education and awareness is absolutely critical and is the foundation upon which successful control is achieved.

The use of IPM to manage bed bugs was recently tested in low-income households (Wang *et al*. 2009a). The methods included education, installation of mattress encasements, and application of steam followed by chemical applications. The apartments were monitored biweekly and retreated when necessary. The cost per one bedroom apartment over 10 weeks period was estimated between $463-482. Bed bugs were eliminated by 50 percent only of the test apartments after 10 weeks. This was because some residents had piles of unwashed clothing on the floor and large amount of clutter. These conditions contributed to the eradiation failure.

We propose the following elements of a sustainable bed bug IPM program for apartment buildings: 1) Establish a management policy which include educating property management staff and residents and maintaining an ongoing bed bug monitoring and reporting program to all units in a building; 2) Maximize the use of non-chemical tools and use chemicals sparingly; 3) Encourage resident's cooperation; 4) Repeat services on a bi-weekly basis (or more frequently) until eradication is achieved.

Resident knowledge and cooperation directly affect the treatment result. In a survey of management staff from 16 housing authorities in New Jersey, 11 of them cited lack of resident cooperation as the main obstacle to bed bug control efforts. Some residents did not seem to care that bed bugs were in their homes, or they were incapable of or unwilling to follow recommendations such as reporting infestations, cleaning, de-cluttering, and installing encasements. Poor cooperation allows bed bugs to remain untreated until they become widespread and established. Lack of awareness among the public also leads to continuing unintentional spread of bed bugs in occupied units.

Some control methods are more expensive than others. The determination of the control method to use is often limited by the financial capability of the clients. This mean that coordination is needed to implement the most cost-effective strategies. Our survey of public housing authorities in New Jersey in 2010 found out that the median control cost for each infestation was $363. Follow-up inspection and treatment of infested units was necessary for the eradication of bed bugs. Only 6.1 percent of the surveyed pest control companies claimed one time treatment could eliminate bed bug infestations (Gangloff-Koffmann *et al*. 2006). These data highlight the need for better cooperation among involved parties and adoption of IPM programs.

COMMUNITY-BASED BED BUG MANAGEMENT

Currently, bed bug management efforts are focused at the individual level. However, bed bugs are often not an individual pest problem but a community-wide pest problem. Wang *et al*. (2010) documented that bed bug infestations expanded from 1 to 101 units within 41 months in a 223-unit apartment building. This shows that lack of community-based efforts favors the rapid dispersal of bed bugs within society. Less than ten years ago, bed bugs were rarely encountered in New York City. However, it is now common for bed bugs to be found in apartment buildings as well as office buildings, public and commercial retail locations. There are several factors that promote the successful spread of bed bugs in cities like New York City. These include: a) General lack of awareness and failure to detect infestations quickly; 2) Failure of people whose homes are infested to take steps to prevent taking bugs with them when they leave their homes; c) Lack of affordable professional bed bug management services; and 4) Lack of effective "self-help" tools and techniques. These factors must be corrected or bed bug problems will continue to spread throughout the community.

Implementing community-based bed bug management is more than an entomological challenge. It is also a social and political challenge which requires the mobilization of the communities and various parties. Establishing laws and regulations governing the management of bed bugs will be extremely helpful. Public education, research, and demonstration of effective bed bug prevention and control strategies are needed to reduce bed bug infestations in society.

CONCLUSION

Methods for better bed bug prevention and control are being actively sought to tackle this emerging public health pest. Effective and safe bed bug eradication hinges upon community-wide IPM action. This incorporates education, multiple tools, and cooperation of all involved parties. Programs are lacking in multi-unit dwellings, where bed bug infestations tend to be chronic and badly infested apartments become reservoirs of new infestations.

Bed bug control is both expensive and difficult. Repeated application of insecticides can result in unnecessary pesticide exposure to inhabitants. The cost and risks associated with bed bug control can be greatly reduced with education, prevention, early detection, and selective use of existing non-chemical and chemical tools. Custom IPM programs need to be designed and implemented with consideration of the resident demographics, income level, building type, and history of pest infestations. Finally more affordable control measures must be identified and safe and effective "self-help" methods developed to provide solutions for those that cannot afford the expensive control options primarily used today.

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