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INTEGRATED SUPPRESSION OF SYNANTHROPIC COCKROACHES

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PERSPECTIVES AND OVERVIEW

Urbanization is a product of human population growth and industrialization. In industrialized as well as developing countries, urbanization has moved humans away from many arthropod pests, but into intimate associations with others. Since the introduction of synthetic organic insecticides, urban dwellers have fought pests almost exclusively with repeated applications of chemicals. In agriculture, such unilateral reliance on residual pesticides has been heavily and effectively criticized, resulting in a gradual shift since the 1950s to Integrated Pest Management (IPM), "a pest population management system that utilizes all suitable techniques in a compatible manner to reduce pest populations and maintain them at levels below those causing economic injury" (153).

Sawyer & Casagrande (139) concluded that the urban pest management process has failed to develop an integrated approach to managing various pests. Rather, they argue, urban (not "integrated") pest management has addressed, in a fragmented manner, single pest types with few management options, usually in isolation from other components of the urban ecosystem. True integration, according to this view, would set the urban ecosystem as the management unit, and design and implementation components would include target pests and natural enemies in the household and structural habitat, on ornamental and shade plants, in private and public housing, parks, etc. The disciplines of entomology, horticulture, plant pathology, soil and environmental science, the social sciences, and governmental agencies would all be elements of this system.

In this review, we de-emphasize this conceptual approach and, rather, employ an empirical operational approach that stresses the importance of

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basic research on the target pest complex that will lead to innovations based on sound ecological and physiological principles. We also emphasize integration of disciplines and approaches in suppressing a "major pest complex." Thus, we are indeed fragmenting urban pest management (see 139), but, in our view, the "urban ecosystem" is not a manageable or a definable ecological unit (see also 56), and integration of disciplines and management options throughout the urban ecosystem is rarely feasible operationally because of organizational, political, and fiscal constraints, especially in early stages of the process. Therefore, we adopt Kogan's (86) view that "by necessity, IPM programs are initially confined within . . . disciplinary boundaries . . ., with either a single pest or a few pests . . . as the target," and as a first step in the development of the urban IPM process, we set the target pest population as the management unit, and use cockroaches to illustrate this approach.

Most literature on IPM in man-made structures may be classified into (*a*) works on the basic biology of pest organisms, including the effects of specific management options (usually insecticides) on pest populations; these are usually well scrutinized by scientists; and (*b*) works on the integration of approaches, details on progress and obstacles in IPM implementation, and cost-benefit assessments of various approaches, which are usually found in the unrefereed trade and technical literature. In this review we attempt to bridge the gap between basic knowledge and its integration into management practices by emphasizing a thorough understanding of the behavioral ecology and physiology of the pest.

THE INDOOR ENVIRONMENT AND PESTS

Secondary ecological communities may be classified as either agricultural, with moderate environmental perturbation and a mix of *r*- and *K*-strategists, or urban, with severe human-dominated modifications and mostly *r*-strategists (120). Within the so-called "urban ecosystem," the outdoors are characterized by surprisingly rich biotic diversity and stability (57, 58, 63). Indoors, human-provided resources and environmental stability interact to support large populations of well-adapted dominant species and smaller populations of associated species, including symbionts and natural enemies. Ecological processes such as succession and species replacement are arrested at an early phase in the indoor environment, and colonizer species (e.g. cockroaches), which assemble in specific perturbed microhabitats (i.e. moist, dark), experience minimal competition, predation, or habitat modification and thus become dominant in the community.

The identification of the appropriate unit of management is more difficult in urbanized settings than in agriculture. For example, in multi-family apartment complexes, each apartment may be considered the managed unit; however, islands of inaccessible pest populations will serve as reservoirs for reinfestations. The apartment complex may be the management unit, but this confers bureaucratic and logistic obstacles on the program. Therefore, management options, and especially pesticide applications, tend to be more heterogeneous indoors. In agriculture, on the other hand, fewer decision makers are involved, the crop and scope of the area to be protected is readily defined, and the managed system is more accessible, although land ownership and diversification may pose problems, as they do in the urban setting.

Surveys of attitudes of pest control operators (PCOs), residents, and entomologists indicate that cockroaches are of greatest concern, although the order of importance of indoor pests may reflect regional and socioeconomic differences among respondents (21, 106, 115). Of the approximately 4,000 cockroach species worldwide, *Blattella germanica* (the German cockroach) is the most abundant, with a relatively even cosmopolitan distribution. The cockroaches *Supella longipalpa* (brown-banded), *Periplaneta* spp. [including *P. americana* (American), *P. fuliginosa* (smoky-brown), *P. australasiae* (Australian or australasian), and *P. brunea* (brown)], *Blatta orientalis* (oriental), and *Eurycotis floridana* (Florida) follow the German cockroach in importance. All are introduced species in the United States (47), as are most domiciliary fleas, ants, and stored product pests. Species that live at the interface of the home and outdoors are potential indoor pests, including the various wood cockroaches in North America *(Parcoblatta)* and Europe *(Ectobius)* and pests of plantations and gardens in tropical regions (e.g. *Pycnoscelus, Panchlora, Epilampra)*. However, the majority of cockroaches are not synanthropic pests and they should be important subjects in the study of comparative behavior and physiology of cockroaches, including the evolution of synanthropy.

The general biology, distribution, and ecology of cockroaches are reviewed in 18, 39, 47, 51, 72, 95, 142.

THE CASE FOR SUPPRESSION OF COCKROACH POPULATIONS

Public health and aesthetic concerns, the harmful effects of insecticides to nontarget organisms and the environment, and legislative requirements are the most often cited reasons for suppressing cockroach populations.

Public Health and Medical Concerns

Because of their movement between sewers and human food materials, cockroaches can acquire, carry, and transfer pathogens either mechanically or in their digestive system. At least 100 species of bacteria have been isolated from cockroaches collected in schools, restaurants, hospitals, pet shops, and homes (130). Although cockroaches generally do not support multiplication of *Salmonella*, they have a significant vector potential because a high percentage of cockroaches in large infestations may be infected (8, 83). This is especially the case in public housing, where cockroach populations are large (85, 140) and salmonellosis is particularly prevalent (36).

Because tuberculous smears ingested by *B. orientalis* appear in the feces and remain positive for eight weeks, it is recommended that clinical material should be stored in closed containers to avoid dissemination by cockroaches, which frequently infest hospitals (2). Occasional physical association of cockroaches with humans and pets can also be problematic, including infections resulting from cockroaches in the human auditory canal (111). The spiny-headed worms (Acanthocephala) infect the small intestine of vertebrate hosts. Their eggs pass out with the host's feces and are eaten by cockroaches, which in turn are eaten by the vertebrate host, thus completing the infection cycle. Sixty percent of the cockroaches collected in an aviary were infected with acanthocephalans, which caused a significant number of bird deaths; the disease was controlled by reducing the cockroach population and by modifying water drainage (25).

Hypersensitivity to cockroaches is particularly common among inner-city residents and workers in entomological labs where both intensity and duration of exposure are high (80, 119, 169). Cockroach exuviae can support large populations of the house dust mite *(Dermatophagoides pteronyssinus)*, resulting in exacerbated cases of bronchial asthma. Air sampling showed that antigen concentrations of house-dust mite were similar in Rochester (Minnesota) and Harlem (New York), but cockroach and mouse urinary proteins were present only in Harlem (156). Although there are differences in allergenicity spectra between cockroaches and house dust mites (81), a "pan-allergy" to insects may occur in people who have been sensitized to one or a few arthropod species (9). This observation has important implications for the diagnosis of allergies in the urban environment, and it supports calls for the removal of all large populations of arthropods from indoor habitats.

Pesticide Use and Harmful Effects

The tremendous amounts of pesticides used in the urban (or nonagricultural) environment are surprising, even to workers within this area. In 1979, it was estimated that 140.7 million kg of active ingredients, which was approximately 27% of all pesticides used in the US, were applied in nonfarm settings (106). The urban environment experiences greater pesticide usage per square kilometer than the agricultural environment (163), and these calculations are even more impressive when the relatively heterogeneous spatial application of urban pesticides is compared with a rather homogeneous application on the farm. The resultant concentration (per square meter of treated surface) appears higher indoors. Surveys have shown that more than 75% of urban respondents use pesticides (21, 34, 65, 89, 163), and most pesticide usage is within the home (138).

Most studies of the chronic effects of pesticides have involved agricultural workers. The few urban exposure studies have been short-term evaluations of PCOs rather than residents. The effects of pesticides applied in the urban environment to manage pests in lawns, turfgrass, ornamentals, rights-of-way, and within the home have been reviewed (61, 70, 97).

Legislative Requirements

The need for effective pest management is particularly evident in the food industry. Therefore, the US Food, Drug and Cosmetic Act states that food shall be considered adulterated "if it has been prepared, packed, or held under insanitary conditions whereby it may have become contaminated with filth, or whereby it may have been rendered injurious to health." This clearly indicates that the presence of pests, not just contamination by pests, poses a health hazard in the food service or food-handling institution. In other sensitive environments such as airplanes, computer facilities, pharmaceutical or biomedical laboratories, and nuclear power plants, cockroaches may cause irreparable damage.

Thus, effective suppression of cockroach populations is needed to alleviate health-related problems and is mandated by federal and local regulations. Although a great number of reports show effective suppression of indoor cockroach populations with insecticides, direct comparisons show that apartments with pest control services and untreated apartments may support equal cockroach populations (85). Such findings illustrate the need to reexamine many of the current treatments that rely exclusively on insecticides and to adopt an IPM approach, using a similar conceptual framework as in agriculture. Other concerns, including management of insecticide resistance and requirements of specific sites (hospitals, schools) also support the adoption of IPM.

ECONOMIC DAMAGE AND AESTHETIC INJURY LEVELS

As in agriculture, the components of the urban IPM process vary, depending upon the specific requirements of the ecological, political, and economic community. Olkowski (110) argued that, in setting action thresholds, urban IPM programs must directly consider the sociological and psychological as well as economic needs of the public. He suggested use of the term aesthetic injury level (AIL), which subsequently has been widely adopted (see 112, 139, 176). Underlying this concept are sociological surveys to assess both the response of the human population to the pest population and the amount of money they would spend to alleviate the problem. Surveys of residents in Virginia, Maryland, Texas, New Jersey, California, and other states indicate that respondents have a low threshold to sighting cockroaches (89, 123, 171, 176), and thus argue for a low AIL. Yet, because pest densities are not measured objectively and because surveys generally are not rigorous, it is not clear how the AIL varies either with the specific surveyed public or with the size of the pest population, and what actions, if any, other than application of insecticides, should be implemented at various AILs. Zungoli & Robinson (176) concluded that the AIL varied positively (but weakly) with the level of the infestation, which suggests that implementation of IPM may become more difficult as the effectiveness of pest suppression increases. It also appears that AILs based on such responses of the public would become asymptotic at a level that would require pest eradication.

To date, no quantitative relationships are available between trap catches and cockroach population density, thus complicating the transition from an AIL based on sociological surveys to action levels based on changes in the pest population. Where programs to suppress cockroaches are implemented, action thresholds are based on arbitrary trap counts: The US Navy uses an average of 2 trapped cockroaches per night, whereas the US National Park Service prefers 2.5 cockroaches as an action threshold (in 170), although neither is based on an empirical understanding of the target pest or human populations.

The indoor environment consists of a variety of habitats, each with its own intrinsic level of pest tolerance and each affected by a specific set of aesthetic, economic, and public health concerns. For example, in greenhouses used for intensive agricultural production, action thresholds for cockroach damage are dictated by economic concerns, and a large choice of responses is feasible, including biological control. In residential settings, aesthetic and public health concerns dictate the action threshold. Aesthetic concerns vary greatly even within a seemingly homogeneous population, and the range of control options is limited. In hospitals the tolerated pest level may be zero, but the range of available control options is limited by public health concerns and strict regulations. Clearly, a range of AILs or an average AIL applied throughout the urban environment may not be very useful. More importantly, since management of the indoor environment should be an ongoing process even in the absence of indoor pests, the AIL concept may be reduced to an academic exercise. That is, although monitoring of pest populations may serve as a general guide to the implementation of pest management options, there appears to be no easily identifiable level at which one option is preferred over others. Therefore, estimates of AIL or Economic Injury Level (EIL) may be reduced to guides for insecticide applications only when all other approaches fail.

Surveys, as components of educational programs (see 123), are essential, especially when human attitudes and practices appear to obstruct implementation of pest management decisions. However, because their utility in setting action thresholds may be unclear, their objectives should be clearly defined at the outset.

DETECTION, SAMPLING, AND MONITORING

Sampling and monitoring indoor pest populations is both a long-term component of IPM and a first step of a well-planned inspection. Whereas the agricultural scout usually estimates pest populations through extensive sampling, the urban inspector evaluates the causes and sources of infestations mainly through intensive sampling of smaller areas. Cultural and business practices, such as traffic patterns of people and goods, may provide critical details about movement of the target pests. The cockroach population is distributed unevenly in a highly heterogeneous environment. Therefore, the inspection for cockroaches must rely on identification of appropriate microhabitats (moist, dark) in addition to intensive trapping.

Movement, Foraging Patterns, and Seasonality

The early literature on population dynamics, movement, and dispersal of cockroaches has been reviewed (47, 142). *Periplaneta* and *B. orientalis* appear to move relatively short distances outdoors, but the incidence and degree of movement from outdoor areas into homes is not known (26, 158). Recent data show that *P. fuliginosa* has a primarily arboreal distribution in association with treeholes (26).

Movement and aggregation of *B. germanica* vary, according to different studies, even at apparently similar population densities: adult males (113), nymphs (127), or adult females and mid-instar nymphs (30) dispersed more in the various studies. Movement of males decreases with population size in laboratory studies (53), but even in heavily infested apartments, movement was independent of population size (113). These discrepancies are at least in part explained by the fact that in the laboratory, field-collected insects moved less than laboratory-reared cockroaches (1).

Seasonal and demographic changes in cockroach populations, especially outdoors, require thorough monitoring if they are to serve as a basis for management decisions. Thoms & Robinson (159) suggested early summer insecticide treatments to suppress increasing adult populations of the oriental cockroach. Structural modifications, other cultural approaches, and inundative releases of oothecal parasitoids also must be carefully timed to coincide with seasonal abundance of sensitive life cycle stages.

Monitoring

The objectives of monitoring must be clearly defined. If monitoring is to be used as a quantitative evaluation of pest problems and of management procedures, unbiased tools are needed to facilitate the process. Barak et al (13) showed that population estimates based on trapped cockroaches did not confirm apparent reductions in the cockroach population based on subjective sightings of cockroaches by workers.

Trapping provides a more representative sample of the population and is less disruptive than visual counts of flushed cockroaches (114, 122). However, the relation between trapping efficiency in the laboratory and in the field is unclear (114), and trapped insects usually do not represent the local density or demography of the population. Baited traps appear to be biased toward attracting nymphs; sticky-surface traps are biased toward trapping adults, especially males; and small traps capture more small oriental cockroach nymphs than large traps (114, 159). Using numerous traps, Ross et al (126) concluded that high trap catches can locate infestations, but density and demographic estimates were influenced by differential movement of the sexes and various age-classes. Thus, in quantitative demographic studies, current use of common trapping methods, without a thorough examination of inherent limitations and assumptions, seems unjustified.

Although numerous reports show remarkable reductions in trap catches following implementation of control measures in research trials, Koehler et al (85) found an average of more than 13,000 cockroaches per apartment regardless of presence or absence of monhtly pest control services. As noted by Schal (140), the repellency of insecticides may result in seemingly large reductions in the population because traps are usually placed where insecticides are applied. Likewise traps are inefficient because they have a very limited capture space and do not sample cockroaches that retreat to deep, insecticide-free harborages. Traps with more attractive baits that can extend the reactive distance of cockroaches are clearly needed.

Attractants: Food and Pheromones

Common foodstuffs such as some soft drink syrups, brown sugar, molasses, and essential oils of banana, sweet orange, apple, and pineapple attract cockroaches in the laboratory (see 92, 132). Single volatile compounds that attract cockroaches include oleyl alcohol, palmitic acid, oleic acid, lauric acid, methyl myristate, cyclohexyl alkanoates, and n-alkyl cyclohexaneacetates (see 132). Currently, the best attractants are small amounts of beer in a bottle (166), white bread (10), and distillers' grain (28). Food attractants that are marketed commercially do not enhance trap catch (10, 122, 166) and are therefore ineffective in monitoring.

The females of most synanthropic species, except *Blattella,* produce volatile sex pheromones to attract males. However, only *P. americana* has been studied extensively in this regard (17, 143). In rice warehouses, significantly more male *P. americana* were trapped with crude pheromone extracts or with racemic sex pheromone than with control traps (37) and isomeric (+)periplanone-B increased trap catches significantly in both laboratory and field assays (19). Research suggests that trapped males may release aggregation pheromones that attract females and nymphs (19, 37). In addition to most blattid species, *S. longipalpa* (Blattellidae) females also produce a volatile sex pheromone of unknown structure (90). It does not appear that the contact sex pheromone of *Blattella* (see 108, 141, 144) will play a significant role in trapping.

Males of most species produce tergal secretions that both attract the female and place her in position for copulation. However, only three species, and none of any economic importance, have been examined in some detail (33). These secretions may be extremely useful in trapping studies, especially when adult females are the intended captures.

In *B. germanica,* 82% of tested adults chose resting places that had been impregnated with cockroach odors (24). The active components of the aggregation pheromone are produced in rectal pad cells and are excreted with feces (79). Cockroaches also aggregated on vertical strips of filter paper conditioned (contaminated) by conspecifics and, in some cases, by other cockroach species (129). Of 150 compounds isolated from *B. germanica* feces, 57 were carboxylic acids, and the aggregation pheromone may be some mixture of these acids (66; see also 98). Brossut (32) reviews the aggregation pheromone components from mandibular secretions of *Blaberus craniifer* and from whole body extracts of *Eublaberus distanti,* both of which are caverniculous species.

Practical use of aggregation and sex pheromones has been hampered by difficulties in identification and a lack of concerted research efforts. To date, no trials have been reported using aggregation pheromones or feces extracts in traps. Studies on incorporation of pheromones into insecticides are summarized below. Lack of efficient trapping methods for cockroaches is probably the most significant single factor contributing to a heavy reliance on scheduled applications of insecticides. Available trapping technology samples only cockroaches that happen to "blunder" into the trap. Traps therefore are inefficient and unreliable for routine pest management operations.

CULTURAL PRACTICES AND HABITAT MODIFICATION

Physical modification of the environment in which cockroaches live is the most important procedure for their long-term suppression. Such modifications can reduce resources that support population growth, facilitate movement that increases contact with residual insecticides, and reduce areas that require insecticide treatment. Cultural practices, such as proper construction and sanitation, are rarely used effectively in cockroach control programs. We provide several examples of how these factors can be integrated in a pest management scheme.

Sorptive dusts, such as the fluorinated silica aerogels, disrupt the outer wax layer of arthropods, which results in dehydration of the insect (51, 54). They are excellent materials for use in "built-in pest control" during construction (52), especially in areas such as wall and cabinet voids and electrical or plumbing ducts that are inaccessible after construction. They are effective against a broad spectrum of arthropods (51), which is clearly advantageous, but they should not be applied in areas to which parasitoids may have access. When corrective rather than preventive action is required in dry environments, nonrepellent inorganic dusts are more appropriate than sorptive dusts. Boric acid provides a persistent deposit that is easily picked up and ingested by cockroaches or absorbed through their cuticle (54). Rust (132) reviews the toxicity and potential applications of boric acid and borax against cockroaches and other household pest arthropods.

Structural Modification and Sanitation

Modification of existing structures can alter cockroach habitats, their routes of movement, and population dynamics. Sealing runways such as common plumbing and electrical ducts between structures is essential. Runstrom & Bennett (131) convincingly documented that movement of adult *B. germanica* between apartments is facilitated by structural features, especially plumbing. Cockroaches are often found in aggregations within specific microhabitats. Both nymphal development and adult reproduction are significantly more rapid in grouped insects than in isolated individuals (67, 168, 172). Thus, dispersion of aggregations through improved sanitation and physical modifications is likely to disrupt population growth.

Availability of food and water can influence the distribution of cockroaches. German cockroaches released on a ship tended to remain close to water and food even after disruption by insecticides (125, 127). Increased movement of cockroaches deprived of food and water, and the influences of food placement on foraging patterns (150), suggest that improved sanitation may disrupt the population, or at least alter movement patterns, which may bring individual cockroaches more quickly in contact with deposits of residual insecticides or toxic baits. Similarly, the dependence on water for survival and reproduction (4, 47) emphasizes the need to control moisture in order to reduce cockroach populations. The size of allergenic mite populations is also directly dependent upon the relative humidity (7).

Although there is a significant positive correlation between reduced cockroach numbers and improved sanitation (140, 149, 173), structural modification, consisting exclusively of sealing and caulking, and cleaning have generally failed to reduce cockroach populations to acceptable levels (60, 158; see also 96). However, because population densities are usually unknown, both visual sightings of cockroaches and trap catches may in fact reflect increased movement in a stressed population due to disruption of preferred habitats. Indeed, foraging patterns and the spatial distributions of cockroaches were disrupted by structural modification and household cleaning (20).

Proper sanitation directly influences other management procedures. Adequate sanitation has many benefits: It increases the efficacy of caulking as a means of reducing cockroach habitats (60); insecticides are more effective in clean environments (71, 140); and cockroach populations increase more in untreated apartments with poor sanitation than in apartments with good sanitation (140). Although pyrethroids are very effective against cockroaches on clean glass surfaces, their activity is significantly reduced by unsaturated surface oils (137). Thus, the greater efficacy of cypermethrin in clean than in cluttered, greasy apartments (140) may have been due to such interactions. Poor sanitation is viewed by the public as a major cause of pest problems. However, residents prefer insecticides over improved sanitation as a means of cockroach control (171). Therefore, educational programs are particularly important where unsanitary conditions hinder pest control efforts.

Modification of outdoor habitats discourages reservoirs of insects that may subsequently enter homes (117). Sealing of treeholes may suppress populations of the smokybrown cockroach in southern regions (26). The Asian cockroach *(Blattella asahinai)* is attracted to lights (29), so outdoor lighting may need to be modified to reduce the attractiveness of buildings.

Current practices of warming structures with diffuse radiative and convective heating support cockroach infestations throughout the structure. Cockroaches are sensitive to freezing and to temperatures 10 °C above their optimum range (4). Therefore, treatment with heat or freezing temperatures, especially of food carts and vending machines in hospitals, can reduce local pest populations.

Repellents

We consider repellents as a form of structural modification rather than as chemical components of population suppression. It is important therefore to distinguish between repellents that lack insecticidal activity and insecticides with repellent properties. Repellents may be used as preventive tools in the transport and storage of merchandise (e.g. returnable bottles) and in protecting sensitive equipment such as computers (48). For these applications, repellents must have low mammalian toxicity and long residual activity. Currently, there are no commercial repellents that can be applied to large areas in order to create "pest exclusion zones." Also, the ultrasonic devices currently in commercial use, which purport to repel cockroaches, are ineffective at disrupting either the distribution or size of cockroach populations (e.g. 69).

Under crowded conditions, *B. germanica* produces repellent, nonspecies-specific salivary proteins (104). A close correlation between secretion, feeding, and the ovarian cycle (128) suggests that secretions may act as alarm or defensive mechanisms. These materials may serve as important chemical templates in the design of similar repellents for use in pest control.

Trapping

Several studies report effective reduction of populations through mass trapping (e.g. 116, 117), but most work does not support this conclusion. Daily trapping of *B. germanica* in experimental chambers reduced the population only when the number of cockroaches exceeded the available shelters (122), and in the field, removal of 7,600 cockroaches per home with up to 36 traps for 8 weeks did not reduce cockroach populations by more than 30% (12). Mass trapping therefore does not appear to be a viable option, particularly because effective attractants are not available.

BIOLOGICAL AND GENETIC APPROACHES

Biological control includes the study, importation, augmentation, and conservation of natural enemies in order to regulate densities of pest populations. With the exception of outdoor populations of public health pests (e.g. mosquitoes), most examples of urban biological control have resulted from the application of successful agricultural controls to the horticultural and silvicultural environments. In urban environments synanthropic cockroaches (and other household arthropods) are disassociated from their natural enemies. Thus, populations are regulated primarily by abiotic and density-related factors rather than by coevolved guilds of parasitoids and pathogens.

Parasites have been used with some success to reduce populations of the American, oriental, and brown-banded cockroaches. Rates of oothecal parasitism average 25% but may range as high as 84% in outdoor populations of *Periplaneta* species parasitized by the eulophid wasp *Tetrastichus hageno-*

wii (62, 73, 118). However, Narasinham (105) showed that *T. hagenowii* was outcompeted by *T. asthenogmus* in inoculative releases and that both primary parasite populations were reduced by the obligatory hyperparasite *Tetrastichus* sp. *A*. Large seasonal population fluctuations, short lifespan, low fecundity, and thermal sensitivity suggested that both parasitoids were relatively ineffective in homes (105).

Inundative and augmentative releases of the encyrtid parasitoid *Comperia merceti* decreased populations of the brown-banded cockroach in university research facilities (45, 152). At high oothecal densities, rapid declines in the cockroach population, progressive changes in the age structure (initial decline in small nymphs followed by declines in medium and large nymphs), and increased parasitism rates indicated effective control (45). However, the parasitoid was relatively ineffective when cockroach densities were low, and large numbers of parasitoids had to be added to maintain wasp densities (45, 152).

Viruses, fungi, bacteria, and protozoa are potentially useful in controlling cockroaches because of their passive dispersal, environmental safety, potentially high specificity, and undetectability in the home. Tsai & Cahill (161) found nine parasitic nematode species in surveys of *B. germanica* in New York City, but studies of pathogenicity of the worms, their life histories, and interactions with the cockroach have not been pursued since this preliminary report. Zervos (174) isolated several nematodes from blattellid cockroaches, but, again, their role in the population dynamics of cockroaches remains to be investigated. Lethal hemocoelic yeast infections, recovered from *B. germanica* (5, 6) and *P. americana* (162) inflicted extensive damage to the fat body, hemocytes, antennal flagella, and wings. Pathogenicity of some *Candida* yeast species to humans dictates the need for careful studies before these isolated organisms can be used against cockroaches (162).

Mass releases of sterile males are potentially useful against cockroaches because they can be easily reared and sterilized in the laboratory, females usually mate only once (38), laboratory-reared *B. germanica* males that are heterozygous for chromosomal translocations assimilate into natural populations and are competitive with wild males (127), and females fertilized by sterile males produce oothecae of limited viability. Because the combined efforts of many hatching embryos are needed to open the ootheca, lethality of 80% of the embryos may "trap" all the progeny within the ootheca (82). Multiple releases of heterozygous males with double translocations reduced laboratory populations of the German cockroach by 98% within eight to nine months, but release rates of nine sterile males to one normal male were required (124). Following insecticide treatment to reduce field populations, the release of genetically altered males (an estimated ten released males to one resident wild male) yielded mixed results: Sterile males tended to remain at the release sites, resulting in a high degree of female sterility and population suppression in those areas; however, nymphs dispersed from the area of insecticide treatment and founded new populations in untreated areas (127).

Numerous constraints operate on biological and genetic indoor controls. Low relative humidity, low light levels, and a highly heterogeneous environment present a hardship to most parasitoids, entomophagous nematodes, and microbial pathogens of insects. The cryptic oviposition behavior and nocturnal foraging of cockroaches, as well as physical barriers of urban structures, compound the difficulties of parasitoids in locating their hosts. Also, differential attraction of pests and their enemies to features of the urban habitat (e.g. lights, moisture) may create barriers between the two. Low air circulation indoors, especially in the voids, cracks, and crevices occupied by cockroaches, hinders the passive dispersion of spores and conidia of pathogenic fungi, thus limiting the initiation and maintenance of epizootics. Persistence of insecticide residues poses a serious challenge to the implementation of biological control programs, particularly where perimeter applications of insecticides may reduce outdoor refuges of parasitoids (see 117).

Human tolerance of arthropods is very low. Therefore, the public expects parasitoids and predators to reduce pest populations to lower densities than those required in agricultural situations. This is clearly not feasible, since parasitoids and predators track pest populations and are most effective at higher pest densities (see 45). In the absence of educational programs, the parasitoid itself is viewed as a pest (e.g. 157), hindering both implementation of biological control programs and their evaluation. In sterile male releases, although the increase in the cockroach population may be temporary, the required release rates may result in significant increases in chronic problems such as asthma, dermititis, and various allergic reactions.

The importation, periodic release, and efficacy assessment of natural enemies are more costly, require much greater effort, and are subject to more failures than applications of broad-spectrum persistent synthetic pesticides. As a result, few studies of the potential of biological control in the urban environment have been undertaken. Where such efforts have been attempted, most have been descriptions of short-term population fluctuations, with little effort devoted to tracking host-parasite population densities through several cycles. Too often, biological control options are disregarded because they are thought to be of limited usefulness in solving all pest problems. It is important to consider biological control in the context of an integrated approach, particularly in areas where pesticide usage is reduced because of specific regulations or fear of environmental or nontarget exposure. The integration of relatively safe insecticide baits and parasitoids exemplifies this approach (73).

In special situations, control of cockroach populations with predators, parasitoids, and genetically altered insects may be more feasible. These approaches generally become more feasible on a continuum ranging from indoor settings with sanitary, public health, and aesthetic concerns, to locations involving less human contact (warehouses, sewers, dump sites), and finally to the pseudo-agricultural setting of greenhouses, where economic injury is more readily measured and there is minimal human interference.

CHEMICAL APPROACHES

Timely, proper, and judicious application of safe formulations of insecticides to areas that harbor cockroaches may provide short-term suppression of cockroach populations. The treated area should be minimized and the efficacy of the insecticide maximized with proper sanitation, structural modification, application of repellents to adjoining areas, and the use of pheromones and other attractants to increase contact with cockroaches. Yet, both consumers and PCOs favor scheduled applications of insecticides with long residual activity because they provide longer intervals between treatments. The usual practice of initial applications at a high rate, followed by regularly scheduled (usually monthly) applications at lower rates, may result in a gradual decrease in both insecticide residues and efficacy (11, 103), which may accelerate the development of resistance. Only when effective monitoring tools become available will scheduled treatments be replaced by judicious timely application of insecticides.

A "crack and crevice" approach to indoor cockroach control was adopted in the US in 1973. Accordingly, insecticides must be directed into areas that harbor cockroaches in order to reduce both the amount of insecticide applied and environmental and food contamination. Because cockroaches prefer small spaces (24), applications to cracks and crevices are a rational biological approach that reduces German cockroach populations more effectively than a broad application of insecticidal spray (175). Other methods of application, such as controlled droplet indoor space treatments, are less effective against cockroaches (e.g. 99). Also, applications outdoors are less effective than treatments of specific, delimited pest habitats. Brenner's (26) findings of a vertically distributed outdoor cockroach population inhabiting treeholes clearly points out the limitations of broad perimeter spraying.

Insect Growth Regulators

Insect growth regulators (IGR) target specific developmental stages. Therefore, their use in agriculture requires reliable monitoring techniques and predictive models of population growth. However, asynchronous and overlapping generations with a large percentage of immatures in most cockroach populations enhance the efficacy of IGRs at any time because the insect progresses through stages that are developmentally sensitive to the IGR.

Juvenile hormone analogs (JHAs) interfere primarily with molting in last instar cockroach nymphs (87, 155), but other roles of juvenile hormone in melanization, regeneration, and normal female reproduction including pheromone production, sexual receptivity, mating, activity of the colleterial glands, and oocyte development (68, 141) have been overlooked in the development and use of JHAs. Because the JHAs are relatively slow acting (four to nine months), they are often combined with residual insecticides and the combination usually outperforms conventional insecticides (23, 27, 109). Antijuvenile hormone agents have been examined in laboratory assays against several cockroach species (154), but, to date, none is available commercially.

Inhibitors of either chitin synthetase or chitin polymerization are faster acting and can impact a much larger range of sensitive stages in the cockroach life cycle. Diets containing chitin synthesis inhibitors result in abnormal molting by nymphs and deformed oothecae and also inhibit oothecae hatching in the German cockroach (84, 165), but none are available commercially.

Repellency of Insecticides

Insecticide efficacy is inversely related to repellency in choice assays (55). Repellent sprays are therefore incompatible with residual activity, and there appears to be no advantage to either repellency or the "flushing action" of residual pyrethroids. Indeed, as metabolic, physiological, and behavioral resistance develops in the pest population, the flushing action may result in a "learned avoidance" of insecticide deposits. The heterogeneous habitat of cockroaches includes discrete areas with low insecticide residues, which would favor the development of hypersensitivity to avoid irritating insecticides. However, although no differences between strains were found in the field (125, 135), insecticide-resistant strains in the laboratory dispersed less than susceptible strains in response to insecticide vapors (22, 31), which suggests that resistance may be accompanied by some general loss of sensitivity.

Cockroach feces and their odor reduced the repellency of insecticide formulations, and an extract of *Blattella* feces increased insecticide efficacy in the field (22, 133, 134). Recent findings of repellent components in polar fractions of feces suggest that the efficacy of insecticides could be improved even more with further chemical fractionation of the extract. Similar results were obtained with isomeric (+)periplanone-B, which stimulated locomotion of *P. americana* males, females, and nymphs, and increased mortality on insecticide-treated panels in the laboratory and in warehouses (19). These results support the hypothesis that repellency hinders the toxic activity of insecticides (55) and suggest that pheromones should be used to increase their efficacy.

Toxic Baits

Toxic baits have an important role in cockroach control because they allow insecticides to be placed in delimited zones and they reduce potential environmental contamination. Some baits may be used almost anywhere including sensitive areas such as hospitals and biomedical laboratories. The intimate association between feeding, molting cycles, and reproduction (40, 74, 75, 88) underlies the utility of baits in cockroach control. However, most of the toxicants used in commercial baits are also used in residual sprays (95, 132), and toxicants with high acute toxicity tend to repel cockroaches from baits (136). Comparisons of acutely toxic (iodofenphos) with less acutely toxic baits (boric acid) showed that the effectiveness of both was increased in the absence of alternative foods or water, but in the presence of other food, boric acid was more effective than iodofenphos (14).

Boric acid, avermectin (41), hydramethylnon (e.g. 101), and some of the fluoroaliphatic sulfones are more effective than conventional insecticides in baits against cockroaches, but there are no empirical data to show whether their superior performance is specifically due to low repellency, efficacy at lower dosages, different modes of action, lack of resistance, or delayed activity.

In addition to attractants, which were discussed earlier, starch, glucose, sucrose, mannitol, maltose, sorbitol, and glycerol either stimulate feeding in cockroaches or increase consumption and efficacy of baits (see 132). Polyols, such as sorbitol, mannitol, and glycerol, act as "humectants" to stabilize and maintain moisture content in the bait over long periods. Because moisture is a limiting resource for cockroaches, and they possess hygroreceptors to detect and orient to moisture (3), humectants may increase attraction, acceptability, and efficacy of baits. Yet, few attempts have been made to integrate knowledge about feeding preferences and physiology into bait design. Commercial hydramethylnon baits, which contain a "non-insecticidal, wax-like substance containing oatmeal and lard" (94), illustrate the need to integrate research on cockroach nutrition into bait development.

Most toxic baits may be easily integrated into management programs of other household pests, including ants (e.g. 167). In the laboratory, a bait mixture containing a rodent bait and boric acid was effective against cockroaches and more effective against rodents than the original rodenticide bait (91). Physical modifications and sanitation are critical where baits are used: Competition with local water and food reduces their effectiveness. Aggregation of cockroaches and the ready movement of materials among them should facilitate the use of pathogens in attractive baits to encourage epizootics (see 148). Some toxic baits can also be used to reduce cockroach populations sufficiently so that genetic controls and inundative releases of parasitoids can be used. Baits were shown to have no adverse effects on parasitoids (73).

Insecticide Resistance

Although resistance in some urban pests has been studied intensively, this information has not been effectively used in practical pest management. Instead, relatively resistant populations are usually battled with higher doses of residual insecticides that are applied more frequently.

SURVEYS AND DOCUMENTATION A historical perspective on resistance in cockroaches is presented by Cornwell (48). Resistance in field populations to propoxur, diazinon, and malathion was noted 4, 5, and 14 years, respectively, after their initial use in the US. Bendiocarb resistance is common in German cockroach strains that had never been exposed to bendiocarb (15, 107). A recent survey of feral German cockroaches observed widespread heterogeneity in organophosphate resistance among strains, with generally low levels of resistance to acephate and chlorpyrifos, moderate resistance to diazinon, and high levels of resistance to malathion (44).

However, various methods of resistance testing yield disparate results. The continuous surface exposure test showed low resistance to propoxur and chlorpyrifos compared with other tests (46, 102); a DDT-selected strain of the German cockroach was highly cross-resistant to pyrethroids when exposed by topical application, but only moderately cross-resistant by the surface exposure method (147). It is particularly important to account for such discrepancies when laboratory-derived resistance profiles are used by Extension personnel as a basis for recommending alternative insecticides in order to manage resistance (e.g. 107, 123, 140).

Insecticides may cause premature dropping of oothecae by German cockroaches (16, 76, 77), which often fail to hatch. Oothecae were dropped more frequently in susceptible females than in resistant females, suggesting behavioral resistance (e.g. 76, 77). However, because ingestion of nonrepellent insecticides, such as boric acid, can also result in abortion of the ootheca (14), physiological resistance appears to be involved: At a sublethal dose for susceptible insects, which causes premature oothecal drop, resistant insects are unaffected, whereas at higher doses (lethal for susceptible insects) resistant females drop their oothecae. Thus, thorough dose-response studies are required before a mechanism of behavioral resistance can be assigned to an observed phenomenon.

RESISTANCE MANAGEMENT Because insecticides have optimal thermal ranges for maximal efficacy, temperature indoors may be regulated accordingly. For example, the effectiveness of propoxur increases above and below ca 25°C and at low humidity (121). For the German cockroach, the toxicities of some pyrethroids and hydramethylnon are higher at higher temperatures (146, 151). Because activity of German cockroaches increases at higher temperatures, this positive temperature coefficient may be important with toxic baits and to a lesser extent with residual insecticide deposits, particularly in multi-unit housing and hot kitchen areas. Modulation of ambient temperature is thus an important feature, which is not available in agriculture. Unfortunately, it is often ignored in cockroach control.

Development of resistance in cockroaches is poorly understood. Resistance to bendiocarb increased significantly after only a single application of bendiocarb to a dieldrin-resistant field strain of the German cockroach (15). Selection with permethrin in the laboratory failed to confer resistance to a field-collected pyrethrin-susceptible strain, but did so within one generation to a field-collected pyrethrin-resistant strain (43). Resistance to pyrethrins is followed by high-level resistance to allethrin and, as selection continues, resistance to other pyrethroids may develop (43). Initial resistance is largely metabolic, but other mechanisms, such as *kdr* (e.g. 145), may follow with continued selection. This is particularly alarming in many developing countries where pyrethroids directly succeeded DDT without the intervening use of organophosphate and carbamate insecticides.

In many insects, organochlorine, carbamate, and pyrethroid resistance tends to be more stable than organophosphate resistance, but no comparative data are available for cockroaches. Early work on DDT resistance indicated that German cockroaches revert to susceptibility nine generations after release from selection in the laboratory (see 48), but no comparable data are available for other insecticides. Stability of resistance must be addressed in order to evaluate whether insecticide rotation is a viable strategy. IGRs and other nonconventional insecticides may offer an important tool for resistance management because they may be used to relax selection when resistance to other insecticides has developed.

Mixing or alternating chlordane and malathion appeared to retard development of resistance in German cockroaches, but only for several generations (see 48). Similarly, although it is assumed that the interaction between IGRs and organophosphates is additive (e.g. 23, 27, 109), it may be synergistic. In the house fly, cypermethrin is synergized better by fenoxycarb than by methoprene, indicating that the synergistic effect may be due to structural features of the molecule rather than to JHA activity (78). If this is true for cockroaches as well, it suggests closer scrutiny when combining IGRs and conventional insecticides. However, Metcalf (100) argued against mixtures of insecticides because they may select for multiple resistance. In the house fly, microsomal oxidases that confer resistance to conventional insecticides are also involved in resistance to JHAs (e.g. 35), but no comparable studies have been conducted with cockroaches.

The most common approach to managing resistance (or, rather, enhancing susceptibility) in the German cockroach is to use metabolic synergists. Resistance to bendiocarb and pyrethrins in field strains can be overcome, and insects are rendered nearly susceptible with piperonyl butoxide and MGK 264; commercial preparations of these mixtures are also effective in the laboratory against field-collected resistant cockroaches (42). However, following selection of pyrethrins-resistant feral cockroaches with fenvalerate (in the laboratory), resistance to various pyrethroids could not be reduced with PBO or MGK 264 (43). The long-term consequences of applying synergists to cockroaches are unknown; although they may retard the development of resistance, it is possible that they may select for different resistance mechanisms. Resistance to synergists has also been reported in several insects.

TECHNOLOGY TRANSFER, IMPLEMENTATION, AND CONSTRAINTS

Implementation of urban IPM programs is complicated by the diffuse allocation and control of resources among residents, landlords, businesses, local and federal agencies, extension personnel, consultants, and PCOs. Because of considerations of space and expertise we exclude the role of policy makers and regulators and concentrate on practical aspects of the process.

Cost Assessment

Residents on the managed site (i.e. the farmer or urban resident) experience different pressures in agriculture and in the urban situation. Reduction of aesthetically displeasing pests that also may create public health hazards are primary goals in residential situations, whereas the primary objectives in agriculture are to reduce costs and maximize gains. Thus, decisions to adopt IPM programs are based on fiscal advantages in agriculture, while pesticide resistance, environmental issues, and grower hazard usually follow in importance (164). In urban IPM, there may be no measurable short-term financial benefit to the resident. Indeed, in switching away from chemically dependent programs, the resident will experience added costs because the relative expense of insecticides is minor compared to labor costs, such as the time required for PCOs to study the design and construction of each structure and the implementation of monitoring, structural modifications, and other options. It is therefore expected that, in the private sector, costs of integrated programs will be higher than conventional pest control, and the added benefits of reducing insecticide usage will ameliorate added costs to the consumer.

However, Robinson & Zungoli (123) were able to reduce pest control costs from $68 to $44 per apartment after implementating an IPM program. This saving was attributed to a reduction in the cockroach population that resulted in reduced insecticide applications; it is not clear what non-insecticidal measures were used to stem a resurgence of cockroaches. Because repeated applications of insecticides continue despite the fact that most field trials report 90–100% reductions in the cockroach population, it is doubtful that such cost reductions can be sustained when such a program is privatized.

Technology Transfer and Education

There is a need to study and shape human attitudes and practices through educational programs (64, 65, 89, 106, 139). Where past control programs have attempted to educate the public, residents have usually responded positively (123, 160). Thus, Thoms & Robinson (157) report that after educating residents about parasitoids of *B. orientalis,* acceptance of the wasps within their homes increased from 11% to 70%. Similarly, Robinson & Zungoli (123) describe an effective program in which cooperative extension personnel, using surveys and educational programs, have successfully altered public attitudes toward cockroach control in public housing in Virginia: The number of residents who endorsed cleanliness as an important component of pest suppression increased following educational and training sessions.

Current practices of education and technology transfer address a multitiered system with information flow from academic and industrial research and development, through Cooperative Extension personnel and consultants, to sanitarians, pest control professionals and managers, and eventually to the general public. The urban public is at a distinct disadvantage. Most land grant institutions in the United States are based in agricultural districts where they are charged with supporting the agricultural community. Extension entomologists usually service a manageable number of agricultural advisers and growers (164), and the tendency is to ignore the distant but more populous urban regions, where the ratio of Extension personnel to the urban population is much smaller.

In the US, all 50 states require passage of written examinations to gain a certificate to apply pesticides commercially. In most states, the applicant is required to pass examinations in general pest biology and control, in specific categories, such as wood destroying pests, and in specialized procedures, such as fumigation. In many states, the pest control industry has initiated training and certification programs. Thus, the PCO should no longer be viewed as an "exterminator"; her/his role as an educator is critical to an effective IPM program. Surveys in California, Texas, and New Jersey indicate that the majority of residents use the PCO either for services or as an information source (89). Right-to-know laws and pesticide application ordinances now legislate even greater interaction between consumers and PCOs. Indeed, because of greater concern with IPM, some pest control firms in the US have integrated janitorial and custodial services into their programs to facilitate coordination of structural modification and pest control.

As in agriculture, technical obstacles are usually greatest in the early stages of IPM implementation. Thus, the lack of simple and reliable monitoring tools and a poor understanding of action thresholds are currently the greatest obstacles to urban IPM. However, focused attention by researchers and extension personnel on these areas should facilitate the adoption of IPM programs.

An important obstacle to implementation of IPM is that some PCOs are averse to the concept of not spraying when pest populations are low or even eradicated. PCOs, like farmers, have experience with chemicals and equipment for application; the cost of advice from the larger number of chemical sales personnel is hidden in the price of the chemical, and chemicals are sold with good marketing skills (164). Frankie et al (64) point out that similar marketing strategies must be used to advance IPM programs in urban areas.

Several reports have noted that in the US most urbanites buy their pesticides in grocery stores, hardware stores, and lumber yards (see 64). Therefore, information regarding these pesticides likely reaches the consumer either via the pesticide label, through advertising, or on the advice of less than qualified sales personnel. Frankie et al (64) report preliminary data on a project to promote a Cooperative Extension publication on pesticides at grocery stores. This marketing approach to education and technology transfer appears to be a successful and cost-effective means of reaching the public.

CONCLUSIONS AND FUTURE PROSPECTS

We have attempted to outline the various tools available for indoor urban IPM. Although we used cockroach populations to illustrate the process, other arthropods would be affected in a similar manner by these approaches. However, in spite of the plethora of available options, current urban pest suppression relies heavily upon multiple applications of broad-spectrum insecticides to ecological islands, with little appreciation of the boundaries of the habitat, mobility of the target pests, and interactions with natural enemies. Where so-called integration of management options has been proposed or employed, it has usually consisted of mixing several related insecticides.

Recent regulation of indoor pest control has resulted in greater emphasis on education and communication among researchers, Extension personnel, consultants, PCOs, and the concerned public. We expect that through such interaction, interest in IPM will emerge. Luckmann & Metcalf (93) estimate that five to 25 years are required to modify agricultural practices and educate growers to recognize the benefits of IPM. This process is just now beginning in the urban sector. In 1980 US federal agencies adopted an IPM policy (50); in 1981 State Cooperative Extension Services met to discuss development of urban IPM programs (59). In 1988, urban IPM has become one of five major research initiatives identified by the US Council of Entomology Department Administrators (49).

In 1980, the greatest expenditures on pest control activities by 16 US federal agencies were in implementation of suppression of pests, almost exclusively with pesticides (50). Expenditures on urban and public health concerns ranged from 0 to 100% of the agencies' budgets, but of these, 94.3% (SE=8.4, range 75–100%) was spent on suppression and very little on monitoring and research. It is clear that in order to adopt an IPM approach a sound research base is needed.

Research is needed on foraging ecology, habitat specificity, food preferences, attractants, and new toxicants with reduced environmental impacts, including pro-insecticides that are selectively activated by the target organism, hormone analogs including both isoprenoids and peptides, and anti-hormone compounds. Research on pheromones and food attractants is critical to the development of effective traps for monitoring and detection. Further research is necessary to elucidate the public health impact of cockroaches and other household arthropod pests by using modern immunoassay techniques to measure indoor insect allergens. Similarly, risk assessments of indoor exposure to insecticides are needed in order to evaluate application techniques. More objective surveys of residents and PCOs, conducted by professional social scientists, are essential in order to assess the public's needs, likes, dislikes, and areas requiring educational input. Laboratory investigations are needed on the behavior of parasitoids on egg cases, isolation of kairomones, development of rearing technologies, and response of parasitoids to insecticides. Environmental factors, such as temperature and humidity, should be evaluated to determine whether they can be exploited to increase the efficiency of cockroach population management. It is important to determine what insecticides are currently used for the control of cockroaches, their impact on control, and the prevalence of resistant populations. A thorough evaluation of the methodology of resistance monitoring is needed, including the relationship between behavioral and physiological resistance. Lastly, as insecticide resistance becomes more prevalent, resistance management strategies will be needed.

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