INSECT MANAGEMENT IN FOOD PROCESSING FACILITIES

JAMES F. CAMPBELL, FRANK H. ARTHUR, AND MICHAEL A. MULLEN

United States Department of Agriculture
Agricultural Research Service
Grain Marketing and Production Research Center
Manhattan, Kansas 66502

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I. INTRODUCTION

After harvest, as grain is stored, converted into processed commodities in food processing facilities, stored in warehouses, transported, displayed on retail shelves, and ultimately held in consumer pantries it is continually under pressure of becoming infested and degraded by insects. There are unsubstantiated estimates in the literature that claim 5–10% of stored grain in developed countries and 35% of stored grain in developing countries are lost to insect damage (Boxall, 1991). In many parts of the developing world, stored grain loss due to insect consumption and contamination can range up to 75% and directly threaten human health (Gorham, 1991). In the developed world, direct loss of grain material due to insect feeding is typically of less concern than contamination of food products. Tolerance for insect infestation of processed food for human and animal consumption is very low, and the direct and indirect cost to the food industry of insect infestation of grain-based products is substantial.

There are limited data on the economic cost of stored-product insects to the food industry, partly due to either difficulty in measuring the economic impact or reluctance to release the information. The diversity of commodities and facilities and the movement and blending of the commodity as it moves through postharvest systems make it difficult to estimate the impact of stored product insects. In bulk storage, insect damage is only a direct cost if the grain is rejected due to high levels of insect damaged kernels or assigned a lower grade, but the market penalties are set by the individual grain buyer and managers can manipulate damage levels by blending grain (Hagstrum *et al*., 1999). Therefore, discounts for insects are highly variable and do not provide much incentive for controlling insects. Domestic flour millers have a zero tolerance for live insects (Kenkel *et al*., 1993), and the presence of insects can result in the rejection of grain, which produces additional expenses associated with insecticide treatment, usually fumigation, and extra transportation costs. These additional costs of rejected loads can be as much as 10–20% of the value of the grain (Hagstrum *et al*., 1999). Estimates of the cost of grain loss due to insect, mold, and mycotoxin damage to the 15 billion bushels of grain stored in the United States each year have ranged from $500 million (Harein and Meronuck, 1995) to in excess of $1 billion (Cuperus, 1995). The only costs that can be calculated accurately for insect damage in stored grain are costs for insecticides, which include contact insecticides and fumigants, and these costs can be quite high. Costs for empty bin treatments range from 0.033 to 25.9 cents/ton and the costs to fumigate bins range from 58.09 to 86.95 cents/ton, depending on the type of structure (Hagstrum *et al*., 1999).

For processed cereal products it is the contamination of the food that is the major issue rather than loss of food material due to consumption by insects. Stored-product insects can add fragments to food that can indicate that the food is adulterated, cause a health hazard, and provoke allergic reactions (Olsen, 1998; Olsen *et al*., 2001), produce excretions that change the taste of food, and potentially carry disease-causing microorganisms (Foil and Gorham, 2000). Infestation of packaged commodities also imposes costs associated with loss of customer good will, degradation of commercial brand identity, failure to meet regulations or pass plant inspections, and handling of product returns and consumer complaints. There are also expenses associated with preventing and treating insect problems in facilities such as fumigation and sanitation. All segments of the food industry are susceptible to insect infestation (baking and confectionary, grain processing, cereals and prepared dry mixes, pasta, canning, meat and poultry, dairy, and frozen foods), but clearly segments that handle whole and processed grain will spend more on stored-product insect management.

Although considerable progress has been made in the protection of stored food using integrated pest management (IPM), many sectors of the food industry still depend primarily on chemical methods, and as chemical control options diminish, the potential for a significant increase in losses could correspondingly increase. Despite the low tolerance for insects in food by consumers and the food industry, pest infestations are still a problem. Surveys of insects in food plants, warehouses, and retail environments frequently document insect populations (Arbogast *et al*., 2000; Campbell *et al*., 2002; Doud and Phillips, 2000; Evans and Porter, 1965; Good, 1937; Zimmerman, 1990). Prevention and treatment of insect infestation of food are ongoing processes for the food industry that require careful monitoring and the application of multiple tactics to be truly effective. Pest management is complicated because a wide range of insect pests infest food, facilities along the food processing and distribution channels are highly variable, pest management within a facility requires continuous monitoring and adjustment of tactics to meet changing conditions, and often different groups of people are responsible for pest management at different points along the food distribution channel.

The goal of a modern integrated pest management program is preventing problems and targeting interventions in both space and time. This approach relies on an understanding of pest biology, behavior, and ecology within the context of food processing and storage facilities. Unfortunately, all too often pest management decisions are made without adequate information about pest populations, which can result in treating when and where treatment is not needed or not treating when and where treatment is needed. The food industry has relied on calendar-based pesticide applications, often applied to the whole structure, but is currently facing profound changes in how pest management is conducted due to the pending loss of many chemical tools (e.g., methyl bromide fumigation) on which they previously relied.

There is a long and productive history of scientific research on stored-product insect biology, behavior, ecology, monitoring, and pest management, but the emphasis of the majority of this work has been on insects in bulk grain. This emphasis has been changing and advances are being made in our understanding of how to manage pest populations in environments such as mills, food plants, warehouses, and retail stores. This article presents an overview of the status of integrated pest management of stored-product insect pests in the processed food industry.

II. FOOD PROTECTION REGULATIONS

Modern food preparation typically occurs in large processing facilities and involves the production of food for thousands of people. Because of the risk of contamination, food processors in the United States are obligated to provide a contaminant-free product for consumers. To enforce these obligations there are laws and regulations that provide guidance on proper practices in food processing. Consumer acceptance and satisfaction are also important factors driving the production of contaminant-free products because consumer tolerance for the presence of insects or insect damage is very low. If an insect is found in a packaged food, the consumer is not only hesitant to purchase the product in the future, but will also tell other consumers about their bad experience and thus compound the negative impact. Allergic reactions to food contamination are also an important issue and its importance is increasing. As a result, food producers are sensitive about issues involving food quality and safety. However, because of the way processed and packaged food is distributed, it is possible for products to become infested anywhere along the distribution channel, not just at the point of manufacture.

Food laws and regulations have played a major role in the purity and quality of our foods and in driving pest management decisions by the food industry. In the United States, the national U.S. Pure Food and Drug Act was passed by the Congress in 1906 in response to two historical circumstances: change from local distribution of food products to national and export distribution and the development of new methodologies to detect adulteration in foods (Von Elbe, 1982). This act prohibited the adulteration or misbranding of food and drugs to protect public health and to secure fair commercial trade. It prohibited interstate commerce of products that were adulterated or misbranded, but gave no authority for action against facilities where products were processed or manufactured and no authority to inspect warehouses.

A revision of the Pure Food and Drug Act, the "Federal Food Drug and Cosmetic Act," passed in 1938, added several provisions that impacted the food industry. Among those provisions were authorized factory inspections and the authority for court injunction to the previous seizure and prosecution actions (Janssen, 1992). Adulterated food was now defined as: "Sec. 402, A food shall be deemed to be adulterated if it consists in whole or in part of any filthy, putrid, or decomposed substance, or if it is otherwise unfit for food, or if it has been prepared, packed or held under unsanitary conditions whereby it may have become contaminated with filth, or whereby it may have been rendered injurious to health." The importance of the *whereby* clause is the concept that a food product need not be contaminated physically to be considered adulterated, but has been exposed to conditions that may have resulted in contamination of the food. This situation is vastly different from that which existed at the time the 1906 Food and Drug Act was passed.

Even though the Food, Drug, and Cosmetic Act of 1938 provided for factory inspections by the Food and Drug Administration (FDA), there was no published guideline for what would constitute conditions "whereby" a food may have become contaminated. In 1969, the FDA promulgated a regulation, "Human Foods: Current Good Manufacturing Practices (Sanitation) in Manufacturing, Processing, Packing, or Handling." This regulation and its revision have outlined conditions and criteria that were considered acceptable practice for producing foods under sanitary conditions. New approaches designed to prevent hazards to food safety from food pathogens, such as hazard analysis critical control points (HACCP), which is currently mandated by FDA for only some food products (e.g., seafood, fruit juices) but which has also been incorporated into FDA's food code and may be expanded to cover other food materials in the future (Hui *et al.*, 2003), may impact insect pest management.

There are three major categories of filth and extraneous material that constitute contamination: potentially hazardous, indicators of insanitation, and aesthetic defects (Zimmerman *et al.*, 2003). Potentially hazardous material includes physical hazards such as hard or sharp objects, chemical hazards such as mites that can cause allergic reactions (Olsen, 1998), or insects that may carry food-borne diseases. Even if insects do not present a health hazard, the presence of insects as foreign matter in food is considered an indication of unsanitary conditions (Zimmerman *et al.*, 2003). The presence of unsanitary conditions can be indicated by the presence of live or dead insects and by intact insects, fragments of insects, or insect products such as feces or cast cuticles. Aesthetic defects are those that do not fall in the first two categories, but would still be objectionable to consumers. An insect example would be agricultural or incidental species harvested with the commodity and incorporated into the final product.

III. STORED-PRODUCT INSECT PESTS

A diverse community of organisms (microflora, arthropods, rodents, birds) are associated with human structures and stored food, and identifying and understanding the biology of the pests present are critical first steps to pest management. There are four major categories of pests that may contaminate processed food products (Zimmerman *et al.*, 2003). Obligatory pests are associated with human environments, are attracted to human stored food, and live and breed in the food product (e.g., stored-product pest arthropods). Opportunistic pests are attracted to human food, are associated with human modified habitats, and often inhabit human structures, but usually do not live in the products they contaminate (e.g., flies, cockroaches, ants, rats, and mice). Adventive pests are associated with human environments but are not particularly attracted to human food and not strongly associated with human structures (e.g., birds, bats, and some insect species). Natural enemies are parasitoids and predators of the other three groups and can occur in human structures, be attracted to food odors and hosts in or near human food, and end up being contaminates of food.

Arthropods are invertebrate animals that have a segmented body, jointed appendages, and an external skeleton (i.e., cuticle). This phylum contains insects, arachnids, and crustaceans, but the important pests of the food industry are in the class Insecta and Arachnida (e.g., mites). Arthropods comprise a large portion of the biodiversity in food storage and processing facilities. For example, 600 species of beetles in 34 families (Hinton, 1945) and 70 species of moths in primarily four families (Cox and Bell, 1991) have been reported to be associated with stored products. Fortunately, not all of these species are widely distributed nor are they all highly damaging. Many of these species are generalists and feed on a wide range of stored commodities, not just grain-based foods. The specific community of arthropods associated with food processing, storage, and retail facilities is influenced by a wide range of factors: geographic location, season, building construction and condition, food products available, management practices, etc. This section focuses on the obligatory pests, the diverse group of arthropods that feed directly on grain and cereal products.

Stored-product arthropods can be grouped in different ways based on taxonomy, feeding preference, and life history traits. To provide an introduction, the arthropods are grouped into 11 groups based in part on the USDA Agriculture Handbook Number 500 and some of the major species in each group are discussed briefly. Some of these groups feed on whole seeds, typically with one portion of the life cycle occurring within the seed, and some feed on damaged (e.g., broken kernels, grain dust) and processed seeds. Insects in the second group tend to be secondary pests in bulk stored grain, but become much more important as pests in processed food facilities. For more detailed information on stored product pest biology and taxonomy, see Gorham (1987, 1991).

A. GRAIN WEEVILS

Grain weevils are in the family Curculionidae and contain three highly damaging pest species: *Sitophilus oryzae* (L.) (rice weevil), *S. granarius* (L.) (granary weevil), and *S. zeamais* Motschulsky (maize weevil) (Longstaff, 1981). Adults are 0.3–0.6 cm in length and have an elongated snout containing the mouthparts that are typical of all weevils. Grain weevils have a worldwide distribution, but none thrive in tropical and subtropical regions. They attack primarily whole grain and seeds and typically do not reproduce on fine products such as flour, but can infest formed cereal products such as pasta. Females deposit eggs singly in holes excavated into seeds and then cover the eggs with a mucilaginous egg plug. Adults live a long time and females can lay a large number of eggs over their lifetime (Richards, 1947). Larvae develop and pupate within the seed and after eclosion adults chew out of the seed. Because larvae, pupae, and adults can occur inside whole kernels, these species can be more difficult to detect and thus contribute to fragment counts in processed grain products.

B. GRAIN BORERS

Grain borers of the family Bostrichidae are another highly damaging group of whole grain pests. Two species of major importance are *Rhyzopertha dominica* (F.) (lesser grain borer) and *Prostephanus truncatus* (Horn) (larger grain borer). *R. dominica* is a cylindrical beetle about 0.3 cm long with its head tucked under the prothorax so that it is not visible from above. This species is cosmopolitan and is associated primarily with whole grain. Both adults and larvae feed and tunnel through grain and females can lay hundreds of eggs over their life. Eggs are laid on the outside of whole kernels and larvae burrow into the seeds. Feeding leads to fragmented kernels, powdery residues, and a characteristic pungent odor. *P. truncatus* originated in meso-America and has since spread widely, although it is not currently thought to be found in North America, and is now one of the most destructive pests of stored corn and cassava in Africa (Hodges *et al*., 1983; Pantenius, 1988). Adults tunnel through grain and lay batches of eggs in side chambers excavated off the main tunnel and then larvae tunnel through the grain in which the eggs were laid.

C. GRAIN MOTHS

Some moth species also attack intact seeds; the Angoumois grain moth [*Sitotroga cerealella* (Olivier)] is one of the most common species. Adults are small (0.125-cm wingspan), buff-colored moths with a fringe of long hairs on both pairs of wings. Adults do not feed and are short lived. Larvae feed and develop within the seed and before pupation chew an exit hole in the seed. Moths commonly attack grain before harvest, laying their eggs on or near grain such as wheat, corn, oats, or rice in the field. This pest can also infest grain after it is stored, especially in open storage such as corn cribs. Modern harvesting and storage methods have reduced the impact of this insect.

D. GRAIN AND FLOUR BEETLES

A diverse group of beetles share the characteristic that they attack primarily damaged kernels or processed grain products. The major pest species of the food industry in this group are two species of *Oryzaephilus*, the saw-toothed and merchant grain beetles, and two species of *Tribolium*, the red and confused flour beetles. The group also includes the flat grain beetle *Cryptolestes pusillus* (Schönherr) and the rusty grain beetle *Cryptolestes ferrugineus* (Stephens), which can be common in bulk grain storage.

Oryzaephilus surinamensis (L.) (sawtoothed grain beetle) and *O. mercator* (merchant grain beetle) (Silvanidae) are two morphologically very similar species. They are small beetles (0.3 cm in length) that have saw-like projections along each side of their thorax. Both are cosmopolitan pests of a wide range of foods, including stored grain, processed grain products, oil seeds, dried fruit, seeds, insect eggs, dead insects, and fungi (Howe, 1956; Loschiavo and Smith, 1970). The sawtoothed grain beetle is one of the major pests of packaged foods. Females start to lay eggs within a week after eclosion and can lay over 250 eggs during their life. Eggs are laid singly, primarily in crevices, and there are three larval instars. Before pupation, a larva will build a pupal cell and fasten itself to a solid object.

Although nine species of *Tribolium* are potential pests (Sokoloff, 1974), *Tribolium castaneum* (Herbst) (red flour beetle) and *T. confusum* (Jacquelin du Val) (confused flour beetle) (Tenebrionidae) are the most widespread and economically important species. Adult beetles are reddish-brown in color and measure 0.3–0.5 cm in length. These beetles do not typically feed on whole grains, although they can feed on broken and damaged kernels. They are most damaging to flour and other milled products. Eggs are laid directly in food material. Adults of both species have developed wings, but only *T. castaneum* has been reported to fly. Adult *Tribolium* can live for more than 3 years and females can lay eggs for over a year under laboratory conditions (Good, 1936).

E. MEALWORMS

The yellow mealworm *Tenebrio molitor* L. and the dark mealworm *Tenebrio obscurus* F. (Tenebrionidae) are the largest of the stored product beetles (1.25 cm in length) (Cotton and St. George, 1929). They are most often associated with decaying grain or cereal products under dark and moist conditions, but will feed on a wide variety of foods. Females can lay hundreds of eggs and live for several months. Larval stages can survive for long periods of time under unfavorable environmental conditions and can wander far from food sources to pupate. Adults are strong fliers and are attracted to lights.

F. DERMESTID BEETLES

A large number of dermestid (Dermestidae) beetles are associated with human structures, but only two species, *Trogoderma granarium* Everts (khapra beetle) and *T. variabile* Ballion (warehouse beetle), are considered to be major food pests. In addition to damage caused by feeding, they can contaminate food with body parts, hairs, or cast larval cuticles that cause gastrointestinal irritation and allergic reactions for asthmatics and sensitized individuals (Olsen *et al*., 2001).

Trogoderma granarium is one of the most destructive pests of grain in the parts of the world where it occurs and it is the only quarantine stored-product pest in the United States. It feeds on a wide range of stored products, but unlike other dermestids, it prefers whole grain and cereal products to animal-based products (Lindgren *et al*., 1955). Adult khapra beetles are short lived, do not require food or water, and most eggs are laid during the first few days of the oviposition period. Larvae may enter a form of diapause where they continue to feed and molt intermittently, but do not pupate, and this diapause can be maintained for over 6 years when food is present (Nair and Desai, 1973). Diapause is influenced primarily by high density, but a density-independent diapause can also occur (Nair and Desai, 1973).

Trogoderma variabile are small (0.3–0.6 cm in length), oval-shaped beetles that are dark in color with varying levels of yellowish banding on the elytra.

This beetle is found on a wide range of foods, but develops best on animal feeds, whole grains, pollen, and various processed food commodities such as egg noodles and wheat germ (Partida and Strong, 1975). Adults are short lived and oviposition peaks after a few days and then declines rapidly. Eggs are laid singly either loosely or in crevices. This species has a larval diapause similar to *T. granarium*.

G. SPIDER BEETLES

Adult spider beetles (Ptinidae) are small (0.08–0.5 cm in length) with long legs and a head that is often not visible from above so they superficially resemble spiders. They feed on a wide variety of foods, including cereal grains, seeds, flour, dried fruits and vegetables, animal nests, and dead animals. They are generally scavengers, but occasionally can become pests, especially in northern regions, on processed grain products such as flour, bran, and feed meal. Typically they become a problem when commodities are stored a long time and near a source of moisture. Eggs are often laid outside of grain sacks and in flour debris in cracks and crevices. Larvae can bore into wood or cardboard boxes to overwinter in a pupal cell. Adults typically live 1 to 6 months and females can lay up to 100 eggs.

H. MISCELLANEOUS BEETLES

Lasioderma serricorne (F.) (cigarette beetle) is one of the most important species in this group. It is found around the world in tropical and subtropical regions and is associated with heated buildings in temperate zones (Howe, 1957). Adults are small (0.2–0.4 cm in length), tan-colored beetles with a hump-shaped appearance. Adults are short lived, on average 18 to 21 days, and can feed (Lefkovitch and Currie, 1967). Despite its name, immatures develop on a wide range of commodities, including spices, nuts, beans, dried fruits and vegetables, grain and grain products, and tobacco. Females lay eggs in crevices, and newly hatched larvae can enter small holes associated with food packages. When mature, larvae create cells of food and waste in which they pupate. A number of other beetles of varying degrees of economic importance are in this group, including the hairy fungus beetle *Typhaea stercorea* (L.) and the drugstore beetle *Stegobium paniceum* (L.).

I. FLOUR MOTHS

A number of moth species are found associated with food storage structures. *Plodia interpunctella* (Hübner) (Indianmeal moth) is one of the most damaging stored-product moths for the food processing industry, retail stores, and homeowners. Adults have a copper-colored band of scales on the distal portion of the forewings and have a 0.13-cm wingspan. Larvae feed primarily on broken and damaged kernels, but sometimes chew into whole wheat kernels. Females lay 60–200 eggs on or near food during their brief life span. Eggs hatch in less than 2 weeks, and during the process of feeding, larvae produce silk that can web food particles together. Larvae feed on a wide range of foods such as dried fruits, flour, nuts, chocolate, pet food, spices, and pasta. Last instars enter a wandering phase prior to pupation and can often be observed crawling in exposed areas. They can also enter diapause to overwinter. Some other related moth species that attack a wide range of commodities and can be important pests in certain regions are *Pyralis farinalis* L. (meal moth), *Anagasta kuehniella* (Zeller) (Mediterranean flour moth), and *Cadra cautella* (almond moth).

J. PSOCIDS

A number of species in the insect order Psocoptera are often associated with human structures and stored food. They are often called book lice or bark lice because of their superficial resemblance to lice. They are small (1–6 mm long) soft-bodied insects with long thread like antennae and the species that occur primarily indoors usually lack wings. They are typically found in areas with high relative humidity that favor the growth of mold, which is a primary food source (e.g., damp spillage and wooden pallets that have become wet and moldy). Psocids typically occur at low densities and are not considered major pests in many parts of the world. However, in tropical countries and in subtropical zones with high temperature and humidity, psocids can build to large numbers and have an economic impact. They are also a problem in stored grain in Australia, where large populations can occur primarily as a secondary pest outbreak due to suppression of natural enemies as a result of fumigations (see citations in Rees and Walker, 1990).

K. MITES

Mites are arachnids in the order Acari and should not be classified or referred to as insects. Mites are typically very small (about 0.5 mm) and have oval bodies with little or no differentiation of their two body regions. Over 50 species of mites have been found associated with stored products: some feed directly on stored products, but others are predators, feed on fungi, or are parasites of other stored-product pests such as birds or rodents (Boczek, 1991). Mites can be important pests of stored food worldwide, but their economic importance varies considerably with location, commodity, and management practices. Some mite species can cause allergic reactions in people. Mites are most likely to be a problem in temperate and humid climates, but some products such as cheese, pet food, and oilseeds are infested under warmer and drier conditions. Mites infest a wide range of stored food products, including grain, flour, cereals, dried fruits and vegetables, herbs, powdered milk, pet foods, cheese, tobacco, oilseeds, and livestock feed. During outbreaks, mites can build up to extremely high densities and become damaging.

IV. FOOD FACILITY LANDSCAPES AND THEIR INFLUENCE ON INSECT BEHAVIOR AND ECOLOGY

The foundation of an effective pest management program is an understanding of pest ecology and behavior at relevant spatial and temporal scales. In other words, we need to look at the environments in and around food facilities from the perspective of the insect and understand how they perceive and interact with this environment to monitor and target pest management more effectively. Most landscapes created or modified by humans tend to be highly fragmented (Wiens, 1976). Fragmented landscapes are a mosaic of resource patches that are separated from each other by barriers to movement or by patches of less hospitable habitat. The structure and dynamics of the landscape mosaic influence ecological processes such as population dynamics and spatial distribution (Turner, 1989; Wiens, 1997; Wiens *et al.*, 1993). Stored-product pests of the food industry are pests in large part due to their effectiveness at exploiting the temporally and spatially fragmented landscapes within food facilities and within which food facilities are located. The pattern of distribution of the food patches in a food facility ultimately influences the spatial distribution and abundance of the insects. Many studies have found that stored-product insects are not distributed evenly either spatially or temporally within buildings (Arbogast *et al.*, 1998, 2000; Campbell *et al.*, 2002). Therefore, targeting pest management in both time and space can increase the probability of suppressing the pest population and reduce the cost of management and risk of negative nontarget effects (Brenner *et al.*, 1998).

Any resource important for stored-product insects may be patchy and influence insect distribution directly or in combination with other factors (e.g., food, favorable environmental conditions, structural features such as harborages or refugia). This section focuses on the patchiness of food resources used for either feeding or egg laying because it is one of the major determinates of insect distribution in food facilities. The spatial scale at which landscapes need to be defined is based on the organism being studied and the questions asked (Pearson *et al.*, 1996; Wiens, 1989, 1997). Food resources for stored product insects are patchy at a range of spatial scales: individual pieces of food, packages of food material surrounded by packaging barriers, packages arranged on pallets, a warehouse, or a processing plant in a landscape that includes other food storage and processing facilities. In bulk storage, for example, a patch might be considered a single seed kernel if we are interested in how insects make oviposition decisions (Campbell, 2002; Cope and Fox, 2003) or a whole bin if we are interested in processes of immigration and emigration (Hagstrum, 2001). In a warehouse, a patch may be an individual piece of spilled product, a crack filled with food material, a whole package of commodity, or even the warehouse itself. All of these patch types can be separated from each other by barriers to movement (e.g., packaging and walls) and inhospitable habitat (e.g., cement floors and walls). The landscape structure at all of these spatial scales probably influences stored product insect populations, although our understanding of these processes is still very limited.

For postharvest pest management, we typically start with material that is considered to be free of live insect infestation (e.g., freshly harvested grain, milled flour, or extruded food) and this material is stored in ways that spatially separate the food into patches. As a result, most infestations of grain-based products, whether it is grain in a bin or a food package, result from failure to adequately remove insects from where product is being added and from stored product insects finding and exploiting the new patch of resource. In a simple classification scheme, we can think about the insects associated with food facilities occurring in one of three locations: outside of the facility, in the structure of the building, and in the target commodity we are trying to protect. Pest management focuses on reducing the infestation of the target commodity patches and responding to these infestations when and if they occur.

Resource patches can be extremely variable in size and quality and, from a pest management perspective, in degree of importance. Some of these resource patches represent the product(s) that we are trying to protect from infestation, some patches may be in or around the building and within the scope of a pest management program, and other patches may be in areas outside of a pest manager's control. Resource patches are also temporally variable due to anthropogenic (e.g., bins are emptied and refilled, packages are moved, exploitation by insects reduces patch quality, sanitation removes or moves patches of spillage) and nonanthropogenic reasons. Some food patches in a structure will tend to persist longer than others (e.g., food material in a wall void that is not accessible versus spillage in an aisle) and have a higher probability of becoming infested and contributing to the increase and persistence of pest populations. Patch quality (e.g., size and nutritional value) has an influence on the probability of being encountered and a strong influence on the level of progeny production from the patch. These long-duration patches can produce large populations of pests that can contribute to pest problems over much larger spatial scales. For example, Campbell *et al.* (2002) identified a major source of warehouse beetles on one floor of a food processing plant and used mark–recapture methods to demonstrate that the beetles dispersed from this source across multiple floors and therefore contributed to pest problems in relatively distant portions of the facility. Thus it is not only necessary to identify and eliminate the food patches that are important for the buildup/persistence of pest populations, but also to prevent/eliminate the exploitation of target food patches.

The influence of environmental heterogeneity on movement behavior can have important consequences for the ecology of organisms (Hanski, 1998; Turchin *et al.*, 1991). Movement patterns of individuals in heterogeneous environments and residency time in different patches together determine spatial distribution (With and Crist, 1995) and the degree to which patches are interconnected (Wiens *et al.*, 1997). In food facilities, the distribution and movement of insects among different resource patches can be due to their own dispersal behavior or through human intervention (e.g., mixing of infested grain with uninfested grain, bringing infested packages into a warehouse, and moving the location of spillage through housekeeping activities).

The extent of insect movement among patches of food will influence the probability that stored products will become infested, the persistence of populations within storage facilities, and many aspects of pest management (e.g., the interpretation of trap catches or the effectiveness of insecticides and insect-resistant packaging). Stored product insects are often observed outside of food patches, can be highly active, and can disperse by walking or flying. Stored-product pests are trapped readily outside grain storage and processing structures (Doud and Phillips, 2000; Dowdy and McGaughey, 1994; Fields *et al.*, 1993; Throne and Cline, 1989, 1991) and are sometimes captured far away from anthropogenic structures (e.g., Cogburn and Vick, 1981; Sinclair and Haddrell, 1985; Strong, 1970; Vick *et al.*, 1987). This suggests that they have the capability for long-distance flight, although these captures may also indicate feral populations in proximity of the traps (Howe, 1965a; Khare and Agrawal, 1964; Stein, 1990; Wright *et al.*, 1990). The flight initiation behavior of several species has been well studied (e.g., Fadamiro and Wyatt, 1995; Perez-Mendoza *et al.*, 1999), but measurements of the actual distance that stored-product pests can fly are more limited. Chestnut (1972) demonstrated that the maize weevil *Sitophilus zeamais* flew up to 400 m, whereas Hagstrum and Davis (1980) found that *E. cautella* flew 300 m during a 10-min flight. *Prostephanus truncatus* flight duration in response to pheromone in a laboratory wind tunnel indicates that most flights are of short duration, but for young adults, long-duration flights

(>30 min) were possible and could lead to dispersal distances in still air of up to 1620 m in an hour (Fadamiro, 1997). Field observations of *P. truncatus* flight report shorter distances (see references in Fadamiro, 1997). Little is known about how far species that do not fly (e.g., sawtoothed grain beetle, confused flour beetle) are capable of dispersing.

Self-mark recapture has been used to measure stored-product insect movement in a commercial facility (Campbell *et al*., 2002). With the self-mark recapture approach, pheromone-based self-marking stations are used where insects are attracted to a pheromone lure and during their visit they pick up fluorescent powder on their bodies. These individuals can then be captured in pheromone traps at other locations. This technique was used originally in stored product environments as a method to estimate pest population density (Wileyto *et al*., 1994). A high degree of male *Trogoderma variabile* mobility was reported by Campbell *et al*. (2002) using the mark–recapture technique. Individual beetles were able to move across multiple floors and from 7 to 216 m through a warehouse. This suggests that there is considerable potential for these species to colonize and exploit patchy resources throughout a facility. Outside of structures, male *T. variabile* and *P. interpunctella* were also highly mobile. *T. variabile* were recaptured on average 75 m (range 21–508; $n = 203$) and *P. interpunctella* were recaptured on average 136 m (range 21–276; $n = 6$) from where they were marked outside a food processing facility (J.F. Campbell and M.A. Mullen, unpublished data). All of these measures of dispersal distance are likely to be underestimates of actual dispersal ability. Both of these species have also been marked outside of processing facilities and recaptured inside (J.F. Campbell, unpublished data), highlighting the potential for outside populations to cause infestations within structures and for outside populations to impact pheromone-monitoring programs within facilities. The downside of using pheromone monitoring for investigating dispersal is that for species with female-produced sex pheromones, only the dispersal of males is measured. In most cases we know very little about female dispersal by stored-product insects, but it is likely that they have different dispersal strategies from males. Hagstrum (2001) found considerable rates of immigration into farm grain storage bins.

Direct behavioral evidence of how stored-product insects move among patches is limited, but what is available shows that stored-product pests readily leave patches of food, can find and exploit multiple patches, and that these processes are influenced by a variety of endogenous and exogenous factors. The time *Cryptolestes ferrugineus* spent in refugia has been shown to be influenced by strain, sex, and age (Cox and Parish, 1991; Cox *et al*., 1989, 1990). A variety of factors have been shown to influence the decision by red flour beetles to leave food patches, including insect density

(Hagstrum and Gilbert, 1976; Naylor, 1961; Ziegler, 1977b; Zyromska-Rudzka, 1966), age (Hagstrum and Gilbert, 1976; Ziegler, 1976), and patch quality (Ogden, 1970; Ziegler, 1977a). Campbell and Hagstrum (2002) found that red flour beetles were often observed outside of food patches and that females visited and laid eggs in multiple patches. Campbell and Runnion (2004) found that female red flour beetles adjusted the distribution of eggs among food patches in response to the amount of food in the patches. Food volatile odors and, for some species, aggregation pheromones are probably important in stored-product insects finding and exploiting patches (Phillips *et al*., 2000b). Endogenous factors such as the sex of the pest will also influence its tendency to disperse and its behavior while dispersing (Campbell and Hagstrum, 2002; Cox *et al*., 1990; Naylor, 1961).

V. INTEGRATED PEST MANAGEMENT

Integrated pest management is a central theme in most insect pest management programs today, particularly for those involving production agriculture such as row crops and fruit orchards. A central theme in this historical development of the IPM paradigm involved scouting and sampling to determine when an economic threshold (ET) was exceeded, thereby avoiding unnecessary applications of a control, which in most cases would be an insecticide. There is a continuum of IPM systems, ranging from those still largely dependent on chemical treatments, but relying on economic thresholds (Stern, 1973; Stern *et al*., 1959) to determine the need for treatment, to those that rely on multiple prevention strategies and rarely if ever need chemical interventions. One of the central tenets of IPM is the reduction in the use of chemical insecticides and using more ecologically based control methods when possible. IPM is ideally a multiple-tactic approach that has redundant tactics to assure that pest populations are kept suppressed. IPM was originally developed by field crop entomologists (Kogan, 1998) and is generally a more information and management intensive operation than conventional chemical-based pest control. In principle IPM can be applied to pest management in food processing facilities, but as discussed later, it is not always directly analogous to pest management of field crops.

There are many definitions of IPM, but most definitions have two important elements: monitoring-based decision making and multiple control strategies (Hagstrum *et al*., 1999). In stored-product systems there are often multiple control strategies available, but it has been difficult to have monitoring-based decision making. Monitoring of stored-product insects falls into three broad categories: direct counting of the number of insects in samples, detection of insect-related damage, and capturing of insects using traps. As raw grains are harvested and loaded into bulk storage facilities, some of the concepts and practices of IPM are similar to management strategies for field crops (e.g., use of multiple tactics and pest prevention using techniques such as aeration). However, it is often difficult to adequately monitor and sample large grain bulks, particularly in commercial elevator facilities, due to the large volume of grain and the relatively low densities of insects that need to be detected. Precise threshold and injury levels have not been developed, and actual standards and rejection criteria are inconsistent and difficult to apply. As a result, treatments based on an economic threshold are not performed and control strategies are often applied preventively, even when using tactics such as fumigation that do not have any residual effect. An expert system has been developed to help manage farm-stored grain in the United States, which includes interpretations of sampling data and predictive models for insect population growth using different management strategies (Flinn and Hagstrum, 1990). A similar system is currently being developed for managing insects in grain elevators, which is based in part on an extensive field project whereby sampling data are used to recommend management strategies and intervention. The multiple-component strategy for managing stored grain is considered by many to be consistent with the IPM concept of controlling insect pests and is discussed in detail elsewhere (Cuperus *et al*., 1990; Hagstrum *et al*., 1999; Longstaff, 1994; Phillips *et al*., 2000a; White, 1992).

As grain products move from bulk storage to processing and milling facilities, then through distribution and marketing channels to consumers, IPM concepts become even more difficult to apply. Once products reach consumers, attitudes toward acceptable insect damage change dramatically. Often there is an idea of "zero tolerance" for insects, and controls become more preventative. There are no precise damage thresholds or injury levels and it may be impossible to adequately sample and monitor insects in some areas. Mills and processing plants routinely use insecticides to ensure that finished products are not infested when they leave the facility. Nonchemical methods such as sanitation, stock rotation, and environmental controls become part of the management strategy. Residual insecticides are used as surface treatments to floors and walls, particularly in urban settings where insects such as cockroaches are often found in the same environment as stored-product insects.

The IPM approach as developed for food processing facilities can involve but is certainly not limited to engineering design, sanitation and exclusion, insect monitoring and spatial analysis, fumigation, alternative environmental manipulations in the form of heat or cold treatments, and residual insecticides. In the food industry, multiple tactics are used to manage pests, although often these tactics are not necessarily integrated optimally and there is still a heavy reliance on chemical insecticides. In retail situations there is even less monitoring and integration of control tactics. A survey of grocery stores in Oklahoma showed that management practices are still pesticide intensive, with little use of IPM alternatives (Platt *et al*., 1998).

As discussed earlier, food storage environments are patchy landscapes and there is a dynamic relationship among insects emigrating from infested patches, moving among patches, and immigrating into uninfested patches. This relationship impacts all components of IPM programs for the food industry and presents a useful framework for viewing pest monitoring and management tactics (Figure 1). Insect monitoring can involve sampling of the commodity itself using visual inspection or traps to determine if the patch is infested or indirect sampling of the insects dispersing among resource patches using tools such as pheromone traps. Sampling the product directly is often destructive and can be difficult or prohibitively expensive, whereas indirect sampling is often easier to perform but the information obtained is more difficult to interpret and to use for making pest management decisions. This is because we are sampling primarily dispersing individuals, and often the methods used to trap these individuals bias capture toward a particular sex and/or physiological state. In most situations, we do not know the relationship between indirect sampling methods (i.e., sampling dispersing individuals) and direct sampling (i.e., sampling individuals in infested material). Nansen *et al.* (2004) showed that in a maize storage

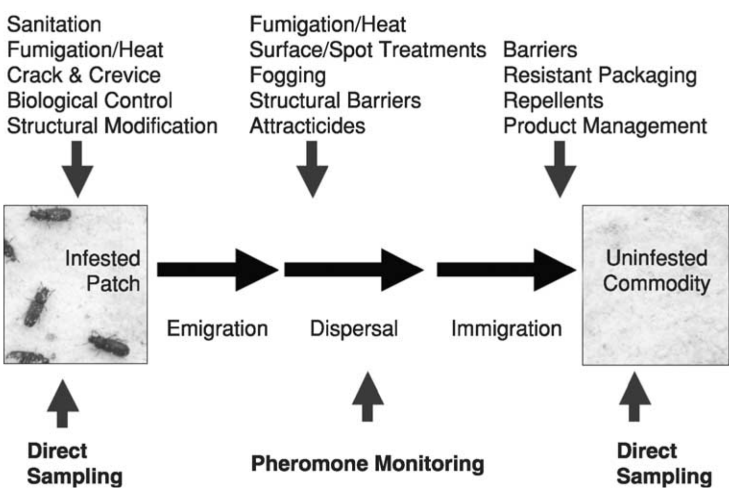

FIG. 1 Diagram illustrating the relationship between stored-product insect distribution and movement among resource patches, and the subsequent targeting of monitoring and pest suppression tools.

warehouse there was not a good spatial relationship between *P. interpunctella* adults captured on passive (no attractant) sticky traps above the surface of the grain and larval captures in the bulk corn.

Pest management practices fall into one of three categories: reducing/eliminating insects in food patches that are currently infested (e.g., fumigation, heat, sanitation, structural modification), putting up barriers to insect movement outside patches (e.g., screening on windows, fogging with pesticide), and reducing/preventing the pest from entering new patches (e.g., insect-resistant packages, repellents). The following sections review the status of many of the components of pest management programs for food processing facilities and warehouses. Our discussion focuses on management for stored-product insects and excludes cockroaches and other traditional urban pests.

VI. STORED-PRODUCT INSECT MONITORING TACTICS

The foundation of a successful integrated pest management program is an effective monitoring system that supplies information on not only the number and type of pests present, but also detects changes in pest populations over time and locates foci of infestation and routes of entry (Burkholder, 1990). With this information, pest management decisions can be based on monitoring data rather than calendar-based applications that may be optimally targeted both temporally and spatially. Monitoring strategies and tactics differ between bulk stored raw commodities and processed commodity facilities. Bulk stored commodity monitoring relies primarily on direct sampling for insects in the product, but for processed commodity facilities, a combination of direct sampling of spillage and indirect sampling is used most widely. The major difficulty with bulk grain sampling is that we need to estimate the number of insects present in a very large volume, but because of the small volume of samples relative to the total volume of stored grain, low density and nonuniform distribution of insects, and the difficulty in taking samples from throughout the grain mass, accurately extrapolating from sample data is not highly accurate. For processed commodities, the major difficulty is relating the number of insects observed and captured in traps placed outside of resource patches with the level and location of infestations.

In bulk raw commodities, the primary sampling methods are based on taking direct samples of grain and counting the number of insects present or the number of seeds showing signs of damage. Various sampling tools (e.g., grain trier, pelican sampler) are available for collecting grain samples depending on the volume of grain to sample and whether the grain is in a bin or being moved (Hagstrum, 1994; Subramanyam and Hagstrum, 1995).

Vacuum probe sampling is a relatively new method that can be used to sample through the whole grain profile, thus overcoming some of the limitations of other sampling methods. In an area-wide IPM project the vacuum probe was the most effective method used to sample large grain elevators (P. Flinn, personal communication). After the grain sample is collected, insects present in the sample must be determined. Sieving using either a hand sieve or an inclined sieve is effective at removing most insects that are external to the grain (White, 1983). The number of insects of each species present or the percentage of samples infested can be used to estimate total insect abundance. Many of the important bulk grain pests are internal feeders and are difficult to detect because only the adult stages that have emerged from the seeds can be sieved out of samples. There is a range of techniques to detect internal feeding insects (e.g., staining, flotation, X-ray examination, sound detection, nuclear magnet resonance, ELISA), but most are relatively labor- and time-intensive to perform (Pedersen, 1992). Near-infrared reflectance spectroscopy (NIR) technology has been used to detect internally feeding insects (Dowell *et al.*, 1998).

An approach used commonly by industry is to assess the number of insect-damaged kernels (IDK) present in samples. Grain Inspection, Packers and Stockyards Administration (GIPSA), formerly the Federal Grain Inspection Service (FGIS), has set a threshold of 32 IDK per 100 g of sample as being considered adulterated and unfit for human consumption, but most flour mills have lower reject levels. The problem with this approach, in addition to the issues associated with extrapolating population levels from small sample sizes, is that the correlation between IDK and number of internally feeding insects is not well established and, in some situations, may not be well correlated (Perez-Mendoza *et al.*, unpublished data). Some of the issues involved in developing sampling programs are reviewed by Subramanyam and Hagstrum (1995).

Traps that capture insects as they move through the grain can be more efficient at detecting the presence of insects than direct sampling, but species differences in mobility can lead to differences in trap capture and, as with direct sampling, only a relatively small portion of the grain mass is being sampled. Probe traps, which are a type of pitfall trap, can be used to sample and detect insect populations in bulk grain (Hagstrum *et al.*, 1998), but they provide an estimate of relative abundance, not absolute numbers. A new advance in this technology that is being commercialized is a probe trap that automatically counts the insects that are captured (Epsky and Shuman, 2001; Toews *et al.*, 2003). This technology is based on the falling insect breaking a light beam as it passes through the trap and this information being sent to a computer where it is compiled. In some cases, traps placed in the headspace above the raw commodity can provide a good prediction of future pest problems. For example, capture of rusty grain beetle [*Cryptolestes ferruginens* (Stephens)] in sticky traps in the headspace of farm bins during the first 3 weeks of storage provided a good indication that the bin would become infested (Hagstrum *et al*., 1994).

Monitoring of insects in food processing and warehouse structures involves either direct visual sampling or the use of traps. Visual inspection done on a regular basis is one of the primary means by which insect infestation is monitored in food facilities (Mills and Pedersen, 1990). This is a time-consuming process that requires training to be done effectively. Its strength is that not only does it detect signs of insect infestation, but it can also identify potential problem areas such as accumulations of spillage before they become infested. It is direct sampling where potential food patches are identified and their status as infested or uninfested can be determined. However, in many cases, food patches are not detectable or access requires destructive sampling (e.g., opening packages), making it difficult to directly evaluate the level of packaged commodity infestation.

The use of traps to monitor insects is also common in food storage and processing environments and a range of trap types are available (e.g., pheromone traps, food attractant traps, sticky boards, light traps). Traps have the advantage that they sample continuously and with appropriate stimuli they can attract insects from a wide area. Thus, trapping can provide information more quickly and easily and, in many cases, earlier than visual inspections. Because most of these traps capture insects that are dispersing between resource patches, it can be difficult to make the connection between numbers captured in traps and actual levels of product infestation. The best use of this information may be to use the relative numbers captured and their spatial distribution to make targeted pest management decisions (i.e., indicative interpretation) rather than trying to estimate total abundance (Arbogast and Mankin, 1999). Areas of high trap capture should be followed up with additional investigation (e.g., direct sampling of packages and spillage, identifying routes of entry) to determine the probable cause(s). Monitoring trends in trap capture data over time is also a useful approach to evaluating the effectiveness of IPM programs.

Most trapping devices use some sort of attractant to increase capture rates (e.g., pheromones, food odors, light). Light traps are used commonly in food facilities for fly management, but some species of stored product insects are attracted to light sources and monitoring the species and number of insects captured in light traps can provide information on the pest flight activity (Hagstrum *et al*., 1977; Keever and Cline, 1983; Pursley, 1987). The type of light trap and its location can influence the effectiveness at trapping stored product pests (Rees, 1985). Food baits have been used effectively in warehouses containing bagged commodities to monitor pest populations

(Hodges *et al*., 1985), but processing these packs can be labor- and time-intensive and, if not collected in a timely manner, can contribute to pest problems within a facility. Unbaited sticky boards can be used for stored product insect monitoring as well, and these may be either suspended vertically in the air or laid flat on surfaces. Because many walking insects will detect sticky surfaces and avoid them, they work best for insects that land or fall on the surface.

Incorporation of an attractant such as a pheromone or food odor can improve the efficiency of a trap. Pheromones are chemical cues produced by one individual that are used to communicate with another individual of the same species. There is a wide range of different functions for pheromones, but the two most important from a monitoring perspective are sex pheromones, which elicit a response in the opposite sex, and aggregation pheromones, which elicit responses from both sexes. Pheromones have been isolated and lures are available commercially for many stored-product insects (Chambers, 1990; Phillips *et al*., 2000b). Several traps designed specifically for stored-product insects are available commercially (Collins and Chambers, 2003; Mullen, 1992; Mullen and Dowdy, 2001; Vick *et al*., 1990). There are two general types of pheromone traps. Traps targeted for flying insects typically use a sticky surface on the inside of the trap where a pheromone lure is placed and insects become trapped when they land near the lure or a funnel and bucket combination that reduces the ability of the insect to escape after entering the bucket to find the pheromone source. Traps that target walking insects are placed on the ground and generally use some type of pitfall to capture insects that walk up to the lure.

Pheromone traps have been demonstrated to be effective at capturing stored-product pests, primarily moths in the family Pyralidae, in anthropogenic ecosystems (Bowditch and Madden, 1996; Mankin *et al*., 1999; Pierce, 1994; Soderstrom *et al*., 1987; Vick *et al*., 1986). Pheromone trap use is increasing in commercial facilities (Phillips *et al*., 2000b). However, many questions remain about the use of these monitoring tools, from the very practical issues such as how many traps are needed and which types work best, to the fundamental issues concerning the relationship between pheromone trap captures and actual pest population density, distribution, and level of product infestation (Arbogast and Mankin, 1999). Research into the relationship between pheromone trap capture and the absolute number of insects present in a structure [i.e., "representative" trap interpretation (Arbogast and Mankin, 1999)] has focused on developing relationships between released insects or insects present in the air and trap capture (Hagstrum and Stanley, 1979; Leos-Martinez *et al*., 1986; Mankin *et al*., 1983; Rees, 1999; Wileyto *et al*., 1994).

Food odors are also important as attractants for traps both on their own or in combination with pheromone lures as synergists or additive attractants. Food odors can be used to improve the capture of species that do not have commercially available pheromone lures, of females that do not respond to traps with sex pheromones, and of immature stages. In a number of situations, pheromones combined with food odor are more attractive then either alone (Landolt and Phillips, 1997; Phillips *et al*., 1993; Trematerra and Girgenti, 1989). Food odor has an advantage over food bait packs because typically the insect is unable to develop on the chemical fraction containing the attractant in contrast to food bait packs. The effectiveness of food attractants can be diminished in environments that contain other food odors.

Some studies have addressed the temporal and spatial patterns to stored-product pest abundance in bulk grain storage containers (Arbogast *et al*., 1998; Brenner *et al*., 1998), flour mills (Doud and Phillips, 2000), food processing plants (Rees, 1999), warehouses (Campbell *et al*., 2002), and retail stores (Arbogast *et al*., 2000). The application of geostatistical techniques for understanding insect spatial distribution is also increasing in pest management (Arbogast *et al*., 1998; Brenner *et al*., 1998; Liebhold *et al*., 1993). Techniques such as contour analysis graphically portray spatial data in a way that is quickly understood and can be used to visualize the sources of insect distribution. It is difficult to get a general picture of what is happening in the entire facility simply from observing the number of insects in each sample or trap. Comparing maps of trap captures over time can also show how distributions spread or contract, where new foci develop, and how populations respond to human intervention. Contour mapping is becoming more widely used by the pest management industry.

Contour mapping of spatial data is a three-step process. First, data from each sample point are assigned x and y coordinates to indicate the location on a two-dimensional surface. Second, a denser grid of data points is generated using interpolation algorithms and there are a number of them that can be used. Finally, this denser grid is used to draw contour lines that join points with equal values. An example of a contour map from a flour mill is presented in Figure 2, with the increasingly dark regions indicating increasing estimated numbers of insects that would be captured. As a practical tool, contour mapping helps plant managers visualize and incorporate spatial distribution information into pest management programs. However, it is also important to take into account the assumptions behind this approach and to set up monitoring programs that will generate data of sufficient quality to address the questions needed. For example, the number of traps and degree of spatial autocorrelation among traps strongly influence our ability to make accurate contour maps (Nansen *et al*., 2003). In addition,

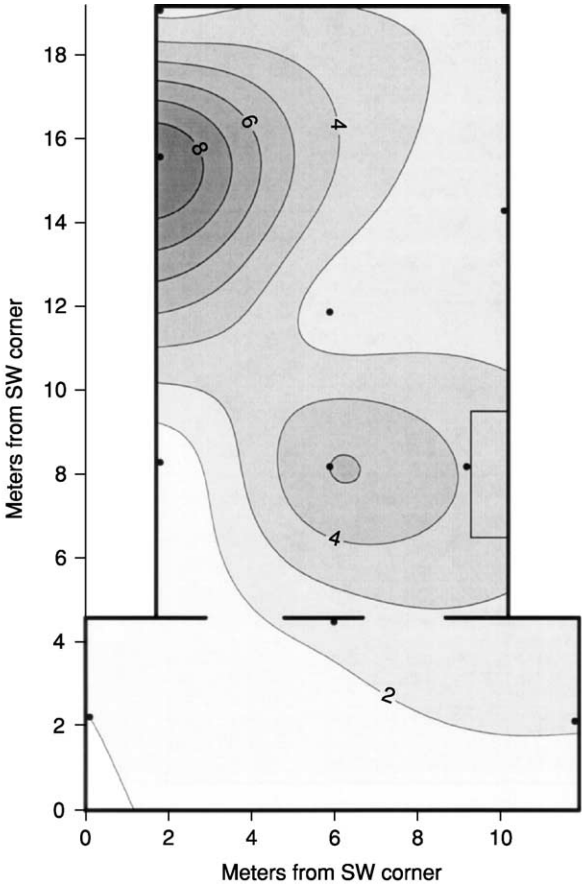

FIG. 2 Contour map of the spatial distribution of red flour beetle, *Tribolium castaneum*, pheromone trap captures in a flour mill (J.F. Campbell and R.T. Arbogast, unpublished data).

insect movement behavior and the environment around each trap can influence trap capture in ways that do not reflect the true distribution of infestation (Campbell *et al.*, 2002).

VII. MANAGEMENT TACTICS FOR STORED-PRODUCT INSECTS

Sanitation includes housekeeping, inspection, physical and mechanical methods, chemical methods, and biological methods (Mills and Pedersen, 1990) and is critical for the production, manufacture, and distribution of clean and wholesome food (Gould, 1994). Housekeeping can be defined simply as cleanliness and orderliness and is most important in reducing the ability of pests to become established. Inspection involves the examination of raw materials, processes and processing equipment, facilities, and finished products for infestation. Physical measures include the use of various types of barriers, including packaging and controlled temperatures and humidity; mechanical methods include traps, irradiation, etc. Pest exclusion relies heavily on physical barriers and fits well into an integrated sanitation management (ISM) program where reduced pesticide use is emphasized. An emphasis has been placed on the reduced use of pesticides; however, situations exist where contact insecticides and fumigants can and are used safely to protect food products. Biological pest control agents such as parasites and predators show some promise in the control of insects, and pheromones have proven effective in monitoring for pest insects and may have some efficacy in pest suppression.

A. HOUSEKEEPING AND EXCLUSION

Housekeeping and pest exclusion are the foundation of food product protection, whether in the storage and transportation of raw agricultural commodities or in the processing, manufacturing, storage, or distribution of finished food products. Housekeeping involves cleaning spillage, removing or sealing damaged packages, and removing out-of-condition products. Because insect populations can build up in refugia in the structure of the building in which food material is stored, eliminating these food habitat patches can have a dramatic impact on the ability of pest populations to establish and persist. The degradation of food material and the presence of moisture can lead to pest problems that would not occur under good housekeeping conditions.

Many aspects of food processing facility design, modification, and repair concern the prevention of pest (birds, rodents, and insect) entry. Pest exclusion involves two major components: reducing the number of external sources of insects and preventing their entry into the facility. For new facilities, site selection can have an important influence on the potential for infestation. Imholte and Imholte-Tauscher (1999) indicated that selection of a plant location requires economic considerations balanced with product safety considerations. Items that fall within this category include smoke, dust, odors, and other sources of contaminants that may originate from the environment and/or nearby manufacturing or other industries. Parking areas and vehicle access ways should be hard surfaced to eliminate the potential for dust being blown into a facility. Other food processing and grain storage facilities in the vicinity can also impact the potential for infestation.

A “buffer” zone surrounding the actual facility is a desirable feature that can be planned for new facilities but may not be present around existing food plants. A properly maintained space surrounding a food plant can reduce greatly the potential for the entry of rodents, birds, and insects. Maintaining the area surrounding a food processing plant free of tall weeds and grass; accumulations of junk or debris and/or unused equipment; accumulations of standing water; or other conditions that favor the attraction and development of rodent, bird, and insect populations is an effective way of “excluding” these pests from close proximity to food processing facilities. Shrubbery or other vegetation adjacent to a plant facility can provide an attractive harborage for rodents as well as a roosting place for birds. Flowering plants can also serve as a source of attraction for certain insects that are attracted to or infest food products. By avoiding these types of situations, the resulting environment tends to exclude pests from close proximity to the processing facility. Exclusion of birds and rodents from the perimeter of buildings may also reduce the potential infestation from stored product insects because many species can also exploit rodent and bird nests.

Because many insects are attracted by lights, part of an exterior exclusion program involves the proper placement of lighting. Exterior lighting at a food processing plant should be placed at the perimeter of parking areas away from the plant rather than being mounted on the building so that insects are attracted away from the plant rather than toward the facility. Sodium vapor lights should be used instead of fluorescent and mercury vapor lights that produce ultraviolet light to which some insect species are attracted (Imholte and Imholte-Tauscher, 1999).

Structurally, food processing plants should be designed to “exclude” pests. For exterior walls, solid concrete construction is preferred over concrete block or sheet metal. Preformed wall sections of solid concrete require proper sealing to effectively exclude rodents and insects. Openings such as windows, doors, loading docks, track-wells, and intake and exhaust vents are pest entry points that must be constructed and maintained properly to safeguard against pest entry. Modern processing facilities minimize the use of windows; where they may be needed for ventilation, they should be screened. Standard window screen will exclude most insects, but heavier mesh screen is needed at ground level to exclude rodents. Screens should be so constructed and installed that they can be removed and cleaned. Intake and exhaust openings should be protected with heavy mesh screen. Intake vents should be fitted properly with filters that are appropriate for the type of plant operation.

Entry and exit doors should be fitted so that no more than 1/8 to 1/4-in. spaces are at the top, bottom, and sides of the door. This should exclude rodents from entering. Insects and dust can enter very small openings. Nylon bristle brush protectors are available to minimize the entry of insect and dust through cracks around doors. Because rodents can gnaw wooden doors, they should be fitted with metal flashing along the door bottom to minimize the opportunity for damage and entry. In most cases, metal doors are preferred. Insect and bird entry during loading operations can be minimized by using strip doors or air curtains that allow fork truck passage. Air curtains can be effective in excluding dust and flying insects. Air velocity is a major factor in the effectiveness of air curtains. They are also affected by other factors: prevailing wind velocity, internal building pressure, and air temperatures. For example, warm air and food odors from internal positive plant pressure may be a strong attractant to flies and other insects.

The roof area of a processing plant is often overlooked as a source of pest entry into the plant. Insects may be attracted to product spillage or dust accumulations on roofs from leaking equipment, such as bucket elevators and cyclones. These accumulations can also provide a breeding area for product-infesting insects as well as microorganisms. Because the air supply for plant ventilation sources is often located on roofs, it is important to keep these areas free of product residues and to protect ventilation equipment so that pests are excluded from the plant by this route. Odors emitted from roof ventilators can be attractive to potentially invading insect pests. Proper equipment and good housekeeping are necessary adjuncts to excluding pests from entering the plant by way of the roof. These criteria apply not only to food processing facilities but also to distribution facilities.

To prevent pests from entering a facility, it is necessary to have an effective monitoring program to assure that products are pest free when they arrive at the site. Raw materials (i.e., ingredients, packaging, and equipment) should be inspected to assure that they do not serve as vehicles for pest entry. Truck and/or railcar unloading sites are possible sources of insect entry into the facility.

Cracks, holes, or loose joints in interior walls, floors, and overhead areas must be sealed so that they do not become harborages for insects or rodents. Equipment used for transporting, processing, and packaging food products should also be designed to minimize the buildup and/or accumulation of food materials within the interior of the equipment.

B. PACKAGING

Packages are designed to protect food products from the point of manufacture to the point of consumption. Packages are usually tailored to fit the product being protected and no one package will provide the protection needed for all products, under all conditions, and against all pests. Infestation of packaged products is a function of the package design; package handling during manufacture, shipping, and storage; and time exposed to potential infestation. The protection of food is not the only concern in package design and needs to be balanced against consumer desires, manufacturing practices, shipping and storage constraints, and ultimately cost. For example, sealing all foods in metal containers would reduce the chance of insect infestation to essentially zero, but would definitely cause problems with the other factors. Almost all nonperishable food package designs have openings that can allow insects to enter due to manufacturing specifications, flaws in manufacturing, or damage that occurs during shipment and storage (Mowery *et al*., 2002; Mullen, 1994).

A complete understanding of insect-resistant packaging must begin with the pests that most commonly attack packaged foods and the methods that they use to enter packages. Highland (1984, 1991) separated package pests into two categories: "penetrators," which are capable of chewing through one or more layers of flexible packaging materials to enter packages, and "invaders" which enter packages through existing openings. Insects such as the lesser grain borer, *Rhyzopertha dominica*; the cigarette beetle, *Lasioderma serricorne*; the warehouse beetle, *T. variabile*; the rice weevil, *Sitophilus oryzae*; and the rice moth, *Corcyra cephalonica* (Stainton) are known to be good package penetrators. Species classified as invaders include the red flour beetle, *T. castaneum*; the confused flour beetle, *T. confusum*; the sawtoothed grain beetle, *O. surinamensis*; the Indianmeal moth, *P. interpunctella*; and the almond moth, *Cadra cautella* (Walker). These are not mutually exclusive categories, however, as most penetrators will also enter packages through existing holes and some species classified as invaders do occasionally chew into packages. For example, under some circumstances, larvae of the Indian meal moth and the almond moth penetrate packages (M. Mullen, personal observation).

Most infestations are the result of invasion through seams and closures, and rarely through penetrations (Mullen, 1997). Insect pests enter packages through existing openings that are created from poor seals, openings made by other insects, or mechanical damage. For example, the adult sawtoothed grain beetle has been shown to enter packaging through openings less than 1 mm in diameter, and the adult red flour beetle can enter holes in packaging that are less than 1.35 mm in diameter (Highland, 1984). Stored product pests can be attracted to the food odors coming from holes in packages and lay eggs near the holes (Barrer and Jay, 1980; Mowery *et al*., 2002, 2003). Females may actually insert eggs through openings that are even smaller in size then those through which they could enter the package. The sawtoothed grain beetle has been demonstrated to insert their ovipositor through packaging flaws 0.4 mm in diameter that preclude adult entrance and lay eggs under the packaging film (Mowery *et al*., 2002). The small early instar larvae that hatch from eggs laid near holes in packaging may enter packages through extremely small openings. Mowery *et al.* (2002) found that first-instar saw-toothed grain beetle larvae would enter holes in packaging film in response to food odors escaping thorough the holes. Packages with holes as small as 0.27 mm can be infested by first-instar larvae of the saw-toothed grain beetle. Many insects prefer to lay eggs in tight spaces such as those formed when multiwall paper bags or paperboard cartons are folded to create closures, and newly hatched larvae would be in a good position to invade packages.

Some products and packages are more susceptible to insect infestation than others. These products can serve as insect reservoirs, leading to the infestation of other products (Highland, 1984). For example, dry pet foods packed in multiwall paper bags are generally not very insect resistant because they lack adequate seals and closures, whereas bird seed packages often contain ventilation holes that can allow insect entry.

There are a variety of improvements in packaging design that can reduce the chance of insect infestation. Seals and closures can often be improved by changing glue patterns or the type of glue used. Generally, a glue pattern that forms a complete seal with no channels for the insect to crawl through is the most insect resistant. Insect resistance can also be improved by overwrapping the packages with materials such as oriented polypropylene films. To maximize the effectiveness of overwraps, they should fit tightly around the package and be sealed completely to prevent insects entering at the corners of the folded flaps. Another means of discouraging insect infestation is through the use of odor barriers (Mullen, 1994). Food odors may be prevented from escaping the package through the use of barrier materials, resulting in a package that is "invisible" to invading insects. Coating the package with materials such as acrylic, polyvinylidene chloride, or EVOH can improve odor retention. However, any flaw in the package will negate the odor-proof qualities of the package (Mowery *et al.*, 2003). Studies reported by Mullen (1997) have shown that when odor barriers were used to protect a commodity, only those packages with flaws became infested.

C. INSECTICIDES

Insecticides that are used in food processing facilities can be sorted into three general groups. (1) Fumigants are insecticides that are toxic in the gaseous phase; two common fumigants used worldwide are methyl bromide (MB) and phosphine. Modified or controlled atmospheres are also toxic as gases and usually involve lowering oxygen concentrations through the addition of carbon dioxide or nitrogen. (2) Aerosols are applied as mists or fogs in small droplets ranging in size from 5 to 30 μm. They can have vapor and contact toxicity. (3) Surface treatments are applied directly to flooring and wall surfaces and may be applied to cover surfaces or be limited to specific areas, such as cracks, crevices, wall baseboards, or as spot treatments to defined target areas. They have contact toxicity and generally give some degree of residual control.

Currently there are only a few insecticides in all three of these classes that are registered in the United States for use in food processing facilities and they are discussed in detail. This section focuses on the insecticides used as fumigants, aerosols, and contact insecticides. An exhaustive list of labeled products is not presented, and specific insecticides are discussed primarily to present concepts and ideas. Also, labeling and registrations of insecticides are constantly changing, and products may be removed from the stored-product market as a consequence of regulatory actions and interpretations. Specific labels and label directions should always be consulted and followed when applying insecticides.

1. Fumigants and modified atmospheres

Methyl bromide has historically received extensive use as a whole-plant structural treatment to mills and processing facilities (Taylor, 1994). It is a highly effective fumigant and penetrates into bulk and bagged commodities, packaging, and can disperse throughout a structure to kill hidden insects and immature states. Quarantine treatments are usually done with MB because it kills quickly compared to phosphine, and whole-plant fumigations are often done during a weekend or holiday period to reduce idle or down time for production facilities. Because fumigants give an immediate kill and offer no residual protection, reinfestation is a constant threat for any structural facility.

Methyl bromide has been identified as an ozone-depleting substance and is being gradually removed from world markets. Current legislation and plans call for the elimination of methyl bromide in most industrial countries by 2005, with possible exemptions for quarantine (UNEP, 1996). Currently there is an extensive search worldwide for products that are alternatives to methyl bromide (Kawakami, 1999). These alternatives are broadly defined and include components of management plans such as sanitation, monitoring, contact insecticides, heat treatments, and modified atmospheres, in addition to new fumigants (Batchelor, 1998).

Phosphine gas is registered in the United States for use inside food processing facilities. Currently, it is used primarily for fumigation of bulk stored grain. While there are several reports of phosphine resistance in stored product insect populations in Asia (Subramanyam and Hagstrum, 1996), there are few published data regarding resistance in the United States.

Low levels of resistance have been reported for some populations of Indian meal moth, almond moth, and red flour beetle populations in stored peanuts in the southeastern United States (Zettler *et al.*, 1989), but no assessments are available for phosphine resistance in insect populations in mills, warehouses, processing plants, and other structural facilities. Phosphine can be corrosive to metals, particularly copper, electrical wiring, and electronic equipment (Bond *et al.*, 1984), which limits its application in food processing facilities and warehouses. A new formulation of phosphine, in which phosphine gas is combined with carbon dioxide and released from a cylinder, alleviates some but not all of the corrosive effects of phosphine and is labeled for use as a structural treatment.

Research is being conducted for fumigants that can possibly replace methyl bromide for use in food processing facilities. The fumigant sulfuryl fluoride appears to be the most likely candidate for replacement of MB (Schneider and Hartsell, 1998) and has recently been registered within the United States. It is effective against adult stored-product insects, but longer exposure times are required to kill eggs compared to methyl bromide (Bell and Savvidou, 1999). Carbonyl sulfide has also shown effectiveness as a fumigant for stored-product insects (Weller and Morton, 2001; Zettler *et al.*, 1997).

Modified atmospheres are known to have toxic effects toward stored-product insects (Adler *et al.*, 2000; Rameshbabu *et al.*, 1991). A low-oxygen atmosphere can be created by replacing oxygen with nitrogen, thereby causing insect mortality from a lack of oxygen. Toxic conditions can also be created by producing atmospheres high in carbon dioxide, regardless of the oxygen content; however, the oxygen is usually reduced somewhat from normal levels. High-oxygen atmospheres are also lethal, but are not generally used for insect control.

Modified and controlled atmospheres have been used with some success to control insects in stored bulk grains (Adler *et al.*, 2000). However, they are not generally used by the milling and processing industry as whole-plant treatments because they are expensive compared to methyl bromide, extensive monitoring and sealing are required for effective control, and there are potential problems with contamination (White and Leesch, 1996). However, modified atmospheres, vacuum sealing, or low-pressure treatments may be useful for small-scale or specialty applications (Mbata and Phillips, 2001). With the impending loss of methyl bromide, there may be more opportunities for using modified atmospheres inside food processing facilities.

The efficacy of fumigants and modified atmospheres can be influenced by factors such as insect species and life stage, physical environments, and environmental conditions (Adler *et al.*, 2000). Insect species and life stages vary in susceptibility (Weller and Morton, 2001). Generally, eggs and pupae are the life stages that are more difficult to kill with conventional fumigants (White and Leesch, 1996) and modified atmospheres (Adler *et al.*, 2000). Diapause may also affect tolerance, as the duration of diapause increased in larval Indianmeal moth, *P. interpunctella*, and almond moth, *C. cautella*, tolerance to MB also increased (Bell and Savvidou, 1991). The efficacy of fumigants and modified atmospheres generally increases as temperature increases, and shorter exposure intervals are required to give equivalent levels of mortality (Adler *et al.*, 2000; Bell and Savvidou, 1999; Locatelli and Daolio, 1993; White and Leesch, 1996). However, there are critical temperature thresholds and fumigations are prohibited if temperatures are outside of the specified range. Temperature requirements are generally given on the product labels.

2. *Aerosols and space sprays*

Aerosols and space sprays are targeted primarily at exposed insects that are flying or walking on a surface. They are dispensed from an aerosol fogger, often through a timed application system, and have low persistence and offer very little residual production. There are few products that can currently be used inside food processing facilities as space sprays, and the insecticide labels will generally give directions for application of a specific amount of product per volume area of space, such as ft^3 or m^3. Synergized pyrethrins, a natural product, and the organophosphate dichlorvos are two insecticides that have historically been used for aerosol applications inside processing facilities and in food warehouses. In the United States, all registered pesticides are being reviewed for compliance with the 1996 Food Quality Protection Act (FQPA), and the continued registration and usage of dichlorvos is uncertain. Some insecticides and formulations are restricted to empty facilities, whereas others can be used only if food material is covered. A venting or release period after application is also required after dichlorvos application.

Pyrethroids are a class of synthetic chemicals that are similar in structure to natural pyrethrins. They have been used in field crops and urban pest management for nearly 30 years, and within the last 5 to 10 years new products have been registered for specific use against stored-product insects. Resmethrin is labeled for use as an aerosol in food plants, mills, and warehouse facilities, but could have potential side effects such as discoloration of surfaces and odor contamination and may be more appropriate for use in empty facilities. Labels generally state to cover any food prior to application. The pyrethroids esfenvalerate (Conquer) and prallethrin (Etoc) are also labeled for use in some situations as an aerosol space treatment in food processing facilities. Laboratory studies indicate the efficacy of new pyrethroid aerosols (Arthur, 1993; Arthur and Gillenwater, 1990), but there are few recent studies whereby efficacy has been assessed in field situations. All aerosols will have restrictions, and each product label must be consulted for precise regulations regarding usage.

An aerosol formulation of the insect growth regulator hydroprene (Gentrol) was labeled several years ago for use in the United States. There are no research reports with hydroprene aerosol, except for Bell and Edwards (1998), which describe a study conducted in Great Britain. In this study, aerosol applications of hydroprene (Protrol) prevented the development of eggs of the red flour beetle, *T. castaneum*, the confused flour beetle, *T. confusum*, and the almond moth, *C. cautella*, that had been placed in exposed dishes with food media.

The status of resistance of stored-product insects to any of the aerosols used in the United States is uncertain, and no new assessments of resistance have been conducted in recent years. Indianmeal moth, *P. interpunctella*, and almond moth, *C. cautella*, populations in peanut warehouses in the southeastern United States showed low levels of resistance to dichlorvos (Arthur *et al*., 1988), but reflected an increase relative to earlier studies (Zettler, 1982). In other studies, 24% of red flour beetle and 64% of confused flour beetle populations collected from flour mills were resistant to dichlorvos (Zettler, 1991).

3. *Surface treatments*

Currently there are few insecticides registered as surface treatments to control stored-product insects. For years the organophosphate insecticide malathion was used as a surface treatment for structural facilities, but stored-product insects throughout the world have developed extensive resistance to malathion (Subramanyam and Hagstrum, 1996). Most of the resistance reports were generated from studies with bulk grains, but in the United States, resistance has been documented for field populations of the red flour beetle, *T. castaneum* (Herbst), and the confused flour beetle, *T. confusum* (DuVal), collected from flour mills (Arthur and Zettler, 1991, 1992; Zettler, 1991). Populations of the Indianmeal moth, the almond moth, and the red flour beetle collected from bulk peanuts and empty warehouses were also highly resistant to malathion (Arthur *et al*., 1988; Halliday *et al*., 1988).

Today one the most common insecticidal surface treatments is the pyrethroid insecticide cyfluthrin (Tempo). It is available as an emulsifiable concentrate (EC) or as a wettable powder (WP), but the WP is much more effective than the EC when applied at the high application rate (19.0 g of 20% [AI] WP in 1 gal of water to cover 1000 ft^2) to concrete (Arthur, 1994, 1998). Resistance to cyfluthrin and other pyrethroids has been reported for the red flour beetle in Australia (Collins, 1990). In the United States, cyfluthrin resistance has been reported in the German cockroach, *Blatella germanica* L. (Cochran, 1996), but has not been reported for stored-product insects. Other insecticides labeled as surface treatment include the pyrethroid prallethrin, but there are no reports on chemical efficacy for this insecticide. The IGR hydroprene is also labeled for use as a general surface application and has activity against red flour beetle and confused flour beetle larvae (Arthur, 2001).

Commercial formulations of the inert dust diatomaceous earth (DE) are also labeled for general surface application inside mills, warehouses, and other indoor structures. DE is a natural product composed of the fossilized cell walls of diatoms, and deposits of this material are found worldwide (Fields and Korunic, 2000). DE is abrasive and damages the insect cuticle, but also interferes with the lipid layer and inhibits water absorption, and the eventual result is death through dessication (Glenn *et al.*, 1999). Some researchers attempt to define DE as "physical control" because neurotoxic mechanisms are not involved, but regulatory agencies such as the US-EPA define DE as a reduced-risk low-toxicity insecticide, often with the acronym GRAS (generally regarded as safe). Most of the research with DE has been conducted on bulk grains (Golob, 1997; Korunic, 1998), and there is comparatively little information regarding actual effectiveness as a surface treatment. In one test in which adult red flour beetles and confused flour beetles were exposed directly to DE, efficacy was inversely correlated with relative humidity and directly correlated with temperature (Arthur, 2000). Mortality was also slower for DE compared to other surface treatments. A 48- to 72-hr exposure period was required to kill both *Tribolium* species with DE, compared to a 2- to 3-hr exposure to the high label rate of cyfluthrin WP (Arthur, 2000).

Several organophosphate, carbamate, and pyrethroid insecticides are labeled as crack-and-crevice treatments inside milling and processing facilities. These include, but are not limited to, the carbamates propoxur and bendiocarb; the organophosphates dursban, diazinon, and acephate; and the pyrethroids fenvalerate, λ-cyhalothrin, and resmethrin. Most of these insecticides cannot be used when the plant is in operation. Cyfluthrin is also labeled as a crack-and-crevice treatment, and some labels permit use when the plant is operational. Also, registrations are changing as a result of regulatory restrictions, and some carbamates and organophosphates are being withdrawn from the market.

D. PHEROMONES

Pheromones are used primarily for monitoring pest populations, but their use as pest suppression tools has also been proposed. These alternative uses include mass trapping, mating disruption, and lure and kill. Although these approaches have been tried with varying levels of success in field and orchard crop systems, they have had limited application for the management of stored-product insects.

The concept behind mass trapping is simple: place a large number of traps in a small area and the product will be protected because a high proportion of the pests will be removed from the population. However, the impact of this approach may be limited because only males are attracted to sex pheromone lures, low trap efficiency, high populations can lead to trap saturation, and high-density trapping can be costly to set up and maintain (Howse *et al*., 1998). In food processing and warehouse environments, moth species such as the Indianmeal moth appear to be the most suitable candidates for population suppression using mass trapping. However, one male Indianmeal moth is capable of mating with up to 10 females (Brower, 1975) so a very high proportion of males would have to be removed before significant population reductions are achieved. Roelofs *et al*. (1970) calculated that for some moth species as many as five traps will be needed for every calling female before a 95% reduction can be achieved. The ability to mass trap is also reduced by the high mobility of male moths and their ability to immigrate from other locations, even from outside the facility (Campbell *et al*., 2002).

Evaluation of the efficacy of a mass trapping program can be difficult. Because of variation among facilities it is difficult to replicate mass trapping programs and compare them to controls. Thus, it is difficult to prove that it is the mass trapping that is causing changes in populations. This can be addressed only by performing long duration studies with alternating periods of mass trapping. An additional problem is that using pheromone traps to monitor the effectiveness of a pheromone mass trapping program can be misleading, as only the male population is measured and not the females or the level of product infestation. Despite these difficulties, there have been some long-term studies that have reported success using mass trapping. Pierce (1994) did mass trapping for the Indianmeal moth, *P. interpunctella*, in a food warehouse using trap densities of one trap per 210 m^3 and reported a 96% decrease in trapped moths for one season. Long-term mass trapping of the cigarette beetle, *Lasioderma serricorne*, over a 9-year period reduced populations (Pierce, 1999).

Mating disruption involves the use of artificially produced high pheromone concentrations in a confined area to impede the ability of males to detect and locate females. This results in fewer matings and ultimately lower pest populations and a decrease in damage (Carde and Minks, 1995). We are not aware of this approach having been used in commercial food facilities. A problem with its application in food facilities is that harborages such as packaged commodities, wall voids, and even locations outside the building exist where mating disruption is not occurring, which may limit efficacy.

Lure and kill is a modification of mass trapping in which the insect is lured by a synthetic pheromone to a location where it is exposed to a pesticide or pathogen that eliminates it from the population. This approach, also known as "attracticide" or "attract and kill," has shown some promise for control. It is an IPM approach for stored product moths that was first described by Trematerra and Battainia (1987). They used a combination of mass trapping and insecticides to control the Mediterranean flour moth *Anagasta kuehniella*. In a similar study, Trematerra (1988) reported that the combination of trapping and pesticides kept population levels below economic levels for 1 year. However, the moths were not eradicated and improved sanitation at the mill may have impacted populations significantly. Shapas *et al.* (1977) used a combination of the protozoan pathogen *Mattesia trogodemae* and pheromone trapping to reduce populations of the dermestid beetle *Trogoderma glabrum*. Vail *et al.* (1993) demonstrated that granulosis virus picked up in pheromone-baited traps by male Indianmeal moth was spread to other individuals. The lure-and-kill technique probably has the greatest potential for the suppression of pest species in commercial facilities, especially if the cost of each killing station is low so that large numbers can be set up.

E. HEAT

With the impending loss of the fumigant methyl bromide, heat treatments are receiving increased attention as a whole-plant structural treatment for insect control (Dowdy and Fields, 2002; Wright *et al.*, 2002). Although the idea is not new (Dean, 1911, 1913), new technologies and advances in heating equipment and design are contributing to the renewed interest in using heat for insect control. Heat can be generated through electrical, diesel, or propane heaters or through an internal steam system, and the goal is to produce temperatures of at least 45 to 55 °C and holding those temperatures for 24–48 hr. Thermal requirements for mortality are known for most of the economically important stored product insects (Fields, 1992; Howe, 1965b; Wright *et al.*, 2002). Many private companies are already actively using heat as a part of their management strategies (Heaps, 1988), but data regarding effectiveness are largely proprietary and not published in the public domain. Most of the recent published research involves tests conducted in experimental situations or facilities. Heat combined with desiccant dusts (DE) effectively reduced the temperatures necessary to kill stored-product insects (Dowdy, 1999; Dowdy and Fields, 2002). In another test, high temperatures typically attained during a heat treatment had no deleterious effects on contact insecticides such as cyfluthrin WP and hydroprene and may have even enhanced the toxicity of cyfluthrin WP (Arthur and Dowdy, 2003). Other research studies have shown that during a heat treatment the temperatures within a facility often are not uniform (Dowdy and Fields, 2002). Contour mapping can be used to plot the temperature accumulations and identify those areas that may not reach target temperatures, which could then allow some insects to survive.

F. BIOLOGICAL CONTROL

Insect populations are regulated by top-down (e.g., natural enemies that feed on the insect) or bottom-up (e.g., availability of food) processes and insects can become pests when this regulation is disrupted. Insects have a suite of natural enemies such as parasites (e.g., parasitoid wasps, nematodes), pathogens (e.g., bacteria, fungi, viruses, protozoa), or predators that exploit the insect as a resource and in the process cause disease and mortality. Biological control uses natural enemies to reduce or maintain pest populations below damaging levels. There is a long history of research into the biological control of stored-product pests and the topic has been reviewed multiple times (e.g., Arbogast, 1984; Brower *et al*., 1995; Burkholder and Faustini, 1991; Haines, 1984; Schöller and Flinn, 2000). Some experimental successes using biological control have been reported for both whole and processed commodity storage situations, but the use of biological control as a component of IPM in the food industry remains very limited. Although not well documented, natural enemies occur in food facilities and can impact pest populations, even if they are not suppressing populations dramatically due to either intrinsic factors or constraint by other management tools. The incorporation of biological control as a component of IPM may increase in the future with the reduction in the use of broad-spectrum insecticides and better pest monitoring.

There are multiple biological control approaches: conservation, classical introduction, augmentative, inoculative, and inundative. Using conservation biological control, conditions are manipulated in ways that attract, retain, or enhance the effectiveness of natural enemies that are already present in the environment. For example, Flinn's (1998) study on the effect of grain temperature on parasitoid wasp *Theocolax elegans* (Westwood) suppression of *R. dominica* populations in wheat indicated that aeration of the grain bin could increase the effectiveness of the parasitoid. Other ways to conserve natural enemies include using safer chemical pesticides and modifying storage structures (Haines, 1984) and providing additional shelter and food/hosts (Arbogast, 1984; Hagstrum, 1983). Classical biological control is used against pests that are not native to an area and lack effective natural enemies in their current location. It involves releasing natural enemies that have been collected from the pest's geographic region of origin. Because most stored-product pests have been widely distributed throughout the world for a long period of time, the classical approach is often not feasible. A notable exception is the larger grain borer *Prostephanus truncatus* in Africa where a natural enemy (a predatory beetle *Teretriosoma nigrescens* Lewis) has been identified from central America, screened and tested in the laboratory, and released in Africa (Böye *et al.*, 1994; Rees, 1991). Augmentative biological control involves the release of commerically produced natural enemies to supplement and enhance a natural enemy population already present, but not present in sufficient numbers at the optimal time to provide the desired level of pest suppression. Inoculative biological control involves a single release of natural enemies to establish them in an area where they are not currently present. Inundative biological control involves the release of large numbers of commercially produced natural enemies to reduce the pest population below the economic injury level and is similar to using natural enemies as a biological insecticide.

1. Insect pathogens

The use of pathogens (e.g., fungi, bacteria, protozoa, viruses) for stored-product pest management has been limited primarily to basic research and rarely have they been used in IPM programs (Moore *et al.*, 2000). This is due to a variety of reasons, including their cost and concerns about pathogens becoming contaminates of the final food product. There is little evidence that consuming food with microbial insecticides presents a health hazard (Burges, 1981; Siegel and Shadduck, 1990), but the use of pathogens, even if specific for insects, around human food does present challenges in terms of public perspective. Despite this relatively dim outlook, some pathogen species have been registered for use on stored-products and some species occur naturally in stored-product pest populations and storage environments where they may impact pest population dynamics (Burges and Hurst, 1977; Krieg, 1987; Morris *et al.*, 1998; Oduor *et al.*, 2000). The emphasis on insect pathogen use has been on inundative releases, but as a single control tactic, insect pathogens are unlikely to be suitable substitutes for chemical insecticides. However, as part of an IPM program using reduced chemical pesticide applications they have potential. A particularly promising area is autoinoculation releases using food and pheromone baits to attract insects that pick up the pathogen and then disseminate it through the environment (Shapas *et al*., 1977; Vail *et al*., 1993; Vega *et al*., 1995) [see Moore *et al*. (2000) for a more in-depth review of insect pathology and stored-product insects].

Many bacterial species are associated with insects and most often they need to be ingested for an insect to become infected. *Bacillus thuringiensis* (Bt) is the most significant bacterial biological control agent: it is formulated and applied like many chemical pesticides. *B. thuringiensis* var. *kurstaki* isolate HD-1 has been registered in the United States for application to grain, seeds, peanuts, soybeans, and tobacco to control some lepidopteran pests, but is not widely used. Bt can be effective at reducing Indianmeal moth populations in wheat, corn, and peanuts (McGaughey, 1982, 1985a). It is harmless to vertebrates, including humans, and is exempt from residue tolerances on raw agricultural commodities in the United States (Dales, 1994). Unfortunately, resistance to Bt has been reported to develop quickly in stored-product moths (McGaughey, 1985b; McGaughey and Beeman, 1988).

Fungi typically infect host insects by spores on the cuticle germinating and growing through the insect cuticle until they enter the insect hemocoel where further growth results in mortality. There are many species of fungi, but most stored-product work has focused on *Beauveria bassiana* (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metchnikoff) Sorokin. A number of laboratory studies have demonstrated that some species and isolates can cause significant mortality in stored-product beetles (Adane *et al*., 1996; Rodrigues and Pratissoli, 1990). Different formulations have also been tested that may reduce contamination of food and increase efficacy (Dales, 1994; Hluchy and Samsinakova, 1989). *B. bassiana* formulated with food pellets with pheromone has been tested for management of the larger grain borer *P. truncatus* (Smith *et al*., 1999). *B. bassiana* has a registration that permits its use on stored products, but is not widely used. Research indicates that synergistic interactions can be achieved by combining *B. bassiana* with DE to control stored-product beetles (Lord, 2001).

Viruses are cellular parasites that spread through the insect's body, typically starting with the gut cells, causing the cessation of feeding within a few days, reduced fertility, and ultimately death. The virus can also be transmitted from the adult female to her eggs (Vail *et al*., 1993). A number of viruses have been isolated from stored-product insects [e.g., nuclear polyhedrosis virus (NPV), granulosis virus (GV), cytoplasmic polyhedrosis virus], most often from Lepidoptera, and they tend to be highly host specific. Most baculoviruses (NPV and GV) are found in the environment protected inside occlusion bodies that, after insect ingestion, are dissolved, releasing the infectious baculovirus particles. A *P. interpunctella* GV has been identified and is the most widely studied virus of stored product insects. Use of GV has been successful experimentally in stored almonds (Hunter *et al.*, 1977) and raisins (Vail *et al.*, 1991) and as a surface treatment in grain (Cox and Wilkin, 1996). Simple GV production and formulation methods were developed and patented (Vail, 1991), but this virus is not used commercially.

Protozoa are single-celled organisms that parasitize primarily the insect fat body and digestive system. They enter an insect by ingestion of spores or can be passed from females to their eggs. Protozoa occur widely in stored product Coleoptera and Lepidoptera and are one of the most extensively studied groups of stored product pathogens in terms of their biology, but research on their use as biological control agents is more limited (Moore *et al.*, 2000). Protozoan infections tend to be slow acting and chronic, causing reduced survival to the adult stage, deformities, reduced fecundity, and mortality, but they can function in regulating insect populations (Brooks, 1988). Protozoan infections can also increase susceptibility to chemical pesticides (Khan and Selman, 1984; Rabindra *et al.*, 1988) and other stressors such as starvation (Dunkel and Boush, 1969). Protozoan safety and ability to persist in stored product environments suggest that they may have potential as part of IPM programs (Moore *et al.*, 2000). The neogregarine protozoan *Mattesia trogodermae* Canning attacks several species of *Trogoderma*, including the Khapra beetle, and has been demonstrated to suppress *Trogoderma glabrum* (Herbst) populations in a simulated warehouse using pheromone lures to facilitate spore dissemination (Brooks, 1988; Shapas *et al.*, 1977).

2. *Parasites and predators*

A suite of parasites and predators are associated with stored-product insects and they have received considerable experimental research, but relatively little field study. Schöller (1998) reported that 58 species of parasitoids and predators that attack 79 species of stored-product pests have been studied in at least 900 published articles. Most species are widely distributed geographically and are often found associated with human storage of food. These species are variable in the host species utilized, the life stage attacked, and their degree of specificity. Some species are specialists and attack only a single or a few closely related species and some are generalists that attack a wider range of not closely related species. Because most food storage environments have multiple pest species, host specificity is an important consideration. The ability of these natural enemies to find insects in hidden and poorly accessible areas such as cracks and crevices and under shelving is an important attribute.

Parasitoid wasps are the most widely studied group of insect parasites. Female wasps lay an egg(s) on or in an insect and the progeny develop utilizing that insect as their sole food source, eventually killing the host. Female parasitoids tend to be host specific and typically exploit a specific host immature life stage (e.g., egg, larvae, or pupae). Most parasitoid wasps are relatively small. Females actively seek out multiple hosts and can find and parasitize host insects in cryptic habitats. There is a wide range of species that attack stored-product insects and a considerable body of research on these natural enemies, only some of which are covered here [see Godfray (1994) for more information on parasitoids and Brower *et al.* (1995) and Schöller and Flinn (2000) for reviews of information specifically on stored product parasitoids].

Internal feeding grain pests are susceptible to parasitoid species that are able to move through bulk grain, detect seeds that are infested, drill through the seed, sting the larvae inside the seed, and lay an egg. Some of the major parasitoid species are *Anisopteromalus calandrae* (Howard), *Lariophagus distinguendus* Förster, *Pteromalus cerealellae* (Ashmead), and *Theocolax elegans* (Westwood). These species tend to be facultative and attack multiple internally feeding species. For example, *A. calandrae* can attack *Sitophilus* spp., *Rhyzopertha dominica, Prostephanus truncatus, Callosobruchus* spp., and *Sitotroga cerealella*, among others (Brower *et al*., 1995). The parasitoid *Anisopteromalus calandrae* has been demonstrated to reduce rice weevil infestations in wheat spillage by 90% (Press *et al*., 1984) and to reduce infestation of bagged wheat (Cline *et al*., 1985).

The immature stages of externally feeding stored-product pests are also susceptible to attack by parasitoids. The eggs of several important stored-product moths are susceptible to attack by tiny wasps in the genus *Trichogramma*. For example, the species *T. pretiosum* Riley and *T. evanescens* Westwood attack the eggs of *Plodia interpunctella, Ephestia elutella*, and *Cadra cautella* (Brower, 1983a,b). *Trichogramma* spp. have been reported from peanut storage environments (Brower, 1984) and weekly releases have reduced moth populations in ishell peanuts (Brower, 1988). *Trichogramma evanescens* Westwood has been used commercially in Europe for the management of stored-product moths in retail facilities (Schöller and Flinn, 2000).

Lepidoptera larvae are also attacked by a suite of parasitoids. *Habrobracon (Bracon) hebetor* is a larger braconid wasp that stings, paralyzes, and lays eggs on late-instar larvae that are searching for pupation sites (Hagstrum and Smittle, 1977). *Venturia canescens* is an ichneumonid wasp that parasitizes pyralid moth larvae, including *P. interpunctella*, and has been recovered from flour mills and other food storage facilities (Carlson, 1979). This species attacks a range of larval instars, which are only temporally parasitized while eggs are laid internally. In simulated warehouses, the parasitoid wasps *H. hebetor* and *V. canescens* are capable of reducing *C. cautella* infestation in food spillage and reducing subsequent infestation of packaged commodities (Cline and Press, 1990; Cline *et al*., 1984, 1986). As discussed by Cline and Press (1990), the combination of packaging that reduces infestation and parasitoid wasps to reduce pest populations in the structure of the building may be an effective approach in certain situations.

Beetle larvae are also susceptible to attack by parasitoids. For example, wasps in the genus *Cephalonomia* attack a range of stored product beetles. *Cephalonomia waterstoni* Gahan attacks several *Cryptolestes* species. Females follow the chemical trails left by wandering larvae and when they find a suitable host they sting and paralyze it permanently before laying eggs (Howard and Flinn, 1990). Natural populations of *C. waterstoni* may be able to reduce populations of *C. ferrigineus* in wheat bins (Hagstrum, 1987). *Cephalonomia tarsalis* (Ashmead) parasitizes larvae of the sawtoothed grain beetle.

Nematodes are another group of insect parasites that have been studied extensively as biological control agents for a wide range of insect pests and crops (Georgis, 1992). They are sometimes considered to be pathogens, but because of their ability to actively seek hosts they are more like parasites (Campbell and Lewis, 2002). Entomopathogenic nematodes (Steinernematidae and Heterorhabditidae), the most studied group of nematodes, are small (<1 mm) round worms that infect only insects. These nematodes have been used primarily as a biological insecticide (i.e., inundative biological control), but they also have the potential to establish and persist in soil environments. Entomopathogenic nematodes have a long list of attributes that make them effective biological control agents (Gaugler and Kaya, 1990; Kaya and Gaugler, 1993): they have the ability to actively seek out insects in cryptic habitats and infect and quickly kill a wide range of insect species, they are not toxic to vertebrates and are exempt from EPA regulation, they can be mass produced and a number of species are available commercially, and they can be applied using conventional pesticide spray equipment. Entomopathogenic nematodes also generally have a good tolerance to various kinds of chemical pesticides and can be tank mixed with many pesticides (Kaya, 1985).

Laboratory studies have shown that a wide range of moth and beetle stored-product pest species and life stages are highly susceptible to entomopathogenic nematodes (Geden *et al*., 1985; Laumond *et al*., 1979; Morris, 1985). A key limitation on the use of entomopathogenic nematodes in bulk stored grain or food products is the requirement for moisture or high relative humidity. This limitation may be reduced when using nematodes to treat refuge populations of insect pests (e.g., crack and crevice, empty bin, outside spillage) rather than the bulk commodity (Brower *et al*., 1995). Nematodes are applied suspended in water like many chemical pesticides and this moisture could generate, temporarily, conditions that will enable the nematodes to move and locate insects to infect.

Many predators can utilize stored-product insects as a food resource, but not all can persist in commodity storage facilities and suppress pest populations effectively. The Hemipteran predator *Xylocoris flavipes* (Reuter), the warehouse pirate bug, is probably the most studied predator that persists in commodity storage facilities such as peanut warehouses and grain bins and can effectively suppress pest populations (Arbogast, 1978). This bug attacks the egg and early instar stages of many externally feeding stored product beetles and moths (Jay *et al*., 1968). Laboratory and small-scale field trials have indicated that this species can reduce pest populations, dramatically, especially external feeding beetles (Arbogast, 1976; Brower and Mullen, 1990; Brower and Press, 1992; LeCato *et al*., 1977; Press *et al*., 1975). The wide host range of this species is an advantage in food environments where multiple species typically occur, but not all species and stages are attacked readily (e.g., late-instar larvae and adults of larger species and internal feeding insects), although Donnelly and Phillips (2001) reported that *X. flavipes* could locate and kill *R. dominica* larvae inside wheat kernels. Combining *X. flavipes* with parasites that specifically target moths and internal feeding pests might be a more effective approach, but has not been tested (Brower *et al*., 1995). A variety of Coleoptera species are facultative predators of stored product pests, but a number of these species (e.g., *T. castaneum*) are also directly damaging to grain or processed commodities (LeCato, 1975). An exception is *Teretriosoma nigrescens*, which is an obligate predator and has been used as a biological control agent of the larger grain borer (Rees, 1987). Although many mite species are pests of stored commodities, some species found commonly in food storage situations are in fact predators of insects or of pest mite species. Mites are commonly found associated with stored product insects and they can cause disease and mortality and some species can be quite effective as egg predators. Predatory mites may be most effective at suppressing populations of other mites. The mite *Cheyletus eruditus* (Schrank) has been found to provide high levels of control of pest mite species such as *Acarus siro* L. in small-scale trials in bulk grain or empty bins (Pulpan and Verner, 1965; Zdarkova and Horak, 1990). Application of mites as biological control agents in bulk grain and food facilities is likely to be limited because some species may also attack humans [e.g., *Pyemotes tritici* (Schrank), straw itch mite or grocer's itch mite (Moser, 1975)] and potentially have negative impacts as human allergens.

VIII. CONCLUSIONS

A wide range of monitoring and management tools are available for stored-product pest management in the food industry, but often the effectiveness of these approaches and how best to integrate them are not well understood. Even as some tactics are being lost, new ones are being developed and tested, and older approaches that have not been used extensively due to the reliance on tactics such as fumigation are being revived. The difficulty for the food industry from an IPM perspective has been how to integrate these various tools into a coherent and effective program. Often there is reluctance or lack of interest on the part of the food industry to move away from calendar-based pesticide treatments to a more integrated approach. In large part this is due to a justifiable concern about making mistakes with pest control in an industry with an extremely low pest threshold. From a scientific perspective, there is also a shortage of experimental data from real world situations with which to make recommendations. With the pending loss of major management tools, such as methyl bromide and organophosphate insecticides, due to government regulations and market demands directly from consumers, there will be increasing pressure to develop IPM programs to keep our food supply safe from insect infestation and a need for the scientific community and the food industry to work together to find these solutions.

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